Volume 1

Handbook of Poultry Science and Technology

Primary Processing

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Consulting Editor
Y.H. Hui, Ph.D.

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A JOHN WILEY & SONS, INC., PUBLICATION

Published by John Wiley & Sons, Inc., Hoboken, New Jersey.
Published simultaneously in Canada.

Library of Congress Cataloging-in-Publication Data:

Handbook of poultry science and technology / editor, Isabel Guerrero-Legarreta; consulting editor, Y.H. Hui; associate editors, Alma Delia Alarcón-Rojo . . . [et al.].
p. cm.
Includes index.
ISBN 978-0-470-18537-7 (2-vol. set)
ISBN 978-0-470-18552-0 (v. 1)
ISBN 978-0-470-18553-7 (v. 2)
1. Poultry–Processing. 2. Poultry plants. I. Guerrero-Legarreta, Isabel.
TS1968.H36 2009
664′.93–dc22

2009014025

Printed in the United States of America
10 9 8 7 6 5 4 3 2 1

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PREFACE

Poultry has been and still is a major animal product in our diets. With the advances in preservation techniques for fresh poultry and processed products, consumer preferences for poultry and poultry products are higher than ever. Information on the science and technology of processing this important food commodity is essential to the work of government, academia, and industry.

Many good professional reference books are available. The preference for any particular one depends on the needs of the users. Most are single-volume books, with some covering general and others specific topics. Excluding encyclopedias, multivolume reference books in the discipline are uncommon for many reasons, such as cost, wide coverage, and standard technical challenges, including but not limited to the involvement of a large number of professionals and pressure of a timely publication. On the other hand, most big technical libraries in the world (government, academia, and industry) prefer comprehensive multiple-volume books because they reduce the needs for several books. From this perspective, our two-volume set is designed especially for libraries, although books of this nature will always serve as useful reference sources for students, researchers, instructors, and R&D personnel. The first volume covers the primary processing of fresh poultry and preservation of raw poultry meats. The second volume covers the secondary processing of raw poultry meats to processed retail products.

Volume 1 emphasizes primary processing and covers poultry and their slaughter practices, with an emphasis on classification, biology, production, transportation, slaughtering, pre- and postmortem handling, and carcass evaluation and cutting. The preservation methods for raw poultry meat are also described, such as heat, cold, chemical compounds, irradiation, and high pressure. Emphasis is placed on refrigeration and freezing since these preservation techniques are of major importance. The remaining topics include the engineering principles of packaging, quality attributes of poultry meat (taste, texture, tenderness, juiciness), safety of products and workers, sanitation, and government requirements for hazard control and risk analyses. Details are also provided for Jewish and

Muslim practices for slaughtering and processing poultry and poultry products. Eggs are always an integral part of a discussion related to poultry and poultry products. Coverage related to eggs includes health, nutrition, and the science and technology of processing eggs. Accordingly, the coverage in Volume I is divided into five sections. The table of contents provides the topics for the 38 chapters.

Volume 2 deals with secondary processing of poultry and poultry products covering the transformation from basic raw poultry meat into safe and wholesome products tailored for consumers. These products are available in many forms, including but not limited to such popular poultry items as sausage and deli meats. Some of these items are raw, some cooked but not ready to eat, and some cooked and ready to eat. Thus, the major goal of this volume is to present the technical knowhow needed for manufacturing such products. To do so, this volume presents a sequence of topics divided into seven sections.

Volume 2 begins with the basic principles in formulating and processing poultry products, including mechanical deboning, marination, emulsion basics, formulation, and breading. Many processed poultry products for consumers contain nonmeat ingredients, and this topic is discussed in detail. This is followed by the practical applications and techniques in manufacturing patties, sausages, bacon, ham, luncheon meats, nuggets, pâté, and other products. To produce a high-quality poultry product, one must be familiar with the color, flavor, and texture of raw and cooked poultry meats, and these quality attributes are described in detail. Obviously, the wholesomeness and safety of the product is a primary concern for all government agencies around the world. Because of the many outbreaks of foodborne diseases from contaminated poultry products, 9 of 39 chapters in this volume are devoted to sanitation and food safety system in the United States, covering topics such as contaminants, microbiology, pathogens, analytical techniques, and the requirements for sanitation, hazards identifications, and risks factors involved.

Although many topics are included in these two volumes, we do not claim the coverage to be totally comprehensive. The work is the result of the combined expertise of more than 150 people from industry, government, and academia: professionals from Argentina, Brazil, Canada, Finland, India, Italy, Japan, Malaysia, Mexico, Spain, and the United States. An international editorial team of 15 members from six countries led these experts. Each contributor or editor was responsible for researching and reviewing subjects of immense depth, breadth, and complexity. Care and attention were paramount to ensure technical accuracy for each topic. In sum, these two volumes are unique in many respects. It is our sincere hope and belief that they will serve as essential references on poultry and poultry processing.

We wish to thank all the contributors for sharing their expertise throughout our journey. We also thank the reviewers for giving their valuable comments, leading to improvements in the contents of each chapter. In addition, we thank members of the production team at John Wiley & Sons, Inc., for their time, effort, advice, and expertise. All these professionals made this two-volume treatise possible. You are the best judge of the quality of their work and we trust that you will benefit from the fruits of their labor.

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PART I

POULTRY: BIOLOGY TO PREMORTEM STATUS

1

POULTRY BIOLOGY, CLASSIFICATION, AND TRADE DESCRIPTIONS

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Handbook of Poultry Science and Technology, *Volume 1: Primary Processing*, Edited by Isabel Guerrero-Legarreta and Y.H. Hui

COMMERCIAL PRODUCTION OF CHICKEN

This book is not the proper forum to provide details on the commercial production of chickens. However, a general introduction is provided here as a frame of reference for discussion in all chapters.

Most commercial production of broiler chickens involves intensive and highly mechanized operations that use small areas in which the birds run on litter floors in large open poultry sheds. This differs from other forms of animal farming that use cages. However, a small percentage of broilers is now produced in larger areas in which the birds can run more freely. These birds are produced for specific markets.

Receipt of Chicks

Fertile chicken eggs are hatched in rooms with control for temperature and relative humidity. A yolk sac containing residue nutrients and moisture will sustain chicks for 2 to 3 days. However, it is important that the birds be kept warm, with feed and water available within easy reach. Within 72 h after hatching, chicks in ventilated boxes should be transported to broiler farms in specially designed air-conditioned trucks.

Housing Structure

On arrival at the farm, the newly hatched chicks are housed in open buildings called *units*, *sheds*, or *houses*. They vary in size, with a typical unit measuring 15 m $\times$ 150 m, holding about 40,000 adult chickens; some units can contain up to 60,000 broilers. There are usually three to 10 sheds or units on one farm. A typical new chicken farm has eight sheds holding about 40,000 birds each, with a total of about 320,000 chicken.

Ventilation by Mechanical Means In some countries, traditional broiler sheds are ventilated, with the sides of the sheds open to fresh air. The amount of fresh air is regulated by opening one or more vents or by leaving curtains open or closed accordingly. Other manual ventilation methods include the use of fans or a water-misting system to implement evaporative cooling in very hot weather. Newer chicken houses use tunnel ventilation: Fans at one end draw cool and fresh air over the chickens and fans at the other end blow it out. Heat sensors regulate the fans to heat and cool the structures at a desired rate of time and speed.

In some countries, including Canada and the United States, modern technology is used to air-condition such units in addition to other computerized systems to optimize management of the birds. Such operations are possible when chickens are mass-produced by multinational corporations under all environmental conditions. Chickens always have easy access to feed and water. Depending on the facility, silos on the outside supply feed into feed lines and pans from end to end of the unit. Drinkers are available at regular

intervals and connected to the water lines running from end to end of the shed.

Grow-out Phase

Key points to remember in the grow-out phase:

1. Provide suitable bedding, such as sawdust, wood shavings, or other material, such as rice hulls.
2. Preheat the unit.
3. Provide proper water and feed lines.

When the day-old chicks arrive at a broiler farm, routine procedures are as follows:

1. The chicks are initially confined to 30 to 50% of the floor space in the unit, usually referred to as the *brooding area*.
2. *Brooders*, gas heaters or heat lamps, are used to provide supplementary heat in addition to the shed heating system.
3. Extra feeding pans and water dispensers are added to assure sustenance. Additional paper is added on top of the bedding to prevent dropped feed from soiling the bedding.

Depending on several factors, including the business environment, a farm or company specializing in rearing male or female chicks for chicken meat may include both sexes in one plant or separate sexes in different plants in the same or different locations. The baby checks must enjoy comfort and good health to maximize their survival rate. The temperatures for proper rearing of baby chicks can be adjusted as follows:

- For the first few days, the optimal ambient temperature is 31 to 32°C.
- Growth is accompanied by less heat to keep them warm. After the first 2 days, the ambient temperature is decreased by about 0.5°C each day, until it reaches 21 to 23°C at 21 days.

The data above are suggestions only. Each farmer or company decides on the best temperature according to flock size, types of sheds, spaces available, and appropriate technical applications. Three factors are important: temperature, humidity, and air quality. All can be managed with the appropriate traditional means (i.e., fans, water vapors, ventilation, etc.) and/or modern technology (i.e., thermostats, pumps, vacuum, etc.).

The brooders are usually removed 4 or more days after the installation. In most cases they should be removed 2 weeks after installation. The space allocated to the flock increases as the chickens grow. Eventually, they are permitted to run freely over the entire shed floor. The farmer or company makes regular checks for the following:

- Is water available at all times or at a specific time?
- Is each water dispenser in working order?
- Is each feed dispenser in working order?
- Is feed available at all times or at a specific time?
- Is the ventilation system working properly?
- Is lighting adjusted to the proper intensity appropriate for the eyes of the chickens?
- Is lighting sufficient for chickens to locate water and feed?
- Is the dark period sufficient for chickens to rest?
- Are ambient temperature, humidity, and air quality adjusted and managed regularly using manual or automatic techniques?
- Is the litter clean and dry?
- Is the health of the flock excellent?
- Are dead, sick, or injured birds handled appropriately?
- Are the performance and health records of the flock acceptable?

Under proper management, a broiler flock usually suffers 3 to 4% loss during the grow-out phase. These birds may die of a variety of causes or from selective culling.

Harvesting Meat Chickens

Harvesting chicken is done several times annually or other defined period, depending on many factors, such as market needs and size of units. This collecting process is also known as *multiple pickup*, *partial depopulation*, *thinning out*, and other regional terms. In addition to being a business decision, this practice provides more space for the remaining birds and lowers the housing temperature. Several factors are involved in the actual process of harvesting:

1. *Days of growth*. The flock may be harvested at 30 to 35 days or as late as 55 to 60 days of growth.
2. *Time of day*. Night harvesting is preferred, to make sure that the birds are settled. Also, temperature plays a part during the summer.
3. *Collecting procedure*. Standard-experience crews pick up the birds in a dimmed lighting environment. This helps to settle the flock and facilitates handling. After being picked up by hand, the chickens are placed in specially designed containers for transport to a processing facility. Truck, rail, or other means of transport follows standard regional requirements.

Cleaning a Unit for a New Flock

Cleaning a unit after a flock has been harvested is essential before accepting the next batch of newborn chicks. The goals are no different from those of other businesses. Health, safety, and many other aspects are important factors

in guaranteeing that products are wholesome, marketable, and optimally cost-effective. So the following considerations are of major concern:

1. One batch of chicks stays for about 60 days, at which point it is removed from the housing unit. The period available for cleaning before the next batch arrives ranges from 5 to 15 days.
2. The extent of cleaning varies with each farmer or company and depends on the size of the flock, the size of each unit, and the types of operations (e.g., manual vs. mechanized vs. high tech). Cleaning covers bedding, floors, feed and water dispensers and accessories, equipment (i.e., fans, vacuum, pumps, etc.), and extraneous matter (i.e., rodent droppings, glass pieces, etc.). The techniques used vary depending on labor, devices, and other factors.
3. Legal requirements must be complied with in all aspects of the cleaning process: sanitation principles, use of such chemicals as disinfectants and insecticides, space allocation, and many other considerations.

Diseases: Precautions, Pest Control, and Records

At some farms, workers are responsible for diseases in the flock. Sources of contamination include hands, footwear, and vehicles. To minimize such risks, precautions include:

1. Enforcing authorized entries to sheds.
2. Enforcing the use of overalls and boots.
3. Requiring disinfection of footwear in specially equipped locations near entrances to sheds.
4. Disinfecting all equipment, including vehicles and pumps, with water or solutions.
5. Visiting flocks from youngest to oldest.

Birds in the environment can infect farmed chickens with diseases through their presence or droppings. Routine cautionary steps include the following:

1. Removing dropped feeds promptly.
2. Keeping domesticated birds in a location far from the sheds.
3. If circumstances permit, avoiding sources of environmental water such as dams and rivers.
4. Assuring that the chickens' drinking water is sanitary.
5. Enclosing the sheds using netting or a roof, or using completely enclosed sheds with proper ventilation.

Standard pest controls must be in place to prevent diseases from rodents or insect parts. There should also be mandatory or voluntary record keeping for chicken health, growth, and behavior.

Growth and Nutrition

Many factors are involved in achieving optimal growth rate and size at harvest, such as breed, gender, nutrition, and feed. *Nutrition* is the sum of processes by which food is selected and becomes part of the body. Balanced nutrition provides the nutrients that best meet bodily requirements for growth, maintenance, and repair. This fact applies to all living creatures. The word *nutrient* refers to a broad category of organic and inorganic compounds. The essential nutrients are carbohydrates (the source of energy), protein, fat, vitamins, minerals, and water.

Supplying enough nutrients to meet the requirements for maximum poultry production can be difficult. It is not feasible economically to supply just the right amount of food to meet requirements because some of the nutrient needs must be oversupplied to compensate for the limiting nutrients in the feed: usually energy and essential amino acids such as lysine and methionine. The formulation of poultry diets considers the essential nutrients of water, energy, protein, fat, vitamins, and minerals in the proper amounts for successful operation. They are provided by animal and vegetable proteins, animal and vegetable fats, macro and micro minerals, vitamin premixes, and cereals. Each separate type of ingredient provides a specific quantity and quality of nutrients to the diet and must be formulated skillfully for maximum growth, egg production, and feed efficiency. Balancing these ingredients to produce an optimal diet for poultry requires knowledge of the needs and composition of the ingredients as well as their cost: The formulation must balance needs vs. ingredients vs. costs.

Feed efficiency refers to the amount of feed required to produce a pound of body weight or the amount of feed necessary to produce a dozen eggs. Feed accounts for 65 to 70% of the cost of production, so producers should pay close attention to the requirements of each species.

Feed

Chicken feeds can come from a variety of sources, including land and marine plants and animal products. Although most feed is made up of land plants such as grains, others may be produced from certain land animal and marine plant and animal products. For ease of reference, let us assume that major chicken feed manufacturers use such grains as wheat, sorghum, barley, oats, lupins, soybean meal, canola, and other oilseed meals and grain legumes.

The use of additives and drugs in commercial poultry is governed by laws and regulations which vary from country to country. Depending on its size and operations, a feed manufacturer offers many options for meat chicken diets formulated to optimal and strict nutritional standards: These formulations will reflect availability, price and quality of the ingredients required, and the location, season, and age of a particular broiler flock.

Other than nutritional considerations, feeds are also produced to meet other requirements, including but not limited to:

1. *Starter feed:* small crumbles for baby chicks
2. *Grower feed:* fully formed pellets for growing birds
3. *Finisher feed:* feed made available after 25 days
4. *Withdrawal feed:* feed provided just before harvest

In the last 50 years, much professional and consumer literature has been disseminated on the rearing, production, and management of poultry. Readers should consult such sources for more details. However, as an illustration, one specific topic, competitive exclusion as a natural part of poultry management, is discussed in Chapter 2.

BIRDS COMMON TO THE LIVE-BIRD MARKETING SYSTEM

For regulatory commercial purposes, the U.S. Department of Agriculture (USDA) recognizes particular birds (poultry) common to the live-bird marketing system (Figure 1). The types of common live birds in domestic and international commerce are listed in Table 1.

BIOLOGICAL AND LEGAL CLASSIFICATION OF POULTRY IN THE UNITED STATES

The U.S. Department of Agriculture (USDA) has classified major poultry and poultry products in commercial transactions (see Table 2).

Ready-to-Cook Poultry

The standards apply to individual carcasses of ready-to-cook poultry in determining the type of poultry and its class. The types of poultry are: chickens, turkeys, ducks, geese, guineas, and pigeons. The classes within each type are described below.

Chickens

1. *Rock Cornish game hen or Cornish game hen:* a young immature chicken (usually, 5 to 6 weeks of age), with a ready-to-cook weight of not more than 2 lb, which was prepared from a Cornish chicken or the progeny of a Cornish chicken crossed with another breed of chicken.
2. *Rock Cornish fryer, roaster, or hen:* the progeny of a cross between a purebred Cornish and a purebred Rock chicken, without regard to the weight of the carcass involved; however, the term *fryer*, *roaster*, or *hen* applies only if the carcasses are from birds with ages and characteristics that qualify them for such designation under the regulations.

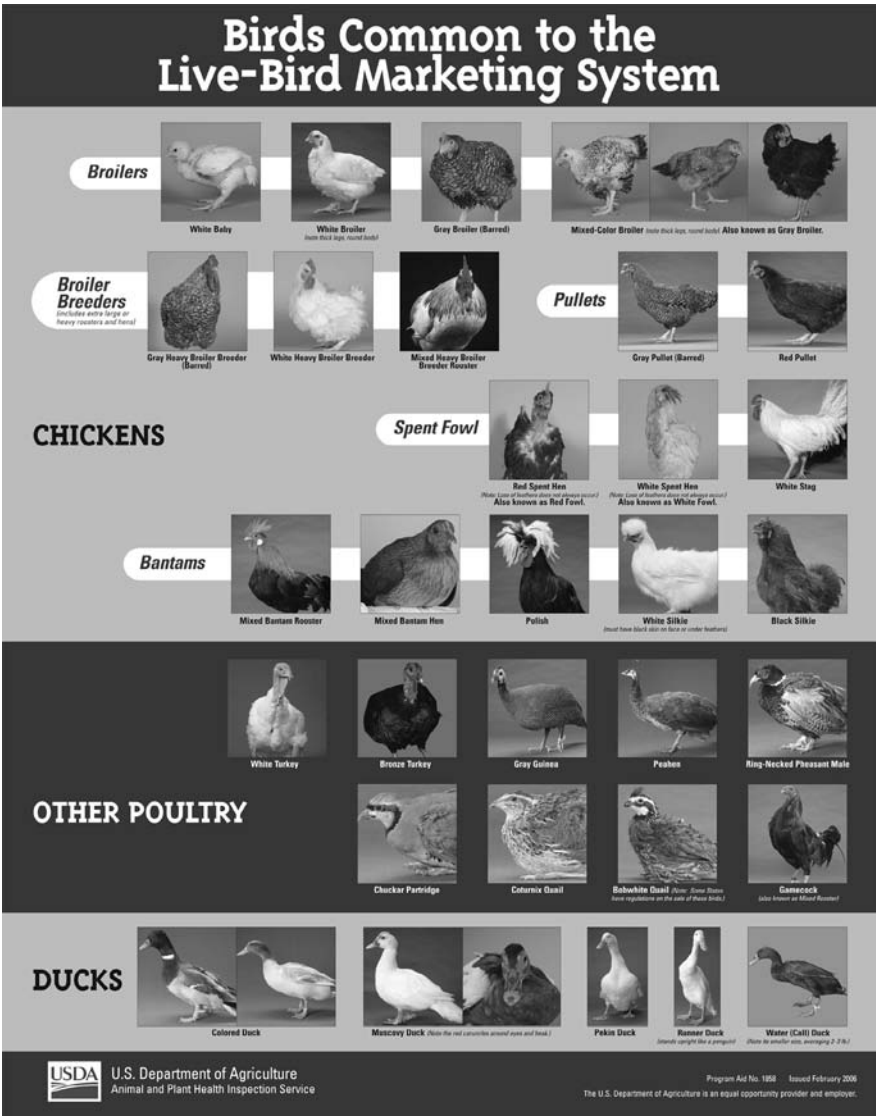

FIGURE 1 Birds common to the live-bird marketing system.

3. *Broiler or fryer:* a young chicken (usually, under 13 weeks of age), of either sex, that is tender-meated with soft, pliable, smooth-textured skin and flexible breastbone cartilage.
4. *Roaster or roasting chicken:* a young chicken (usually, 3 to 5 months of age) of either sex that is tender-meated with soft, pliable, smooth-textured skin and breastbone cartilage that may be somewhat less flexible than that of a broiler or fryer.

TABLE 1 Birds Common to the Live-Bird Marketing System

Chicken	Type
Broilers	White baby
	White broiler (note the thick legs and round body)
	Gray broiler (barred)
	Mixed-color broiler (note the thick legs and round body); also known as gray broiler
Broiler breeders (includes extralarge or heavy roosters and hens)	Gray heavy broiler breeder (barred)
	White heavy broiler breeder
	Mixed heavy broiler breeder rooster
Pullets	Gray pullet (barred)
	Red pullet
Spent fowl	Red spent hen (note that loss of feathers does not always occur); also known as red fowl
	White spent hen (note that loss of feathers does not always occur); also known as white fowl
Bantams	Mixed bantam rooster
	Mixed bantam hen
	Polish
	White silkie (must have black skin on face or under feathers)
	Black silkie
Other poultry	White turkey
	Bronze turkey
	Gray guinea
	Peahen
	Ring-necked pheasant, male
	Chuckar partridge
	Coturnix quail
	Bobwhite quail (some states have regulations on the safety of these birds)
	Gamecock also known *as* inlixed rooster
Ducks	Colored duck
	Muscovy duck (note the red caruncles around the eyes and beak)
	Pekin duck
	Runner duck (stands upright like a penguin)
	Water (call) duck (note its smaller size, averaging 2 to 3 lb)

5. *Capon:* a surgically unsexed male chicken (usually, under 8 months of age) that is tender-meated with soft, pliable, smooth-textured skin.
6. *Hen, fowl, or baking or stewing chicken:* a mature female chicken (usually, more than 10 months of age) with meat less tender than that of a roaster or roasting chicken and a nonflexible breastbone tip.

TABLE 2 Poultry and Poultry Products Common in Commerce

Ready-to-Cook Poultry	Ready-to-Cook Poultry Food Products
Chickens	Poultry roast
Turkeys	Boneless poultry breasts, drumsticks, thighs, and legs
Ducks	Skinless poultry carcasses and parts
Geese	Poultry tenderloins and boneless, skinless parts
Guineas	Size-reduced poultry products
Pigeons	

7. *Cock or rooster:* a mature male chicken with coarse skin, toughened and darkened meat, and hardened breastbone tip.

Turkeys

1. *Fryer–roaster turkey:* a young immature turkey (usually, under 16 weeks of age), of either sex, that is tender-meated with soft, pliable, smooth-textured skin, and flexible breastbone cartilage.
2. *Young turkey:* a turkey (usually, under 8 months of age) that is tender-meated with soft, pliable smooth-textured skin and breastbone cartilage that is somewhat less flexible than in a fryer–roaster turkey. Sex designation is optional.
3. *Yearling turkey:* a fully matured turkey (usually, under 15 months of age) that is reasonably tender-meated and with reasonably smooth-textured skin. Sex designation is optional.
4. *Mature turkey or old turkey* (*hen or tom*)*:* an old turkey of either sex (usually in excess of 15 months of age), with coarse skin and toughened flesh.

For labeling purposes, the designation of sex within the class name is optional, and the two classes of young turkeys may be grouped and designated as "young turkeys."

Ducks

1. *Broiler duckling or fryer duckling:* a young duck (usually, under 8 weeks of age), of either sex, that is tender-meated and has a soft bill and a soft windpipe.
2. *Roaster duckling:* a young duck (usually, under 16 weeks of age), of either sex, that is tender-meated and has a bill that is not completely hardened and a windpipe that is easily dented.
3. *Mature duck or old duck:* a duck (usually, over 6 months of age), of either sex, with toughened flesh, a hardened bill, and a hardened windpipe.

Geese

1. *Young goose:* may be of either sex, is tender-meated, and has a windpipe that is easily dented.

2. *Mature goose or old goose:* may be of either sex and has toughened flesh and a hardened windpipe.

Guineas

1. *Young guinea:* may be of either sex, is tender-meated, and has flexible breastbone cartilage.
2. *Mature guinea or old guinea:* may be of either sex and has toughened flesh and a hardened breastbone.

Pigeons

1. *Squab:* a young, immature pigeon of either sex that is extratender-meated.
2. *Pigeon:* a mature pigeon of either sex, with coarse skin and toughened flesh.

Poultry Parts

Individual carcasses of ready-to-cook poultry, parts of ready-to-cook poultry, and individual units of specified poultry food products are categorized as noted below. Clear to semiclear marinades or sauces may be added to ready-to-cook poultry products, provided that the ingredients do not alter or affect the appearance or definition of the product. Poultry parts are:

1. *Backs*
2. *Breasts* are separated from the back at the shoulder joint and by a cut running backward and downward from that point along the junction of the vertebral and sternal ribs. The ribs may be removed from the breasts, and the breasts may be cut along the breastbone to make two approximately equal halves; or the wishbone portion may be removed before cutting the remainder along the breastbone to make three parts. Pieces cut in this manner may be substituted for lighter or heavier pieces for exact weight-making purposes, and the package may contain two or more such parts without affecting the appropriateness of the labeling (e.g., “chicken breasts”). Neck skin will not be included with the breasts, except that “turkey breasts” may include neck skin up to the whisker.
3. *Breasts with ribs* are separated from the back at the junction of the vertebral ribs and back. Breasts with ribs may be cut along the breastbone to make two approximately equal halves; or the wishbone portion may be removed before cutting the remainder along the breastbone to make three parts. Pieces cut in this manner may be substituted for lighter or heavier pieces for exact weight-making purposes, and the package may contain two or more such parts without affecting the appropriateness of the labeling (e.g., “breasts with ribs”). Neck skin will not be included, except that “turkey breasts with ribs” may include neck skin up to the whisker.

4. *Drumsticks* are separated from the thigh by a cut through the knee joint (femorotibial and patellar joint) and from the hock joint (tarsal joint).
5. *Halves* are prepared by making a full-length back and breast split of an eviscerated poultry carcass so as to produce approximately equal right and left sides.
6. *Front poultry halves* include the full breast with corresponding back portion, and may or may not include wings, wing meat, or portions of wing.
7. *Rear poultry halves* include both legs and adjoining portion of the back attached.
8. *Legs* include the whole leg (i.e., the thigh and the drumstick), whether jointed or disjointed. Back skin is not included.
9. *Legs with pelvic bone* consist of a poultry leg with adhering meat and skin and pelvic bone.
10. *Quarters* consist of the entire eviscerated poultry carcass which has been cut into four equal parts, but excluding the neck.
11. *Breast quarters* consist of half a breast with the wing and a portion of the back attached.
12. *Breast quarters without wing* consist of a front quarter of a poultry carcass from which the wing has been removed.
13. *Leg quarters* consist of a poultry thigh and drumstick with a portion of the back attached.
14. *Tenderloins* consist of the inner pectoral muscle, which lies alongside the sternum (breast bone) of the poultry carcass.
15. *Thighs* are disjointed at the hip joint and may include the pelvic meat but not the pelvic bones. Back skin is not included.
16. *Thighs with back portion* consist of a poultry thigh with a back portion attached.
17. *Wings* include the entire wing (consisting of three segments) with all muscle and skin tissue intact, except that the wing tip (third segment) may be removed.
18. *Wing drummettes* consist of the humerus (first segment) of a poultry wing with adhering skin and meat attached.
19. *Wing portions* consist of a poultry wing with adhering skin and meat attached, except that the drummette (the first segment) has been removed The wing portion may consist of the second segment only, or the second and third segments.
20. *Wishbones* (pulley bones), with covering muscle and skin tissue, are severed from the breast approximately halfway between the end of the wishbone (hypocledium) and from the point of the breastbone (cranial process of the sternal crest) to a point where the wishbone joins the shoulder. Neck skin is not included with the wishbone.

Some factors that detract from quality:

1. Feathers
2. Exposed flesh (resulting from cuts, tears, and missing skin)
3. Discolorations (whether or not caused by dressing operations and bruises)
4. Disjointed and broken bones
5. Freezing defects

INTERNATIONAL TRADE IN POULTRY

Each country sells and buys poultry and poultry products according to its own legal, commercial, and cultural considerations, in addition to other factors. These products are in high demand worldwide, and transactions between countries have varied widely for many years. For nearly a decade, the USDA has been working with other countries to develop a system to facilitate international trade in poultry and poultry products. In 2000 a document entitled *United States Trade Description for Poultry* was distributed by the USDA to achieve this goal. This document is related primarily to chicken and has been updated several times since 2000. Next we discuss selected parts of the document as a frame of reference for this book.

The document provides useful information on the following: species, product, style, bone, skin class, quality level, certification requirements, state of refrigeration, production and feeding systems, slaughter system, postslaughter processing, and skeletal diagrams for chicken. The species of chicken is the domesticated bird, *Gallus domesticus*. Items to be traded include, for example, whole breast, wing, thigh, or liver. Style is a marketable form of a product to be traded. Styles may differ in composition, cut, and/or method of processing. A description for the presence of bone:

1. *Bone-in*. Bones are not removed from the product.
2. *Boneless*. All bones are removed from the product.
3. *Partially boneless*. Some but not all bones are removed from the product.

A description of poultry skin is as follows:

1. *Skin-on*. White or yellow skin is not removed from the product, and the purchaser will accept product with whitish or yellowish skin color.
2. *Skinless*. Skin is removed from the product.
3. *Skin-on, white*. Skin is not removed from the product, and the purchaser requires a whitish skin color.
4. *Skin-on, yellow*. Skin is not removed from the product, and the purchaser requires a yellowish skin color.

Chicken can be classified as follows:

1. *Broiler/fryer:* young chickens that are usually 6 to 10 weeks of age with a dressed weight of 1.13 kg (2.50 lb) or more.
2. *Roaster:* chickens that are usually 7 to 12 weeks of age with a dressed weight of 2.27 kg (5 lb) or more.
3. *Heavy fowl:* breeding hens and roosters, also called *baking hens*, that are usually more than 10 months of age with an approximate dressed weight of 1.81 kg (4 lb).
4. *Light fowl:* hens that have produced table eggs, also called *stewing hens*, which are usually more than 10 months of age with an approximate dressed weight of 1.13 kg (2.50 lb).
5. *Capon:* neutered male chickens that are usually less than 4 months of age.
6. *Rooster:* mature male chickens that are usually more than 10 months of age with a dressed weight of 2.72 kg (6 lb) or more.
7. *Cornish game hen:* young chickens that are usually less than 5 weeks of age with a dressed weight of 0.91 kg (2 lb) or less.

Chicken products are graded or evaluated to meet certain levels of quality designated by the processor or government authority. The purchaser may request third-party certification of the product's quality level (quality grade) and/or purchaser-specified options. This certification is usually issued by a governmental agency.

Meat may be presented chilled, chilled with ice or CO_2 packed in a container, hard chilled, frozen, frozen individually without ice glazing, or frozen individually with ice glazing. Product storage temperatures should be such throughout the supply chain as to ensure uniform internal product temperatures as follows:

1. *Chilled*. Internal product temperature is between -2.8 and 4.44°C (27 to 40°F) at all times following the postslaughter chilling process.
2. *Chilled, ice packed*. Product is packed in a container with ice (frozen water, not dry ice) to maintain the internal product temperature between -2.8 and 4.44°C (27 to 40°F) at all times following the postslaughter chilling process.
3. *Chilled, CO_2*. Product is packaged (must be placed in an internal package) and packed in a container with solid carbon dioxide (dry ice) to maintain the internal product temperature between -2.8 and 4.44°C (27 to 40°F) at all times following the postslaughter chilling process.
4. *Hard chilled*. Internal product temperature is between -18 and -2.8°C (0 to 27°F) at all times following the postslaughter chilling process.
5. *Frozen*. Internal product temperature is -18°C (0°F) or lower (also known as *deep-frozen*) at all times after freezing.
6. *Frozen individually without ice glazing*. Product is individually frozen so that the pieces do not stick together when packaged. Internal product

temperature is −18°C (0°F) or lower at all times after freezing. This option is available for parts only.

7. *Frozen individually with ice glazing*. Product is individually frozen and glazed with water to assist in protecting the individual pieces from freezer burn. Internal product temperature is −18°C (0°F) or lower at all times after freezing. This option is available for parts only.

The most common production and feeding systems for chicks and chickens include:

1. *Traditional production and diet*. Birds are raised in heated and air-cooled growing houses and fed a precisely formulated high-protein diet.
2. *Free-range production with traditional diet*. Birds are raised in heated and air-cooled growing houses with access to the outdoors and fed a traditional high-protein diet. Because birds have access to the outdoors, diet and biosecurity are not controlled closely. Specific production requirements may need to be defined by buyer and seller.
3. *Pastured/pasture-raised production with traditional diet*. Birds are raised outdoors using movable enclosures located on grass and fed a traditional high-protein diet. Specific production requirements may need to be defined by buyer and seller.
4. *Traditional production with organic and/or antibiotic-free systems*. Birds are raised in heated and air-cooled growing houses and fed an organic diet (without hormones or nonorganic additives) and/or raised without antibiotics (drugs that are intended to prevent or treat animal illnesses). Purchaser must specify such system requirements.
5. *Free-range production with organic and/or antibiotic-free systems*. Birds are raised in heated and air-cooled growing houses with access to the outdoors and fed an organic diet (without hormones or nonorganic additives) and/or raised without antibiotics (drugs that are intended to prevent or treat animal illnesses). Purchaser must specify such system requirements.
6. *Pastured production with organic and/or antibiotic-free systems*. Birds are raised outdoors using movable enclosures located on grass and fed an organic diet (without hormones or nonorganic additives) and/or raised without antibiotics (drugs that are intended to prevent or treat animal illnesses). Purchaser must specify such system requirements.

The most common slaughter systems include:

1. *Traditional*. Poultry products are slaughtered and processed in accordance with industry-standard processing practices.
2. *Kosher*. Poultry products are certified as meeting Jewish dietary laws and standards regarding slaughter and processing.

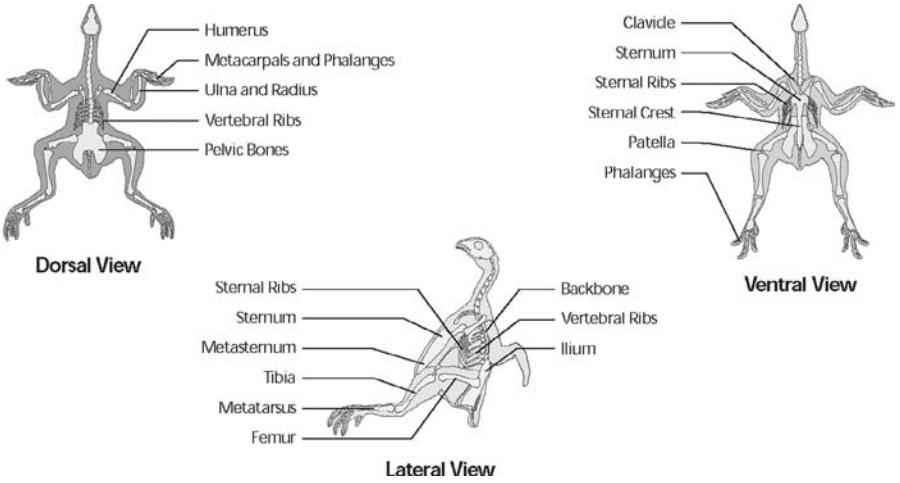

FIGURE 2 Skeletal diagrams of a whole chicken.

3. *Halal*. Poultry products are certified as meeting Islamic dietary laws and standards regarding slaughter and processing.

The most common postslaughter systems include:

1. *Immersion chilled*. The product is chilled by immersing it in cold water immediately after slaughter. U.S. producers typically use immersion chilling.
2. *Air chilled*. The product is chilled by exposing it to cold air immediately after slaughter.

Another tool used in international trade of chicken is the skeletal diagram, which is illustrated in Figure 2. Two of the three skeletal diagrams of a whole chicken shown in the figure are used to illustrate the composition of each whole-muscle product style. These three diagrams show the major bones of the chicken in dorsal or back view, ventral or breast view, and lateral or side view. The shaded areas of views for a particular product style represents the portion of the chicken included in that style.

2

COMPETITIVE EXCLUSION TREATMENT IN POULTRY MANAGEMENT

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INTRODUCTION

The gastrointestinal (GI) tract of an adult bird harbors complex populations of microbes, and these organisms play an important role in maintaining the health and well-being of the host. The mature gut flora competes effectively with any invading organisms that may be harmful to avian or human health and can prevent them from colonizing the digestive tract. Microbial colonization of the GI tract normally begins soon after hatching and especially when the bird starts eating (Mead, 2000; Revolledo et al., 2006). However, under the conditions of modern, large-scale poultry production, a mature gut flora is slow to develop. This is because the birds are hatched and reared initially in a highly sanitized environment, and there is no contact with the mother hen (Pivnick and Nurmi, 1982). In the 1950s it had been observed that the resistance of young chicks to *Salmonella* colonization increases with age, so that 2-week-old birds were more difficult to infect, even with relatively high doses of *Salmonella*, but there was no explanation of the phenomenon at that time (Milner and Shaffer, 1952).

The high susceptibility of the young bird and its lack of competitive gut flora were highlighted by Esko Nurmi in Finland 35 years ago. In 1971, the Finnish broiler industry suffered from a widespread outbreak of *Salmonella infantis* infection, the origin being a contaminated lot of raw feed material (Nurmi et al., 1992). The majority of broiler flocks became *Salmonella*-positive, and at the same time the incidence of human cases from this serotype increased considerably. In an attempt to solve the problem of *Salmonella* infection in poultry, research was begun at the National Veterinary and Food Research Institute. Nurmi and his research group were the first to demonstrate experimentally that administering intestinal contents from healthy adult birds to newly hatched chicks prevented them from becoming colonized by *Salmonella* (Nurmi and Rantala, 1973) and that the protective microflora could be cultured for administration by a relatively simple method (Rantala and Nurmi, 1973). The Nurmi approach has been widely adopted in different countries in relation to *Salmonella* control in poultry and is referred to as the *Nurmi concept* or *competitive exclusion* (CE; Pivnick and Nurmi, 1982). The treatment has been defined as "the early establishment of an adult-type intestinal microflora to prevent subsequent colonization by enteropathogens."

CE treatment was originally intended to prevent intestinal colonization of young chicks with food-poisoning salmonellas, but over time the approach has been extended to cover other human and poultry enteropathogens (e.g., pathogenic strains of *Escherichia coli, Campylobacter* spp., *Clostridium perfringens*, and *Listeria monocytogenes*). Improvements in bird performance have also been shown in well-controlled laboratory-scale studies as well as in the field (reviewed by Pivnick and Nurmi, 1982; Schleifer, 1985; Mead and Impey, 1987; Stavric and D'Aoust, 1993; Mead, 2000; Schneitz and Mead, 2000; Schneitz, 2005; Revolledo et al., 2006).

In this chapter, the development and applicability of the CE concept in poultry management, and factors affecting the efficacy of the treatment are reviewed

and discussed. In addition, the nature of the protective mechanism and differences observed between various CE preparations and other types of probiotics are considered.

COMPETITIVE EXCLUSION (THE NURMI CONCEPT)

The *competitive exclusion* of one type of bacterium by others was a term first used by Greenberg (1969). He studied the intestinal flora of blow-fly maggots and claimed that exclusion of *S. typhimurium* from the maggots was so effective that the organism survived in the gut only if the normal microflora was simplified or eliminated. A similar phenomenon in higher animals had been demonstrated earlier by Luckey (1963). *Colonization resistance*, a term synonymous with CE, was introduced by van der Waaij et al. (1971) when examining the intestinal flora of mice. The term *competitive exclusion* was used in relation to poultry for the first time by Lloyd et al. (1974).

The CE concept involves the following points, as stated by Pivnick and Nurmi (1982):

1. Newly hatched chicks can be infected by only a single cell of *Salmonella*.
2. Older birds are resistant to infection because of the autochthonous microbiota of the gut, particularly in the ceca and colon, but possibly in other parts of the GI tract as well.
3. Chicks hatched by sitting hens are probably populated more rapidly by the autochthonous gut microflora of the adult.
4. Hatcheries have replaced sitting hens, and the mass production of chicks is carried out in such a sanitary environment that the autochthonous microflora is not introduced at the hatching stage.
5. The growing houses in which newly hatched chicks are placed are usually thoroughly sanitized and the floors covered with fresh litter before new batches of birds arrive. Thus, the autochthonous flora of the adult is not readily available to populate the gut of the chicks.
6. The artificial introduction of an adult intestinal microflora makes most of the recipient chicks immediately resistant to 10^3 to 10^6 infectious doses of *Salmonella*.
7. The intestinal flora of adult birds can be introduced as a suspension of fecal or cecal material, or as an anaerobic culture of such material. The treatment preparation may be introduced directly into the crop or by addition to the drinking water and possibly the feed. Spray treatment is also possible (see below).
8. The source of the treatment is usually the homologous bird species, although preparations derived from chickens will protect turkeys, and vice versa.

CE Treatment with Undefined Mixed Cultures

Initially, use was made of diluted material from the crop, small intestine, and ceca of healthy adult cocks (Nurmi and Rantala, 1973). The study showed that day-old chicks became well protected against relatively high doses of *S. infantis*. Then the same workers used successfully anaerobic broth cultures of intestinal material (Rantala and Nurmi, 1973). As a result of these studies, five commercial CE products have been developed: Aviguard, AviFree, Broilact, Mucosal Starter Culture (MSC), and Preempt/CF-3/DeLoach 29. They are all mixed cultures from the cecal content and/or wall of domestic fowl. Broilact, developed by the Orion Corporation in Finland, was the first commercial CE product. It was launched in Finland and Sweden in 1987. It appears that Preempt and MSC are no longer produced commercially.

An ability to associate with the intestinal epithelial surface is a common characteristic of microbes that colonize the alimentary tract (Rolfe, 1991; Schneitz et al., 1993). Competition for adherence sites on the mucosa is one of the CE mechanisms suggested, and Broilact is based on this hypothesis (Nurmi et al., 1987). Since 1991, all batches of Broilact have originated from the washed cecal walls of a single 33-week-old grandparent breeder hen reared in quarantine. Continued use of the same basic inoculum ensures that each production batch is comparable in both composition and quality.

Aviguard was developed in 1993 by Life-Care Products Ltd. in the United Kingdom. It was previously marketed by Bayer AG Animal Health and taken over in 2007 by Schering-Plough Animal Health. Aviguard is an anaerobic culture of whole cecal content from adult specific-pathogen-free (SPF) chickens.

AviFree is also an anaerobic culture of whole cecal content from adult chickens. It was developed by Alltech Ltd. and launched in 1996. Very little information is available concerning the effectiveness of AviFree, but according to Newman and Spring (1996), it was moderately protective against *S. typhimurium* 29E.

Preempt (DeLoach 29 in Japan) was a mixed-culture preparation developed by Corrier et al. (1995b) using a continuous-flow culture system and low-pH culture medium to select for certain facultative and obligate anaerobes. The starting material was a homogenate of cecal tissue and content obtained from 10-week-old broiler chickens (Corrier et al., 1995a; Nisbet et al., 2005).

The preparation designated MSC, which was identical to "mucosal competitive exclusion," was developed by Stern et al. (1995). The preparation was derived from scrapings of washed ceca or cecal sections and incubated under anaerobic conditions in an appropriate culture medium (Stern, 1990).

Thus, commercial CE products contain a wide variety of viable bacteria obtained by culturing cecal material from selected donor birds. Their exact composition is unknown, and such products must be tested extensively to ensure the absence of all known avian and human pathogens and with no other demonstrable hazard to either users or recipients of the material (Barrow et al., 2003).

The criteria applied to current undefined CE products are essentially those described by Nurmi and Nuotio (1994):

- Use of one or more healthy donor birds from a regularly monitored flock, preferably SPF [requires both pre- and postmortem examination of the donor bird(s)]
- Meticulous examination of primary inocula for human and avian pathogens in laboratories certified by licensing authorities
- Adoption of good laboratory and manufacturing practices throughout the production process

Additional or supportive measures for the safety of an undefined CE product include:

- A low incidence of contagious diseases in the country or region where the CE preparation is produced
- A series of consecutive cultivation steps in manufacture that provide a dilution of the original material of at least 1 in 100 million
- Media used for propagation of the organisms that do not support the proliferation of mycoplasmas or viruses
- Quality control of the final product using appropriate indicator organisms

To standardize the method used to evaluate different CE preparations, Mead et al. (1989a) described a chick assay. Newly hatched chicks are treated orally on day 1, challenged orally with *Salmonella* 24 hours later, and examined 5 days postchallenge to determine both the proportion of positive birds in treated and control groups and the levels of *Salmonella* carriage in infected individuals. The efficacy of the treatment is determined by calculating an *infection factor* (IF) value, which is the geometric mean of the number of *Salmonella* bacteria per gram of cecal content for all chicks in a particular group. A *protection factor* (PF) value is obtained by dividing the IF value for the control group by that for the treated group (Pivnick et al., 1985; Mead et al., 1989a). A PF value of 4.0 has been suggested as the lower limit for acceptance of a CE preparation for use in the field.

However, a better way to evaluate the efficacy of a treatment material may be to use the difference between the IF values of control and treated groups (difference = Δ IF value; Schneitz and Hakkinen, 1998). The reason for this is evident from the following two examples. If the IF value is 6.0 for the control group and 1.5 for the treated group, the PF value is 4.0. On the other hand, if the IF value for the control group is 3.0 and 0.3 for the treated group, the PF value is 10, but the Δ IF values between control and treated groups are 4.5 and 2.7, respectively, giving a clearer indication of the degree of protection obtained.

The efficacy of each batch of Broilact is tested in a chick assay trial and the batch is accepted only if the Δ IF value is 5.0 or more. The efficacy of the last 20 batches against *S. infantis* has been tested in assays involving a total of 419 chicks (one chick died during the test period). The mean IF value for the Broilact-treated chicks was 0.3 and that of the control chicks 6.1, the mean Δ IF value being 5.8 and the mean PF value 20.3.

The value of CE treatment in poultry production has been confirmed by several research groups around the world, and a number of comprehensive reviews on the topic are available (Pivnick and Nurmi, 1982; Schleifer, 1985; Mead and Impey, 1987; Stavric and D'Aoust, 1993; Mead, 2000; Schneitz and Mead, 2000; Barrow et al., 2003; Schneitz, 2005).

Conventional Probiotics

The concept underlying the use of probiotics originates from the views of Elie Metchnikoff, a Russian biologist working at the Pasteur Institute at the beginning of the twentieth century (Metchnikoff, 1908). He thought that the health and longevity of Bulgarian peasant families were due mainly to their consumption of large amounts of milk fermented by *Lactobacillus* spp. The term *probiotic* is derived from Greek and means "pro life." It was introduced by Lilly and Stillwell (1965) to describe growth-promoting factors produced by microorganisms. Over the years, there have been many definitions of the term. Fuller (1989) defined probiotics as "live microbial feed supplements that improve microbial balance in the animal gastrointestinal tract, and, therefore, are beneficial." Marteau et al. (2002) preferred "microbial cell preparations or components of microbial cells that have a beneficial effect on health and well-being."

Probiotics are used primarily to enhance the growth performance of food animals or to control conditions such as scouring. They are given in feed or water, often over a long period of time (Mead, 2000). Improvement in weight gain was shown when a commercial probiotic that included *L. acidophilus* and *L. casei* was included in different broiler diets that were low in certain nutrients (Angel et al., 2005). Improved weight gain and feed efficiency in broilers exposed to daily heat stress for 3 hours from day 21 to day 42 were also reported by Zulkifli et al. (2000) when the birds were given a probiotic containing a mixture of different lactobacilli. Slightly improved body weight gain in the final week of production was obtained by O'Dea et al. (2006) when using two commercial probiotics containing *L. acidophilus, L. bifidus*, and *Enterococcus faecalis* (probiotic 1) or *L. acidophilus* and *E. faecalis* (probiotic 2). However, there is very little evidence that conventional probiotics of unspecified origin exert any useful influence on enteropathogens such as *Salmonella*. On the contrary, it has been shown in small-scale trials that such products can even enhance *Salmonella* shedding (see below).

The anti-*Salmonella* activity of several probiotics containing different mixtures of *Bacillus, Enterococcus*, and *Lactobacillus* spp. were tested in small-scale trials by Hinton and Mead (1991). No protection of chicks could be shown. Similar results were obtained by Stavric et al. (1992) when testing the efficacy of a probiotic containing *L. acidophilus* and *Bifidobacterium bifidum*, and a commercial yogurt fermented with *L. acidophilus* and *Bifidobacterium* spp.

The effects on broiler body weight of nine commercial probiotics that were given continuously for 4 weeks either in feed or water were tested by Fuller (1997), but no benefit could be demonstrated. As an indicator of possible effects on *Salmonella*, levels of cecal Enterobacteriaceae were monitored in the trials.

The initial numbers of lactobacilli and other organisms in the treatment products seemed to have no effect on the level of carriage of Enterobacteriaceae in cecal content.

La Ragione et al. (2004) tested the efficacy of *L. johnsonii* F19785 obtained from a culture collection in reducing colonization by, and shedding of, *S. enteritidis*, *E. coli* O78:K80, and *C. perfringens* in poultry, when given on the day of hatch as a single dose in separate trials. There was no significant effect on *S. enteritidis*, while colonization of the small intestine by *E. coli* O78:K80 was reduced significantly 24 h postchallenge, but only temporarily. No differences could be observed in cecal and colonic counts between treated and control birds. However, the treatment organism was able to reduce counts of *C. perfringens* significantly when given to 20-day-old chicks as a single dose.

The protective effect of a probiotic containing *L. reuteri*, produced and marketed by BioGaia Biologics AB, is based on its ability to produce reuterin, a bacteriocin that has been shown to have broad-spectrum antimicrobial activity against *Salmonella, E. coli*, and *Campylobacter* spp. (Talarico et al., 1988; Fuller, 1997). According to Fuller (1997), young chicks were protected by *L. reuteri* against death associated with exposure to a challenge with *S. typhimurium*. In treated birds, approximately 5% died after challenge, whereas in control birds the proportion was about 40%. It has also been claimed that *in ovo* treatment with *L. reuteri* reduces chick mortality caused by *Salmonella* (Dunham et al., 1994). In another study, however, *L. reuteri* given *in ovo* to turkey poults had only a minor effect against *S. typhimurium* (Edens et al., 1991–1997).

Hofacre et al. (2000) tested the efficacy of commercially produced freeze-dried *L. acidophilus* culture against *S. kedougou* in day-old turkey poults. An aqueous suspension of the culture was both sprayed on the birds and given in the drinking water during the first 4 days of the rearing period, as suggested by the manufacturer, but no protection against *Salmonella* could be demonstrated.

The results of a study conducted by Kobayashi et al. (2002) indicated that *Bifidobacterium thermophilum*, given orally as either heat-killed or disrupted cells, or as an enzyme-digested lysate, decreased the numbers of *E. coli* injected into the air sacs of 2-week-old chickens. The treatment was thought to enhance natural antibacterial activity in the birds.

The efficacy of a Brazilian probiotic was compared with that of Broilact against *S. infantis* in three chick-assay trials. The origin and composition of the probiotic was not given, but three facultative anaerobes could be isolated from it: *L. saerimneri, L. reuteri*, and *Enterococcus faecium*. The chick assay described in Schneitz and Hakkinen (1998) and slightly modified from that of Mead et al. (1989a) was used in the trials. For the Brazilian probiotic, the mean Δ IF value was 0.8, compared with 6.4 for the Broilact-treated groups. Of the Brazilian probiotic-treated chicks, 77 of 80 became *Salmonella*-positive after challenge, while only one *Salmonella*-positive individual occurred among the Broilact-treated birds. All birds in the control groups were *Salmonella*-positive (unpublished results).

A single oral inoculum of *Bacillus subtilis* spores (10^9) was given to 1- and 20-day-old chickens prior to challenge with either *S. enteritidis* or *C. perfringens*. At

day 36 of the rearing period, there was a 0.4 log reduction in *Salmonella* counts and a 3.2 log reduction in *C. perfringens* in the cecal contents of the treated birds. In the duodenum and ileum, however, both *Salmonella* and *Clostridium* counts were higher in the treated birds than in the controls (La Ragione and Woodward, 2003).

Probiotics of Poultry Origin

If it is necessary for a probiotic organism to colonize the recipient host in order to achieve its goal(s), the organism may need to originate from the same host species and even the same part of the GI tract as the target site for colonization (Havenaar et al., 1992). Until now, the only consistently effective CE preparations of this type have been undefined mixed cultures of fecal or cecal material. Pure-culture preparations of equivalent efficacy and stability have yet to be developed. However, because the use of undefined treatment products is prohibited in the United States one of the main poultry-producing countries, and conventional probiotics are relatively ineffective in poultry against human bacterial enteropathogens, there is much interest in developing effective pure-culture preparations of poultry origin.

Effective anti-*Salmonella* treatments containing 10, 28, 48, 50, or 65 isolates have been developed in the past (Impey et al., 1982, 1984; Stavric et al., 1985, 1991; Gleeson et al., 1989). According to Stavric et al. (1991), the efficacy of a pure-culture preparation depends on the complexity of the bacterial mixture. In practice, according to Gleeson et al. (1989) and Stavric et al. (1991), mixtures of pure cultures prepared from stored isolates gradually became ineffective. For unknown reasons, the most stable were mixtures containing 28 or 50 different bacteria. Loss of efficacy upon subculture was reported by Schneitz et al. (1993). In some studies, however, beneficial effects have been observed with even a single-component organism. When 10^8 CFU of *L. salivarius* CTC2197, originally isolated from the crop of a chicken, were given by oral gavage to newly hatched chicks, together with 10^8 CFU of *S. enteritidis* as a single dose, the pathogen was eliminated from the birds, but only after 21 days (Pascual et al., 1999).

Shin et al. (2002) tested the ability of a *L. fermentum* culture to prevent colonization by *S. typhimurium* in two chick-assay trials. The results showed that chicks inoculated with *L. fermentum* on day 1, challenged with *S. typhimurium* on day 3, and killed 7 days later, had *Salmonella* colonization reduced by 0.99 (trial 1) and 0.15 log unit (trial 2). Compared to the ceca of controls, the ceca of the treated birds were abundantly colonized with *L. fermentum*.

Bielke et al. (2003) selected 24 facultatively anaerobic bacteria for in vivo efficacy testing in turkey poults, depending on their ability to inihibit in vitro the growth of *S. enteritidis*. The preparation included 14 isolates of *Escherichia*, two of *Citrobacter*, two of *Klebsiella*, one of *Enterobacter*, two of *Staphylococcus*, one of *Enterococcus*, and one of *Bacillus*. Treatment-related protection ranged from 0 to 100% in three trials. For some unknown reason, the greatest protection was related to the lowest concentrations of the protective microflora in each trial.

Zhang et al. (2007a) isolated from nine donor chickens 636 isolates inhibitory to six *C. jejuni* strains in vitro. Of these, 194 isolates were strongly inhibitory to *C. jejuni*, and 41 of them inhibited the growth of both the *C. jejuni* strains and five different serotypes of *Salmonella*. In their next study (Zhang et al., 2007b), the researchers tested the efficacy of 56 potentially protective isolates in vivo. Different *L. salivarius* and *Streptococcus crispatus* strains were tested either together or separately for their ability to reduce colonization of chicks with *S. typhimurium*. The best result, a reduction of 2.99 log units, was gained by combining one strain of each organism.

MECHANISM OF COMPETITIVE EXCLUSION

Although little is known about the essential properties of the protective organisms in undefined CE preparations, the one certainty is that protection depends on the oral administration of viable bacteria (Mead, 2000). According to Rantala (1974), to be fully effective, the protective material must be cultured under anaerobic conditions. However, recent studies have shown that aerobically incubated cecal cultures gave protection equal to that obtained from anaerobic incubation against *S. typhimurium, S. infantis, S. agona*, and *S. enteritidis* in newly hatched chicks (de Oliveira et al., 2000; Filho et al., 2003). Actually, this is not entirely surprising because static broth cultures develop very low redox potentials, due to the many facultative anaerobes in the inoculum, and thus obligate anaerobes may be able to multiply sufficiently.

Several mechanisms have been proposed to explain the protection provided by the naturally occurring enteric microflora and therefore by effective CE cultures. These include competition for binding sites and limiting nutrients, production of antimicrobial substances, and immunostimulation. Nevertheless, their relative importance in the protective process remains unclear. Native microflora may completely exclude pathogenic bacteria by blocking potential attachment sites on gut epithelia, thus increasing resistance to *Salmonella*. Protection by this mechanism is thought to be primarily physical, because the effect is so rapid (Donoghue et al., 2006). Chickens are relatively well protected against an oral *Salmonella* challenge, even a few hours after CE treatment (Seuna, 1979; Soerjadi et al., 1981; Stavric, 1987; Hume et al., 1998b). A similar observation was made by Mead et al. (1989b) when studying the effect of CE treatment on the transmission of *S. enteritidis* in chick transport boxes. Stavric (1992) examined washed ceca of young chicks given an anaerobic fecal culture as an anti-*Salmonella* treatment. The protective flora remained attached to the cecal wall after successive washings, suggesting the importance of adherence in this respect. Evidence of competition for unspecified receptors is demonstrated by the mat of microbial cells and interconnecting fibers of the glycocalyx that form a physical barrier in the GI tract of older birds (Costerton et al., 1981). This has also been observed in chicks after oral administration of a CE preparation (Mead, 2000).

As well as competition for adherence sites on the mucosa, there are many other factors that could be involved in the protective process: for example, local

immunity; pH and Eh (redox potential); peristalsis; diet and body temperature of the host; and inhibitory substances such as bacteriocins, H_2S, deconjugated bile acids, and short-chain fatty acids (Meynell, 1963; Savage, 1977; Barnes et al., 1979; Mead and Barrow, 1990; Corrier et al., 1995a,b; van der Wielen et al., 2000). The last-mentioned authors showed that *Bacteroides* and *Eubacterium* spp. were established at stable levels in the cecal contents of chicks after 14 days and propionic and butyric acids were detected in 12- to 15-day-old birds. Simultaneously, a decrease in numbers of Enterobacteriaceae was observed. When pure cultures of these organisms were grown in the presence of volatile fatty acids, growth rates declined as the acid concentrations were increased. Hume et al. (1998b) have also shown that chicks challenged only 4 h after CE treatment are relatively well protected against *Salmonella* colonization. Significant increases in cecal propionic acid concentrations were observed within 1 day of the treatment.

APPLICATION OF CE TREATMENT

Originally, the only way of administering CE preparations in the field was through the first drinking water, which is still used in some cases. A slaughterhouse in Finland monitored the effect of CE treatment given in the drinking water by comparing the incidence of *Salmonella* infection in treated and untreated flocks. During a three-year period from 1986 to 1988, CE treatment was given to 400 broiler flocks, and another 192 flocks were left without treatment. Of the treated flocks, 6.5% were *Salmonella*-positive at the time of slaughter, while the corresponding figure for the untreated flocks was 21% (Nurmi et al., 1990). The drinking water method was used even more successfully in Sweden by Wierup et al. (1988, 1992), because of 179 CE-treated flocks, only one was *Salmonella*-positive at slaughter. The same method was used beneficially by Martin et al. (2000).

To achieve the best possible result, CE treatment should precede the *Salmonella* challenge. From this point of view, a spray application in the hatchery is the most suitable method for dosing chicks under field conditions. Also, despite the above, drinking water application is not always reliable. Chicks hatch over a 2-day period and the youngest often fail to drink initially, resulting in an uneven spread of the protective organisms among the flock (Schneitz et al., 1991). Thus, the most oxygen-sensitive anaerobic organisms in the CE preparation die over time, and the product becomes ineffective before all the chicks have consumed an adequate dose (Seuna et al., 1978). Additionally, chicks may be exposed to *Salmonella* during transportation to the farm and even earlier if there is hatchery contamination or vertical transmission from infected breeders. Although CE treatment cannot be expected to stop vertical transmission of *Salmonella* via the egg, many cases of early chick infection could be prevented by using a spray application in the hatchery.

The idea of using an aerosol generated by a spray method for administering a CE preparation was first raised by Pivnick and Nurmi (1982). Later, Goren

et al. (1984b, 1988) developed such a method for treating chicks, either in the hatchers themselves or in the delivery trays. Spraying in the hatchery followed by drinking water administration on the farm was used by Blankenship et al. (1993) to ensure maximum efficacy of the treatment, but inevitably, this would increase the cost. Manual spray application employing a handheld garden spray (Schneitz et al., 1990) preceded automated spray cabinets, which offer a much more rapid and even treatment to each tray of chicks (Schneitz, 1992; Chen et al., 1998). Spray application does not have any adverse effects on the health or performance of the birds during grow-out (Corrier et al., 1995a).

The use of CE treatment has also turned out to be beneficial for those flocks that become *Salmonella*-positive in the hatchery. A field trial carried out in France showed that of 34 CE-treated flocks, 13% were already *Salmonella*-positive at 1 day old, but only 6% were still carriers at 45 days of age. Of the 34 control flocks, 25% were positive at 1 day old and 42% at day 45. In addition, CE treatment significantly reduced contamination of neck-skin samples taken at the processing plant (Palmu and Camelin, 1997). Another field trial in the Netherlands confirmed that treatment of *Salmonella*-positive chicks with a CE preparation can reduce the subsequent level of infection (Bolder and Palmu, 1995). Reynolds et al. (1997) found that treatment of 11 infected breeder flocks with enrofloxacin, followed by a CE preparation, resulted in a long-term reduction in *Salmonella* in two trials and a short-term reduction in another five trials.

The possibility of chicks becoming infected during the hatching stage has encouraged researchers to look for a method of administration that would enable the birds to be treated prior to hatch (Cox et al., 1990, 1991). Cox and Bailey (1993) developed an *in ovo* method in which the CE preparation was introduced into either the air cell or the amnion of the egg a few days before hatching. However, the use of a cecal culture resulted in depressed hatchability when the material was introduced into the air cell, whereas inoculating the amnion killed all the embryos (Cox et al., 1992; Cox and Bailey, 1993). Similar results were obtained with Broilact by Meijerhof and Hulet (1997). Nevertheless, it may be possible to develop effective preparations that do not affect hatchability.

PATHOGEN AND HOST SPECIFICITY OF CE TREATMENT

It has been shown by several research groups that the CE concept applies to all serotypes of *Salmonella* that are capable of intestinal colonization in the chick (Cameron et al., 1997; Ghazikhanian et al., 1997; Schneitz and Hakkinen, 1998; Ferreira et al., 2003). Thus, CE preparations have been shown to give good protection against both cecal colonization and invasion of specific organs (heart, liver, and spleen) by *S. enteritidis* PT4 or *S. typhimurium* (Mead et al., 1989b; Cameron and Carter, 1992; Nuotio et al., 1992; Schneitz, 1992; Methner et al., 1997). The efficacy of CE treatment against *Salmonella* has also been demonstrated under field conditions (Wierup et al. 1988, 1992; Bolder et al., 1992; Blankenship et al., 1993; Corrier et al., 1995a; Deruyttere et al., 1997; Palmu and Camelin, 1997).

In addition to the ability to control *Salmonella* infections in poultry, it has been shown experimentally that CE treatment can protect chicks against pathogenic *E. coli* (Soerjadi et al., 1981; Weinack et al., 1981, 1982, 1984; Stavric et al., 1992; Hakkinen and Schneitz, 1996; Hofacre et al., 2002), *Yersinia enterocolitica* (Soerjadi-Liem et al., 1984b) and *Campylobacter jejuni* (Soerjadi et al., 1982a; Soerjadi-Liem et al., 1984a; Hakkinen and Schneitz, 1999; Stern et al., 2001). Also, CE treatment can decrease mortality due to necrotic enteritis and hepatitis and reduce levels of cecal *C. perfringens*, which is considered the main causative factor in necrotic enteritis (Barnes et al., 1980; Snoeyenbos et al., 1983; Elwinger et al., 1992; Hofacre et al., 1998; Craven et al., 1999; Kaldhusdal et al., 2001). Furthermore, CE treatment significantly reduced cecal colonization by *L. monocytogenes* in chicks (Hume et al., 1998a), although according to another study, most chicks became *Listeria*-negative within 9 days without treatment (Husu et al., 1990).

Protection of newly hatched chicks against *Salmonella* colonization using treatment material from adult birds of the same species seems to be independent of the breed, strain, or sex of the birds, although differences exist among individual donor birds with respect to protective capability. Chickens can be protected to some extent by the microflora of a few other avian species (Snoeyenbos et al., 1979; Weinack et al., 1982; Impey et al., 1984), but material from animals such as the horse or cow was shown to be ineffective (Rantala and Nurmi, 1973). Weinack et al. (1982), Impey et al. (1984), and Schneitz and Nuotio (1992) showed that native chicken and turkey microfloras provided reciprocal protection in chicks and turkey poults, but the last-mentioned authors observed some host specificity with Broilact. Cox et al. (2001) demonstrated that CE cultures generated from mucosal scrapings of adult turkeys effectively controlled *Salmonella* in turkey poults during brooding. Hofacre et al. (2000) showed that fresh turkey cecal material was significantly more protective in turkeys than the commercial CE product Aviguard containing a chicken microflora. Bamba et al. (1997) showed that levels of *S. typhimurium* decreased significantly in artificially challenged Japanese quails that had been treated on day 1 with chicken cecal contents. Pheasant chicks were successfully protected against *S. infantis* by Broilact (Schneitz and Renney, 2003).

EFFECTS OF CE TREATMENT ON BIRD PERFORMANCE

As with some conventional probiotics, CE treatment has been shown to enhance bird performance parameters. An improvement in growth rate was observed in commercial broiler flocks sprayed with a CE preparation in the hatchery (Goren et al., 1984b). Corrier et al., (1995a) reported an improvement in the efficiency of feed utilization by broiler flocks that were given CE treatment on the day of hatch. Improvements in body weight and feed conversion, together with lower mortality, were reported by Abu-Ruwaida et al. (1995). Higher body weights and lower mortality were also observed by Bolder et al. (1995).

A laboratory-scale study was conducted with Broilact to investigate the nutritional effects of CE treatment. Broiler chicks were treated orally on the day of hatch, and ileal and cecal samples were taken at 12 and 31 days of age. It was found that CE treatment decreased the viscosity of ileal contents significantly and increased fecal dry-matter content. It also improved the ME value of the feed by 1.6%, increased concentrations of propionic acid in the ceca, and decreased that of butyric acid in the ileal contents (Schneitz et al., 1998). In another study, Bilal et al. (2000) showed that Broilact improved total feed digestibility significantly at 35 days. Increases in body weight and fecal dry-matter content were also observed, as well as an improved feed conversion ratio, but the effects were not significant.

FACTORS THAT MAY INFLUENCE THE EFFICACY OF CE TREATMENT

Hume et al. (1998b) have shown that chicks challenged 4 h after CE treatment are relatively well protected against *Salmonella* colonization. According to Seuna (1979), treatment given only 1 h beforehand still conferred considerable protection against the challenge organism. However, commercial hatchery environments can be contaminated with *Salmonella*, and parent stock may be carriers (Cox et al., 1990, 1991), both of which are likely to reduce the efficacy of CE treatment (Bailey et al., 1998).

Other potentially negative factors include bird stress and disease. Starving chicks for the first 24 h of life reduced the protective effect of CE treatment (Goren et al., 1984a), whereas in older birds, the protective flora was more difficult to disrupt (Snoeyenbos et al., 1985). With the day-old chick, physiological stress induced by high or low environmental temperatures or removal of feed and water either interfered with the colonization process or reduced the protection provided by the administered organisms; however, there was no obvious effect at 2 weeks of age (Weinack et al., 1985).

Lafont et al. (1983) studied CE-treated chicks that were carrying low numbers of *Salmonella* in their intestines and administered oocysts of *Eimeria tenella* at a level known to produce cecal coccidiosis. The birds then shed large numbers of *Salmonella* for more than 2 weeks. In a recent study, Collier et al. (2008) showed that coccidial infection induced a host mucogenic response, providing a growth advantage to *C. perfringens*. Exposure of CE-treated chicks to aerosols of *Mycoplasma gallisepticum* and/or infectious bronchitis virus increased the number of birds shedding pathogenic *E. coli* or *S. typhimurium*, following a challenge 2 days after protective treatment (Weinack et al., 1984).

Subjecting broilers to feed withdrawal at the end of the rearing period and induced molting of white leghorn layers have also been shown to increase both levels of *Salmonella* in the GI tract and the proportions of infected birds (Holt and Porter, 1993; Holt et al., 1995; Macri et al., 1997; Ramirez et al., 1997; Corrier et al., 1999; Kubena et al., 2005). According to Corrier et al. (1999),

birds can become infected with *Salmonella* by pecking at contaminated litter in the house during the period of preslaughter feed withdrawal. The results of a preliminary study indicated that CE treatment of the drinking water at this time could prevent the birds from becoming infected (Schneitz, 2006). The use of growth-promoting antibiotics was banned within the European Union beginning in January 2006, so their possible effects on CE treatment are not discussed here. Anticoccidials, which are still commonly used, have not been found to reduce the efficacy of CE treatment.

With regard to therapeutic use of antibiotics, the results of a pilot-scale study showed that treatment of newly hatched chicks for five consecutive days with either furazolidone or trimethoprim–methoxasole sulfate did not eliminate the CE effect of Broilact (Bolder and Palmu, 1995). CE treatment has also been given successfully to older birds after therapeutic doses of antibiotics to regenerate the intestinal microflora (Johnson, 1992; Uyttebroek et al., 1992; Humbert et al., 1997; Reynolds et al., 1997). The effect of *in ovo* administration of gentamicin or ceftiofur on the efficacy of CE treatment has been a matter of concern. McReynolds et al. (2000) reported that both could cause a marked depression in levels of cecal propionate that were used to indicate whether or not a microflora had become established from treatment of chicks with Preempt. On the other hand, Bailey and Line (2001) demonstrated that gentamicin, at a rate of 0.4 mg per egg and administered *in ovo* on day 18, had no adverse effect on the efficacy of MSC.

DISCUSSION AND CONCLUSIONS

The observation that the early introduction of an adult intestinal microflora in newly hatched chicks increases considerably their resistance to colonization by food poisoning *Salmonella* serotypes was first made in Finland by Nurmi and Rantala (1973). This study also served to explain the true significance of the conditions under which most chicks are hatched and reared commercially, having no contact with the mother hen and therefore no opportunity to rapidly acquire a protective gut microflora.

Broilact, the first commercial CE product, was launched in 1987 as a broth culture, but from 1994 onward, it has been sold in freeze-dried form. CE treatment used consistently has contributed significantly to the present low incidence of *Salmonella*-contaminated poultry flocks and carcasses in Finland (Hirn et al., 1992). To confirm this, broilers, turkeys, geese, guinea fowl, ducks, and egg-producing birds are examined at all stages of production, including the hatchery. The objective of the Finnish *Salmonella* control program is to maintain the annual prevalence of *Salmonella* below 1% at the national level (Finnish Food Safety Authority). The program covers all serotypes of *Salmonella*, not only the invasive *S. enteritidis* and *S. typhimurium*. Sampling is carried out at regular intervals, starting with the introduction of new birds into a poultry house. Further samples are taken during the growing period and again before the birds are sent for

slaughter. Additionally, carcass samples are taken regularly from the processing plant (Maijala et al., 2005).

It has been suggested that the consistent long-term use of CE cultures in Finnish broiler flocks has also contributed to the low incidence of *Campylobacter* in broilers (Aho and Hirn, 1988). In 2005, of the 104 flocks examined at slaughter from January to May and November to December, only one flock was found to be *Campylobacter*-positive. Of the 1320 flocks examined from June to October, when the prevalence of *Campylobacter* is normally highest in Finland, only 7% were contaminated, according to the Finnish Food Safety Authority.

There would be obvious advantages in being able to use a CE preparation with a completely defined strain composition. Inclusion of any potential poultry pathogen could be avoided with certainty and quality control of the treatment product during manufacture would be much easier (Mead, 2000). However, consistent protection of newly hatched chicks against *Salmonella* infection has been obtained only with undefined, mixed cultures. Fully effective defined preparations have not yet been developed. The work is difficult because the mechanism of CE is poorly understood, as is the nature of the organisms that need to be included. Only defined preparations containing large numbers of strains of different genera have been comparable in effect to undefined, mixed cultures (Stavric, 1992). Not only would these present problems to the probiotic manufacturer, but pure-culture preparations tend to lose their protective properties during storage and subculture (Gleeson et al., 1989; Stavric et al., 1991; Schneitz et al., 1993). Therefore, appropriate means of regulating undefined CE preparations need to be developed by official bodies. The World Health Organization (WHO) has suggested that there should be a special category for the licensing of CE products (WHO, 1994). The category is termed *normal gut flora* and is described as follows: "In relation to the avian intestinal tract, 'normal gut flora' is an undefined preparation of live obligate and facultatively anaerobic bacteria, originating from normal, healthy, adult individuals of an avian species, which is free from specific pathogenic microorganisms and is quality controlled. The purpose of such a preparation is to compensate for any deficiencies in the composition of the normal intestinal microbiota that relate to the natural control of undesirable microorganisms and arise from modern systems of poultry production." According to Wray and Davies (2000), the European Union is currently reviewing its position on CE and, at the time of writing this chapter, no final decision has yet been announced.

Competitive exclusion is a very effective measure to protect newly hatched poultry, and even game birds, against infection with *Salmonella* and other enteropathogens. The results of studies carried out by various research groups and the long-term field experience in Finland have shown that CE treatment is effective against all host nonspecific *Salmonella* serotypes that are able to colonize the alimentary tract of the bird. There are also studies showing that current CE products may be of value in controlling infections with other enteropathogens, including *C. perfringens* and pathogenic *E. coli* (avian and human strains). Some protection against *Campylobacter* has also been demonstrated under experimental conditions (Hakkinen and Schneitz, 1999;

Stern et al., 2001), but treatment is less effective when cultured material is used. To improve the results, different protective bacteria may need to be included because of the specific location of *Campylobacter* in the mucus layer of the cecal crypts (Beery et al., 1988). Whatever the target pathogen, the ability of CE treatment to enhance bird growth and feed utilization, and reduce chick mortality, are of great importance in compensating for the cost of the treatment when such benefits can be realized.

The efficacy of CE treatment may be adversely affected by antimicrobials, stress, disease, forced molting, feed withdrawal, infected breeders, and a contaminated hatchery environment. The best results are achieved when the grandparent and parent stock are free of *Salmonella* and treatment of broilers is supported by an overall control program that includes a high standard of flock biosecurity. In Scandinavian countries, the maintenance of very low levels of *Salmonella* in poultry production is based on five key principles (Bolder and Mulder, 2007):

1. The breeding pyramid is kept free of *Salmonella*. All grandparent birds are imported, quarantined, and tested repeatedly for *Salmonella*.
2. Feed and water given to the birds must be *Salmonella*-free. This is achieved through:
   a. Import control of raw materials
   b. Mandatory heat treatment of all compound feeds used for poultry
   c. HACCP-based *Salmonella* control in the feed industry
3. As much as possible, chickens must be kept in a *Salmonella*-free environment. This involves high standards of hygiene and biosecurity.
4. There is regular monitoring of the entire production chain. Samples are taken from farm to slaughterhouse.
5. Immediate action is taken whenever *Salmonella* is detected.

In Finland, the control of *Salmonella* is undertaken jointly through voluntary commercial measures and mandatory rules and regulations that have been in place since the 1960s. For example, for over 40 years, the Feedstuff Act has been applied to control *Salmonella* in feeds, and the use of CE in broiler production was initiated at an early stage (Maijala et al., 2005). The method has been used routinely in Finland since 1976 and on a commercial basis since 1987 (Nurmi et al., 1992; Schneitz, 1993). Antibiotics have been used for many years as growth-promoting agents, and this has led to the appearance of bacteria with multiple drug resistance (Khan et al., 2005; Simjee et al., 2007). The ban on growth-promoting antibiotics within the European Union started in June 1999, and their use was totally prohibited in January 2006. Removal of these substances is likely to increase the variability of broiler performance and lead to greater use of therapeutic treatments (Bedford, 2000). To reduce antibiotic use, which can result in bacterial resistance and in the formation of residues in organs and tissues of treated birds, the use of biological methods such as CE treatment should be considered. Commercial, safety-approved CE products could be combined

with suitable management programs for commercial poultry, as has been done successfully in Finland for many years.

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3

PREMORTEM HANDLING

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INTRODUCTION

Handling birds before slaughter is a critical point to in maintaining adequate standards of poultry meat quality. Under this premise, some factors should be observed and considered during the preslaughter period, such as catching, transport, environment temperature, or fasting, but certainly all of these conditions have a common point: They cause stress. In fact, it is widely known that stressing conditions are the detonator of a series of alterations that can modify the

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structure and characteristics of carcass and, consequently, of meat. Moreover, animal welfare demands humane handling of birds prior to slaughter. Nowadays, consumers are particular sensitive to how birds are handled before and during slaughter, as well as to stunning methods used to produce the meat they buy in the market. There are campaigns against animal cruelty around the world, all of them attempting to stop any practice that might cause animals pain or unnecessary suffering. It is evident that most of these practices would be carried out between bird catching and slaughtering. Therefore, any preventive action must be taken during this time, referred to as the *premortem handling* period, and must be considered an important factor in obtaining high-quality meat. Establishing conditions that prevent unnecessary suffering of birds will render high-quality meat. Nevertheless, as Mitchell and Kettlewell (1998) have stated, there is some confusion regarding this point, as concepts such as *stress*, *suffering*, or *animal welfare* could be misleading if confronted by moral, ethical, or philosophical points of view. Future research on this topic must be carried out to reduce to a minimum any stress, pain, or suffering of birds prior to humane slaughter.

STRESS

According to Broom and Johnson (1993), *stress* is defined as the condition where a bird is exposed to an unpleasant situation with negative effects on its behavior, metabolism, or even in the carcass and meat. Therefore, the "unpleasant" situation could be a wide series of "situations" with a large series of "responses," depending on environment, management, or handling. Therefore, the point at which birds enter a given stressful condition could be difficult to establish. However, conditions such as fear, hunger, thirst, extreme environmental conditions, or any harmful agent that can change the physiological status of birds are all sources of stressful conditions that can modify the homeostatic balance of the body; if these conditions are maintained for an excessive length of time, they can evolve into a pathology (Rosmini and Signorini, 2006). On the other hand, birds have mechanisms of defense when exposed to stress factors. That is, they can adapt to adverse conditions, although this mechanism is limited and depends on time, physiological status, and the intensity of the stressor. Adaptation implies the presence of several physiological reactions in a bird's organism as a response to an adverse situation, to avoid negative effects. Therefore, secretions of adrenal glucocorticoids should be reduced or minimized, as these secretions are responsible, at least in part, for chemical and metabolic reactions associated with negative effects of stress. In general, adaptation has limits; when a stressor affects the bird condition, time is required to reach a controlled stress situation. Therefore, it is obvious that depending on the stressful condition, birds are able to adapt and avoid negative stressor effects.

A model of animal response to stressful events suggested by Broom and Johnson (1993) is shown in Figure 1. It establishes the presence of three main

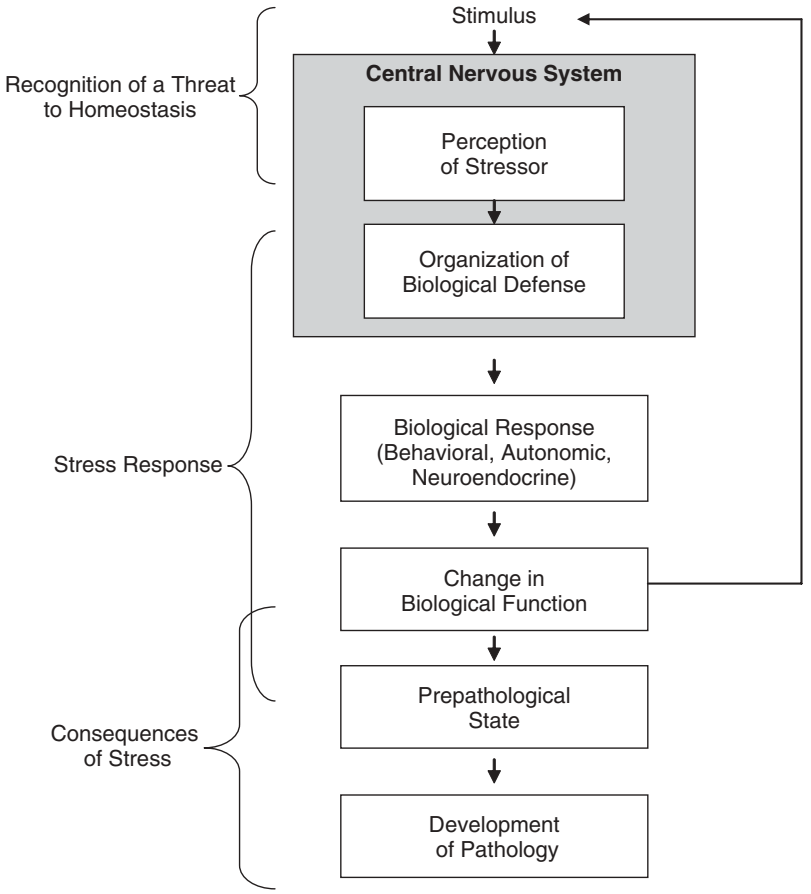

FIGURE 1 Model for response of animals to a stressful event. (From Broom and Johnson, 1993.)

phases during a stressful event. In the first phase the organism can recognize the stressful condition; that is, the bird receives a stimulus from the central nervous system to perceive the stressful factor. Next, the organism develops a response to this stimulus in different ways, but usually, resulting in a change in a given biological function, generating a new stimulus aiming to avoid negative reactions. Finally, in the third phase, the stress is expressed as a process of developing a pathology. This model assumes that the physiological responses of birds usually follow a linear sequence. Adaptation represents changes in biological functions that initiate new stimuli to the central nervous system and probably modify the stressor perception and thus avoid a pre-pathological state. However, if the new stimulus does not change the stressor perception, the biological defense is not enough to prevent the consequences of stress and a pathology will develop.

HANDLING BEFORE SLAUGHTER

Premortem handling involves three different points of view, usually interrelated but sometimes opposite: processing efficiency, workers' safety, and humane attitudes (Thaler, 1999). At present, handling and slaughtering methods are developed taking into consideration the effect of stress on meat quality. However, the cost–benefit and humane considerations are increasing in importance during the entire process. It is clear that in the future, these considerations will be the main criteria for developing handling and slaughtering methods, associated with meat quality. It is well known that premortem mishandling could be a source of stress, causing alterations in the muscle glycogen metabolism as well as increasing muscle pH; therefore, meat is susceptible to developing undesirable characteristics such as discolorations, microbial contamination, and fast spoilage conditions. Prevention of any stressing conditions prior to slaughtering is necessary to avoid these undesirable responses (Gregory, 1996). Moreover, normally, poor bird handling before killing is a cause of important economic losses (Rosmini and Signorini, 2006). Prevention of stressing conditions in all handling methods by slaughtering is relevant in poultry production, as birds are particularly susceptible to damage by mishandling. As a consequence, it is clear that these conditions affect the expected profit in the poultry industry.

CATCHING

An important premortem stage is the action of catching birds. When they reach the expected weight, or at the end of the growing phase, birds are loaded into crates and transported to the slaughterhouse (Barbut, 2002). This practice could affect carcass and meat quality, due mainly to mishandling when collected before loading in trucks. This may produce bruises or, in extreme cases, bone breaking. Birds are usually caught by hand, held by a leg, inverted, and carried in groups of four or five animals by a worker. According to Barbut (2002), on large farms 7 to 10 trained workers can catch and encage birds at a rate of 7000 to 10,000 per hour. It is clear that these conditions may be the cause of birds injuries, with negative effects on the carcass and meat. Catching and loading in crates cause severe stress, with negative consequences on poultry, due to the body-inverted position. It promotes an increase in epinephrine and glucocorticoid production, both chemicals that affect meat quality (Nijdam et al., 2005).

An improved method of bird catching is by mechanical harvesting (Lacy and Czarick, 1998). It seems that This method appears to produce less stress on poultry because birds are not placed in an inverted position; it is carried out using a machine equipped with rubber fingers with the birds transported by conveyor. Even though the speed at which this operation is carried out could be a serious stressing factor, and it has not be proved that this method can produce better meat quality (Nijdam et al., 2005), in general, good bird handling during caching and loading, independent of the method, manual or mechanical, is basic for avoiding stress.

TRANSPORTATION

One of most stressing factors in handling animals is transportation from the farm to the slaughterhouse. Several stressing factors are involved: temperature, acceleration and speed of the vehicle, animal immobility, vibration, motion, impacts, fasting, water deprivation, noise, and in general, welfare alterations. All these conditions produce a wide range of consequences, from discomfort to death (Mitchell and Kettlewell, 1998). Moreover, transportation and loading in crates are causes of an increase in adrenal hormones and plasma corticosterone production affecting bird welfare. Transportation can also increase the levels of epinephrine and glucocorticoids, thus affecting meat quality and increasing the probability of PSE (pale, soft, and exudative) meat or physical damage such as bone breaking (Kannan et al., 1997). Although PSE has been widely reported in swine, numerous reports have also been published on PSE in poultry, evidenced by pale color, soft texture, and low water retention. The causes of PSE meat in swine and poultry are the same: primarily, mishandling. The poultry industry reports 5 to 30% in turkey and 5 to 50% in chickens (Daigle, 2005). PSE is normally associated with short-term stress, as is the case of transportation prior to slaughtering, caused by an acceleration of muscle metabolism which continues at a high level even after a bird has been slaughtered. This condition affects muscle pH when the temperature is still high; consequently, protein is denaturalized, affecting meat quality. At the same time, the levels of β-endorphin, corticosterone, cortisol, and creatine phosphokinase increase (Owens and Sams, 2000; Daigle, 2005). Stress by transport was studied by Owens and Sams (2000) using turkeys as a reference. These authors analyzed the effect of transportation on meat quality assuming that this stressing factor was the cause of PSE meat. They concluded that transporting turkeys immediately before processing does no produce PSE, although it depends on transportation time. Another variable associated with stress by transportation is the season of the year, due to variations in temperature and relative humidity (RH). Extreme temperature conditions can cause severe stress, even more so if the birds are transported for long periods (there will be an incease in damaged or dead birds). Temperature and time of transportation also increase the incidence of meat discolorations and endogenous microbial growth (Vecereck et al., 2006). This stressing factor has been studied by Petracci et al. (2006), who established that the season has a significant effect on the mortality of birds arriving at the slaughterhouse, particularly summer. The authors reported that mortality is lower in small slaughter plants than in medium-sized and large plants. The number of dead birds on arrival at a slaughterhouse can be around 5% of the total, but if handling is not adequate or if any stressor factor is present, the losses can be up to 65% or even more in hot environments (Gregory, 1996). Transport is usually carried out in trucks, sometimes for long distances. Under these conditions, poor ventilation is another detrimental factor, which may increase the negative effects of temperature and relative humidity (Mitchell and Kettlewell, 1998).

FASTING

Feed withdrawal before slaughtering is a common practice used to reduce or prevent microbial carcass contamination, to decrease the chance of excreta coming into contact with the carcass during evisceration and washing. The fasting time must be long enough to clean the gastrointestinal tract but not so long as to cause weight loss or to affect the carcass yield. Usually, 8 to 12 h is enough to meet these goals (Taylor et al., 2002; Schettino et al., 2006). Fasting notably reduces the energy contained in muscles, affecting pH level and postslaughter muscle reactions, such as glycolysis, which, in turn, affects meat color and other meat quality characteristics (Daigle, 2005).

ENVIRONMENTAL TEMPERATURE

Temperature extremes are important stressors, particularly when birds are waiting in truck crates before slaughter. It has been reported that during waiting periods, birds show liver and muscle glycogen alterations that negatively affect such meat quality characteristics as color, tenderness, and appearance (Holm and Fletcher, 1997; Petracci et al., 2001). If birds are subjected to high ambient temperatures, they normally present high stress levels, resulting in reduced production and meat yield. Some of the negative physiological effects are blood alterations associated with an increase in plasma activity, muscle metabolism alterations, and onset of PSE meat (Sandercock et al., 2001). Table 1 summarizes the effects of acute heat stress on chicken breast muscle at two ages; the negative effect of heat on muscle characteristics is clear.

TABLE 1 Effects of Acute Heat Stress on Meat Quality in the Breast Muscle (Pectoralis Major) of Broiler Chickens

	Environment			
Muscle Variable	CTL at 35 Days	AHS at 35 Days	CTL at 63 Days	AHS at 63 Days
Breast weight	181 ± 21^{b}	175 ± 23^{b}	549 ± 45^{a}	537 ± 51^{a}
pH_i	6.18 ± 0.13^{a}	5.74 ± 0.11^{a}	5.83 ± 0.11^{a}	5.64 ± 0.08^{b}
pH_u	5.74 ± 0.13^{a}	$5.68 \pm 0.10^{a,b}$	5.63 ± 0.09^{b}	5.60 ± 0.07^{b}
72-h drip loss (%)	2.0 ± 0.6^{a}	3.7 ± 0.6^{a}	1.6 ± 0.7^{b}	2.0 ± 0.8^{a}
Hemorrhage score	2.5 ± 0.8^{b}	3.5 ± 1.0^{a}	3.3 ± 1.1^{a}	4.0 ± 0.9^{a}
Color score	1.7 ± 0.7	1.5 ± 0.5	1.5 ± 0.5	1.3 ± 0.4

Source: Sandercock et al. (2001).

[a,b]Means within a row with no common superscript differ significantly ($p \leq 0.05$).

Environmental conditions: CTL = control, 21°C and 50% RH; AHS = 32°C and 75% RH over a 2-h duration.

pH_i = muscle pH obtained within 15 min of slaughter.

pH_u = ultimate muscle pH obtained 24-h post slaughter.

TABLE 2 Effects on Broiler Carcass Traits of Supplementing with Chromium

Carcass Traits (percentage of live weight)	Control (C)	Chromium-Supplemented Levels (ppb)			Pooled SE	Significance C vs. Cr
		500	1000	1500		
Carcass	71.9^{b}	73.4^{a}	73.4^{a}	72.9^{a}	0.302	$p < 0.01$
Abdominal fat	2.41^{a}	2.11^{b}	1.88^{b}	1.83^{b}	0.12	$p < 0.01$
Liver	2	1.98	1.88	2.01	0.056	NS
Heart	0.42	0.39	0.38	0.41	0.017	NS
Pancreas	0.189	0.204	0.203	0.206	0.008	NS
Gallbladder	0.099	0.090	0.093	0.093	0.007	NS

Source: Toghyani et al. (2006).

^{a,b}Means within a row with no common superscript differ significantly ($p \leq 0.05$). NS, not significant.

Petracci et al. (2001) reported that negative effects on meat can be a consequence of disturbances in the blood acid–base ratio and skeletal muscle membrane integrity when chickens were exposed to higher temperatures before slaughter; the authors concluded that birds should not be exposed to high temperatures, to prevent heat stress. Some alternatives to preventing the negative effects of higher temperatures are related to stocking-density modifications, according to the season (Petracci et al., 2006), or the inclusion of supplements in poultry diets. In this respect, Toghyani et al. (2006) suggested that the inclusion of chromium supplements in chicken diets could reduce heat stress in relation to bird performance and production and, consequently, increase carcass yield (Table 2). These authors reported that trivalent chromium is useful in preventing stress conditions when birds are under heat-stressing situations, basically because stress increases chromium metabolism in body tissues, the chromium being excreted through the urinary system.

DEHYDRATION

In general, birds do not receive water during transport or at the abattoir before slaughtering. Depending on the journey's duration, poultry could present dehydration symptoms, such as severe thirst, hot and dry body, dry tongue, loss of coordination, and even death. As these conditions are severe stressing factors and cause alterations in blood and plasma volume, they can result in deterioration in meat quality, mainly as to texture and water retention (Gregory, 1996).

BRUISING

Bruising is a result of mishandling, usually resulting in broken wings or legs, with birds suffering consequent pain and inflammation. This condition severely affects carcass yield, grading, and meat quality, not to mention the lack of humane

handling, and must be avoided at all times during preslaughter handling (Gregory, 1996).

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4

TRANSPORTATION TO THE SLAUGHTERHOUSE

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Handbook of Poultry Science and Technology, *Volume 1: Primary Processing*, Edited by Isabel Guerrero-Legarreta and Y.H. Hui

INTRODUCTION

Worldwide, tens of billions of broiler chickens are slaughtered annually. Before this operation takes place, the animals are subjected to various events. Feed is withdrawn to reduce fecal contamination, then the birds are caught and put into crates or containers. After being transported to the processing plant, they wait in the stockyard before they are slaughtered (Nijdam et al., 2004). Mortality of broilers between catching and the moment of slaughter is of great economic significance (Nijdam et al., 2006b). Death losses among broilers transported to processing plants are caused by poor handling. The number of birds dying during transport and in processing plants shortly after arrival may serve as an indicator of the quality of handing during loading and transport (Vecerek et al., 2006). Birds that die between catching and the moment of slaughter are called *dead on arrival* (DOA) (Nijdam et al., 2004). Domestic animal handing during the process of transport is under the supervision of each country, which has its own rules and regulations for good practice before, during, and after transport, therefore assuring adequate handing before slaughter (Maldonado et al., 2007; Mota-Rojas et al., 2008). All codes and regulations emphasize the responsibilities of the poultry producer, agent, catch crew, and transport personnel. These regulations encourage humane treatment of birds so that transport stress and injury are minimized. Codes for poultry transportation in Western Australia, state that the general objective is to minimize any adverse effects on birds by ensuring that they are transported to their destination as safely as possible (CPTPWA, 2003). Animal well-being during transportation has drawn the interest of investigators, as evidenced by the large number of articles published on the matter (Stevenson, 1993; Mitchell and Kettlewell, 1998; Dawkins et al., 2004; EFSA, 2004; Nijdam et al., 2004; Vecerek et al., 2006; Drain et al., 2007; González et al., 2007; Mota-Rojas et al., 2008; Voslarova et al., 2007; Whiting et al., 2007).

WELL-BEING AND TRANSPORT

Well-being of chickens in broiler production is becoming a consumer concern in relation to methods of production and transportation to slaughterhouses (Metheringham and Hubrecht, 1996; Mitchell and Kettlewell, 1998). Before broilers are slaughtered, they are exposed to events such as feed withdrawal, catching, and placing in crates. Subsequently, broilers are transported to the processing plant, and finally, they have to wait in the stockyards of the plant before being slaughtered (Nijdam et al., 2005b). Most of these events cause adverse effects on the birds, ranging from mild discomfort to death (Knowles and Broom, 1990). Death losses among broilers transported to processing plants are caused by poor handling. The number of birds dying during transport and in processing plants shortly after arrival may serve as an indicator of the quality of well-being during loading and transport (Vecerek et al., 2006). Trauma is one of the most common features found at postmortem examination. Gregory and Austin (1992) found signs of

trauma in 35% of the DOA. A dislocated or broken hip is the most common type of trauma, especially when the broilers suffer from femoral head necrosis. Trauma may be caused by rough handling at catching, loading, and unloading (Stuart, 1985). The data obtained by Petracci et al. (2005) indicate that this might be used to establish limit values for DOA well-being indicators before the birds are slaughtered. In fact, the term *well-being* is relevant only when an animal is alive, but death during handling and transport is preceded by a period of poor well-being (EFSA, 2004). The official veterinarian should check to see if the DOA percentage exceeds established limit values, and the owner or keeper of the abattoir should be notified by the authorities to improve catching and loading operations and conditions during transport and holding at the abattoir, as indicated in the recent European Commission Directive 2005/99/EC for the European Union.

Good management at the processing plant can reduce the effects of some of the factors that affect mortality or the percentage of bruises and therefore improve animal well-being. Finally, to reduce broiler DOA, it is recommended that processing begin around midnight rather than at 5 a.m. Changing the processing time may also reduce the bruise percentage. Better insight into the effect of these risk factors on the physiology of broilers is necessary to reduce stress and suffocation and thereby reduce DOA percentage; such changes would improve the well-being of the broilers during the last day of life (Nijdam et al., 2004).

LOADING AND SPACE ALLOWANCE

The owner or agent must ensure that only fit and healthy birds are selected for travel. Sick, injured, or weak birds must be rejected. The person in charge of the flock is responsible for assisting in the selection process and must remove birds that are unfit for transport prior to the arrival of transportation (CPTPWA, 2003). It appears that the method of catching does not influence the percentage of bruises or meat quality. Moreover, corticosterone levels indicate that both methods induce the same amount of stress. The dynamics of corticosterone, glucose, and lactate levels show a similar pattern. Plasma levels increase at the start of catching, and they increase further during transport, shackling, and stunning. However, during catching itself, no large changes have been observed. The findings of Nijdam et al. (2005a) indicate that attempts to reduce stress in broilers during the last day of life could better be focused on factors other than catching. Broiler chickens should be caught in sheds in which the lighting has been reduced and should be placed in crates in a manner that minimizes movement of the chickens and prevents injury and stress. For broiler chickens weighing 2.0 kg or less that are loaded by hand, five chickens can be carried in each hand. For chickens weighing more than 2.0 kg, three or four chickens should be carried in each hand, depending on their weight (CPTPWA, 2003).

Cumulative death loss during the growing phase of production was associated consistently with increased transport mortalities in load-level models and when

comparing high- with low-death-loss truckloads. The loading density of the truck was the major factor associated with exceptional death loss (Whiting et al., 2007). The number of birds per container depends on the available floor space, body size of the birds, and the prevailing environmental conditions at the time of transport. All birds should be able to rest on the floor at the same time and remain evenly distributed. Weather conditions should be considered when determining load densities for growing and adult birds (CPTPWA, 2003). An increase in the compartment stocking density is likely to result in an increase in environmental humidity due to water evaporation from the birds' respiratory tract, skin, and excreta. Under these circumstances, heat loss will be more difficult and can lead to hyperthermia. Heavier body weight also makes it more difficult to lose heat (Nijdam et al., 2004).

Warriss et al. (2005) suggest that a maximum day temperature of about 17°C has little or no effect on the mortality of broilers in transit to slaughter. Above this temperature there are progressively larger increases in mortality, and ideally, steps should be taken to improve the damaging effects of transport on bird well-being. These could include restricting the transport of birds to the cooler parts of the day, such as early in the morning, changes in the design and stacking of transport containers to improve their ventilation, or effective mechanically assisted ventilation. The overall average mortality rate for transported birds is likely to vary among processing plants because of factors other than temperature. However, the relation between mortality and maximum day temperature is likely to be similar, and a limit of 17°C should generally apply.

Finally, cages and crates should be designed, monitored, and managed so that birds are not injured when being placed in or taken out. Cage doors should be as large as practical and should not be less than 20 cm wide and 25 cm high. Crates or cages used for the transport of poultry should be of a design that when properly maintained and managed, prevents escape from, or the protrusion of any part of a bird through, the crate, so that it could be trapped or damaged during handling or transport. Cage floors should be rigid or supported to prevent collapse onto structures or crates below (CPTPWA, 2003).

ANIMAL WELL-BEING AND STRESS IN BROILER TRANSPORTATION

Stress is a cumulative response of an animal to its surroundings and may be increased when birds are subjected to major changes. Birds being transported are subject to several stress factors, including (1) catching and handling, (2) food and water deprivation and freedom of normal movement, (3) changes in climatic conditions, and (4) unfamiliar surroundings, noises, and sensations (CPTPWA, 2003). According to Nijdam et al. (2005a), the catching method does not affect the plasma corticosterone levels. However, they mention that the catching method was associated with plasma lactate concentrations. Thirty minutes after the start of the catching process, plasma lactate levels were significantly higher for mechanically (52.62 ± 1.12 mg/dL) vs. manually (48.70 ± 1.31 mg/dL) caught flocks.

A catching method effect was also found regarding plasma glucose concentrations. Thirty minutes before the end of the catching process, plasma glucose levels were significantly higher for mechanically than for manually caught flocks (222.2 ± 2.45 mg/dL vs. 213.8 ± 2.13 mg/dL).

Regarding feed restriction, some experiments have demonstrated that broilers which had feed withdrawn before transport showed a higher thyroxine concentration and lower triiodothyronine, triglyceride, glucose, and lactate concentrations then those of broilers that had access to feed before the transport intervention. These findings indicate a negative energy balance and stress. A possible explanation for the significantly lower glucose and lactate concentrations in broilers that had feed withdrawn before transport compared with the levels in broilers that had access to feed before transport may be that transport intervention demands more energy obtained by oxidation of glucose than the additional neoglucogenetic effect of corticosterone increase by combining stress and feed withdrawal. Oxidation of glucose is possibly the preferred initial energy source. However, high concentrations of nonesterified fatty acid also indicate increased lipolysis (Nijdam et al., 2005b).

Changes in ambient temperatures are closely related to increased DOA percentages; thermal stress could explain the increase in this variable. Mitchell and Kettlewell (1998) linked physiological stress to thermal microenvironment during transport with a combined index called the *apparent equivalent temperature* (AET). This parameter combines the dry-bulb temperature and vapor density, which can be calibrated by physiological indicators to give a measure of stress. An AET value below 50°C is considered safe for the transport of poultry. Apparent equivalent temperature values between 50 and 70°C are potentially stressful if maintained for prolonged periods and may lead to some mortality. Values above 70°C are considered stressful with a high risk of mortality.

According to the results of some authors, the season of the year can also influence animal well-being and stress when animals are transported. Yalçin et al. (2004) indicate that preslaughter treatment (catching, crating, and transportation) during the summer increase blood uric acid, albumin, and glucose levels, which are reliable indicators of stress in broilers. In addition, during the summer months, high premortem temperatures affect the postmortem metabolism of muscle and subsequent meat quality via adrenal or other physiological responses or simply through fatigue (Bianchi et al., 2006). Therefore, the transportation of broilers causes a significant increase in plasma corticosterone concentration levels ($p < 0.001$) and the plasma lactate level ($p < 0.001$) after transportation at the shackling line in the slaughterhouse (Nijdam et al., 2005a). The effect of stress during quail transportation significantly reduced lactate and pCO levels for birds without rest compared to baseline samples. The effect of rest had a direct influence, showing a gradual decrease in pH and in hot and cold carcass temperatures. There was no significant effect on the weight of the carcass or organs caused by transport with and without rest (González et al., 2007).

BROILER CHICKENS DEAD ON ARRIVAL AT THE SLAUGHTERHOUSE

Conflicting published mortality and injury rates suggest multiple risk factors. Broilers exposed to such factors are more likely than unexposed birds to die or get injured. According to the literature, catching crew or methods are factors that influence DOA percentage (Ekstrand, 1998), transport time (Warriss et al., 1992), stockyard time, type of transport crates, time of day caught and transported, ambient temperature, stocking density per crate, mean body weight, age at slaughter, and sex of the birds (Bayliss and Hinton, 1990; Nijdam et al., 2004). Previous studies of broiler death in transit have focused largely on the cause of individual bird death or risk factors associated with loading and transport. Drain et al. (2007) examined farm production variables that may contribute to transport-related mortality. The final regression model in their study supports a hypothesis that death in transit is associated with larger birds, which had been reported previously (Bayliss and Hinton, 1990), and with unidentified factors common to the risk of increased death loss during the grow-out period (Drain et al., 2007).

Broiler mortality in transit is also influenced by the time of year. Voslarova et al. (2007) found the highest mortality rate in summer and winter months. Broilers stress caused by transport to processing plants is reflected in higher transport-related mortality of the birds. Long-term trends point to an increase in loss caused by broiler death. Longer transport distances as well as transportation in the summer and winter months have led to an increase in broiler loss due to death while being transported to processing plants (Vecerek et al., 2006). According to a study by Nijdam et al. (2004), a significantly increased percentage of DOA birds were associated with high ($>15^{\circ}$C) and low ($<5^{\circ}$C) ambient temperatures. Moreover, a significantly increased percentage of DOA birds were found if the broilers had been transported during the morning, or daytime, compared with night transport. In addition, the percentage of DOA birds increased with increasing body weight, increasing number of birds per compartment, increasing flock size, increasing transport time, and increasing stockyard time. Finally, the interaction term between ambient temperature and transport time indicated a decreased percentage of DOA birds when the temperature during transport was above 15°C and lower or equal to 20°C. We have observed that death rates among hens and roosters were influenced by the transport distance to poultry processing plants (Voslarova et al., 2007). Warriss et al. (1992) found that the mean DOA percentage was 1.81 times higher when broilers had been transported for more than 4 h compared to shorter distances.

During loading and transport to a slaughterhouse, broilers are exposed to factors that are responsible for mortality, injuries, health risk, and changes indicating increased stress (Vecerek et al., 2006). Gregory (1996) studied well-being and hygiene during preslaughter handling, noting that broilers were subject to procedures that caused suffering during such handling. Nijdam et al. (2006b) pointed out that infectious diseases, trauma, circulation, and heart disorders play an important role in the incidence of DOA broilers. DOA broilers with an abnormal heart

ratio more frequently showed ascites and hydropericardium. Good health status as well as additional attention to the catching and crating process is crucial to decreasing the percentage of DOA broilers. Prevention of an increased heart ratio and of ascites will improve living conditions in the broiler house and also decrease the DOA rate enormously.

A multilevel analysis was performed by Nijdam et al. (2004) to identify and quantify risk factors associated with mortality and bruises occurring between catching and slaughter of broiler flocks. Data included 1907 Dutch and German broiler flocks slaughtered in 2000 and 2001 at a Dutch processing plant. The mean DOA percentage was 0.46 and the mean bruise percentage was 2.20. Factors associated with corrected bruise percentage were season, time of transport, and ambient temperature. Unfortunately, these factors are quite difficult to manipulate. Factors associated with DOA percentage were ambient temperature, time of transport, catching company, breed, flock size, mean body weight, mean compartment stocking density, transport time, stockyard time, and "transport time $\times$ ambient temperature" interaction. The most important factors influencing DOA percentage, which can be reduced relatively easily, were compartment stock density, transport time, and stockyard time. Transport and stockyard time reduction, particularly, could have a major influence, due to their large variations. Reducing or removing these factors will reduce DOA percentage and thus increase profitability and animal well-being. Voslarova et al. (2007) indicated that the number of hens and roosters dying during transport to processing plants could be reduced. A factor that could help significantly reduce the death of hens and roosters in transport is a reduction in transport distance. Also, reducing the exposure of hens and roosters to climatic conditions may help decrease death losses during transport, particularly during cold months.

REQUIREMENTS DURING TRANSPORT

One of the most important recommendations for bird transportation to the slaughterhouse is that they should not be held in containers for longer than 24 hours unless they have access to water. When a delay is expected and holding time is likely to exceed 24 hours, birds should be released into a shed where they have access to feed and water, or immediate slaughter should be arranged at another slaughterhouse (CPTPWA, 2003).

One of the major stress factors to which broilers are subject during transport to slaughter is thermal stress (Kettlewell et al., 1993). Temperatures between top, bottom, front, and back can differ significantly, and transporters must be aware of this when considering the well-being of transported birds. Air circulation in transport units should (1) provide enough oxygen for the birds, (2) remove smells and gases, and (3) control temperature and humidity. Containers must be stacked in a way that facilitates good ventilation. Insufficient spacing can prevent heat loss and interfere with air circulation between containers.

Regarding hygiene during transportation, cages should be cleaned thoroughly and, if necessary, disinfected before birds are loaded into them (CPTPWA, 2003),

to avoid contamination from contact with sick birds. Taylor et al. (2001) made a study observing defecation patterns of birds according to the height of cages for transporting birds. They observed that broiler transport cage height had no effect on defecation patterns, live shrink, or fecal shedding. Cage ventilation, as a function of transport cage design (i.e., height, solid floors, dimensions, etc.), may have more of an effect on broiler live shrink than cage height on bird behavior. It is also important to mention that the driver of a road vehicle is responsible for the care and well-being of birds during transport unless either an attendant or an agent appointed by the owner travels with the consignment (CPTPWA, 2003).

EFFECTS OF TRANSPORT ON MEAT QUALITY

During transport, known stress factors include heat (due to high temperature and humidity), cold (due to drafts at high vehicle speed and wet feathers), crowding (inability to thermoregulate, move around, social stress, and other behavior), vibration, acceleration, noise, and food and water deprivation. Increased corticosterone levels after 1 to 3 h of transport, although ranging widely, indicate transport stress (Knowles and Broom, 1990). Reports on plasma glucose levels are contradictory, ranging from no difference after 6 h of transport to a reduction of 1.0 to 1.5 mM (Warriss et al., 1993). Basically, transport induces a complex of stimuli, any of which can be stressful to chickens and compromise animal well-being and meat quality (Savenije et al., 2002). For example, catching and crating pretransport can cause severe stress. Handling broilers in an inverted position leads to increased plasma corticosterone and prolonged tonic immobility reactions. Crating leads to increased corticosterone in broilers. Preslaughter stress can cause increased production of epinephrine and glucocorticoids, which can negatively affect meat quality. Broilers that are caught mechanically are pulled up gently by rubber-fingered rotors on a conveyer belt so that the birds are not inverted, which may reduce preslaughter stress (Nijdam et al., 2005a).

In practice, broilers are not fed several hours before being collected and transported to the slaughter plant. If broilers exhaust their internal energy stores, they may lack enough energy to cope with the conditions to which they are subject. Meat quality is affected by the energy stored in the muscle at time of slaughter and its rate of decrease postmortem (Savenije et al., 2002). Feed withdrawal affects a number of metabolic processes. Feed deprivation causes a shift from anabolism to catabolism, from lipogenesis to lipolysis, and a reduced metabolic rate. Broilers that had no access to feed before being caught, loaded, and transported had higher thyroxine and lower triiodothyronine, triglyceride, glucose, and lactate concentrations than those of broilers that had access to feed before catching, loading, and transport, which indicated the combined effect of both actions (Nijdam et al., 2005b). This effect on well-being may be caused partly by exhaustion of the animal's energy stores. The metabolic state of the animal at the time of slaughter determines the initial metabolic state of the muscle postmortem, and modified by processing, affects final meat quality. Several studies have described

the effects of preslaughter treatment on the animals' metabolic and stress-related parameters as well as the characteristic meat measured (Savenije et al., 2002).

Chicken breast muscle naturally discontinues energy consumption at 6 h. The muscle can maintain its internal energy balance for up to 2 h postmortem through means other than glycolysis. Between 4 and 6 h, postmortem rigor mortis sets in, after which time deboning can be completed without risk of cold shortening. Energy consumption in the muscle is not limited by the amount of glycogen available, but by pH and availability of adenosine triphosphate. Glycogenolysis continues after the glycolysis has come to a halt. It was shown that feed withdrawal and transport quickly decrease chicken central energy supply (Savenije et al., 2002). According to Warriss et al. (1993), factors that can influence pH are feed withdrawal, transport, shackling, and stunning. However, reports on the effects of transport on meat quality are sometimes contradictory, ranging from no differences to decreased muscle glycogen and increased pH levels after transport (Savenije et al., 2002).

Energy exhaustion compromises animals' well-being and makes them progressively less capable to cope with further stress. Neither feed deprivation nor transport under good conditions for short periods of time affect meat quality significantly (Savenije et al., 2002). On the other hand, in some studies birds had water withdrawn, and the total withdrawal times differed. A large amount of the body weight reduction is due to clearance of the gastrointestinal tract (Warriss et al., 2004). However, there will also be loss of edible parts due to dehydration and losses of fat and protein (Knowles et al., 1995). These changes can influence meat quality by affecting muscle glycogen content at slaughtering and therefore reduce the rigor rate as well as the final pH (Fletcher, 2002). In Mexico today, good-quality carcass meat is not paid for [PSE (pale, soft, and exudative) and DFD (dark, firm, and dry) meat are the same price]; it does not matter if the pH descends drastically, if the animals were stressed, or if well-being regulations were followed (Maldonado et al., 2007). Alteration of glucose in muscle may affect color and other meat quality attributes after sacrifice, since it is related directly to the final pH (Sams, 1999). Agitated birds exposed to stressful conditions before or during sacrifice use the glucose they have left, and muscles consume energy quickly, which accelerates rigor mortis and has a negative effect on meat softness (Ramos, 2005).

Mortality and stress of broilers transported to processing plants shows long-term increasing trends and is particularly alarming. Poor handing during transport is not the only cause of increased broiler mortality and number of injured birds, but also has a negative effect on the color of thigh meat (Kannan et al., 1997), causing dark, firm, and dry meat (Gregory, 1996). Holding time and temperature exert the most important effects on broiler breast meat color. However, other environmental conditions, such as transportation distance, may affect the color of the final product (Lyon et al., 2004; Bianchi et al., 2006). Kannan et al. (1997) suggested that higher preslaughter stress levels may affect the color of thigh meat in broilers. We have observed that the breast fillet from birds transported the shortest distance (<40 km) exhibited a higher ($p < 0.01$) breast meat redness

($a*$; 3.59) than that of birds transported distances of 40 to 210 or over 210 km ($a* = 3.28$ and 3.04, respectively). Furthermore, breast meat from birds transported the longest distance (>210 km) exhibited a higher $H*$. However, these color differences may not be of practical importance, as consumers may not be able to differentiate between fillets with such a slight difference in $a*$ and $H*$ (Bianchi et al., 2006). In a recent study, Debut et al. (2003) found no differences in breast meat color between transported and nontransported broiler chickens.

Environmental conditions during transport and holding of birds have been shown to have an effect on processing yield and meat quality (Petracci et al., 2005; Bianchi et al., 2004). The range in body weight (BW) losses is great because in some studies broilers had feed withdrawn, and in others they were transported before slaughter. BW losses will be greater at high ambient temperatures (Chen et al., 1983). The season, time of transport, and ambient temperature were also associated with bruise percentage for broilers. Ambient temperature, catching company, number of broilers in the flock, mean BW, mean compartment stocking density, transport time, and stockyard time were all associated with the DOA percentage of broilers (Nijdam et al., 2004).

The birds may be exposed to a variety of potential stressors during transit, including the thermal demands of transport microenvironments, acceleration, vibration, motion, impact, fasting, and withdrawal of water, social disruption, and noise (Mitchell and Kettlewell, 1998). These factors cause adverse effects on the birds, which may range from mild discomfort to death (Knowles and Broom, 1990). The authors stated that handling and transportation influenced the number of birds that were dead or bruised and resulted in a high incidence of bone breakage. More careful bird handling to reduce trauma has been reported as being a crucial factor in the reduction of mortality and carcass defects, such as hemorrhaging, bruising, and broken bones (Warriss et al., 1992; Nijdam et al., 2004). Whyte et al. (2001) illustrated the effects of transportation and associated stresses on *Campylobacter* spp. excretion rates when handled under modern commercial conditions and support previous works that identified transportation as a major risk in relation to carcass contamination and subsequent end product safety.

CONCLUSIONS

The well-being of chickens in broiler production is becoming a consumer concern in relation to both production method and transportation to slaughter. The number of birds dying during transport and in processing plants shortly after arrival may serve as an indicator of the quality of animal well-being during loading and transport. During transport, known stressors include heat, cold, crowding, vibration, acceleration, noise, and feed and water deprivation, inducing a complex of stimuli, any of which can be stressful to chickens, compromising animal well-being and meat quality. Careful bird handling to reduce trauma has been reported as a crucial factor to reduce mortality and carcass defects, such as hemorrhaging,

bruising, and broken bones. Any code of practice for animals should be reviewed frequently based on need, to take account of advances in the understanding of animal physiology, behavior, and technological changes in animal husbandry and their relationship to the well-being of animals.

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PART II

SLAUGHTERING AND CUTTING

5

SLAUGHTERHOUSE BUILDING AND FACILITY REQUIREMENTS

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Handbook of Poultry Science and Technology, *Volume 1: Primary Processing*, Edited by Isabel Guerrero-Legarreta and Y.H. Hui

INTRODUCTION

Establishments where animals are sacrificed and distributed are called *slaughterhouses* or *abattoirs*. These establishments can sacrifice up to 1000 domestic birds daily. Comparatively, 35 domestic birds can be slaughtered in the same time that it take to slaughter one cow (Official Mexican Regulation NOM-194-SSA1, 2004). Slaughterhouses and poultry-processing plants can be established successfully if they are located, designed, and operated properly, but have the potential to cause environmental damage if they are not (Planning SA, 2001). Therefore, sanitary specifications must be established and carried out by establishments that sacrifice animals for distribution, transportation, and sale. In this chapter we emphasize certain fundamental specifications regarding slaughterhouse facilities for birds; we also comment on international regulations. We discuss operational practices that favor proper development of, and procedures for, slaughterhouses, since we believe that the key point in proper management lies in good practices and in perfecting procedures, considering much more than merely design and construction of the space to be used. Our focus is not on the specific steps that should be taken, such as the amount of space needed for certain corridors or the distance between pieces of equipment, since most such information is well known.

BUILDING REQUIREMENTS

Before going into detail, we will discuss the general construction and provide some quick references, starting with the domestic bird slaughterhouse location, including bird processors, which should be at least 200 m away from inhabited areas, livestock farms, and any industrial or other structures that may emit fumes or other materials that may contaminate poultry meat (S.L.36.38, 1995). For wastewater lagoons, the separation distance is 1000 m (Planning SA, 2001).

The bird slaughterhouse should be properly equipped to provide both owners and employees with all the services required for proper sacrifice, such as inspection, refrigeration, and related activities (NOM-194-SSA1, 2004). The buildings of the slaughterhouse, including structures, rooms, and compartments, must be of sufficient size to allow processing, handling, and storage of the product so that it is suitable for human consumption and meets required regulations. The design of the slaughterhouse must work in a directional flow to prevent cross-contamination between live poultry and dressed carcasses. Proper signage should be provided for all rooms.

A separate slaughtering room for stunning, bleeding, scalding, and defeathering must be provided. There must be a wall between the live-bird holding area and the bleeding and defeathering area. A room for evisceration next to the slaughtering room must be provided. Defeathered poultry from the slaughtering room should enter the evisceration room by a rail system or chute.

Walls, ceilings (constructed and finished to prevent condensation and leakage), partitions, and doors must be constructed with smooth and durable materials

impervious to moisture that are easily cleaned. Waterproof floors must be constructed with nonslip materials and unevenly graded to prevent water stagnation and drained off into the sewer system to trapped outlets protected by grilles. Slaughterhouses must also have liquid waste treatment, storage and disposal facilities, as well as storage of solid/semisolid wastes and wastewater tank sludge disposal. Some specifications require a description of techniques to be used to minimize water demand and encourage careful use and recycling where practicable.

Intense, good-quality lighting must be provided in areas where food is processed, handled, stored, or examined; in areas where equipment and utensils are cleaned; in hand-washing areas, dressing rooms and locker rooms, toilets, and so on. All light fittings must be covered with nonshattering material, walk-in refrigeration units, dry-food storage areas, and other areas and rooms during cleaning periods must be lit with 110 lux (10 footcandles). Inside equipment such as reach-in and under-counter refrigerators as well as in areas used for hand washing, equipment washing, equipment and utensil storage, and bathroom rooms must be lit with 220 lux (20 footcandles). All surfaces where food employees work with food or work with utensils or equipment such as knives, slicers, grinders, or saws where employee safety is a factor must be lit with 540 lux (50 footcandles). All measurements must be taken from a distance of 75 cm (30 in.) above the floor.

Ventilation must be adequate to control odor, vapor, and condensation; heating, ventilating, and air-conditioning systems must be designed and installed so that air intake and exhaust vents do not contaminate food-contact surfaces, equipment, or utensils or cause food contamination. Overheating must be avoided, and the premises must be comfortable for employees.

Reception of Live Animals

Adequate holding facilities must be provided for live birds awaiting slaughter, and the birds must be given sufficient rest and water before slaughtering. The live animal unloading area should be constructed so that waste and dirty water can be drained into a manure sump so that pollution will not contaminate other parts of the building. The shipping and receiving area must have water-resistant roofs that can be easily cleaned, as well as natural ventilation or air-conditioning. The floor must be nonskid pavement or concrete. The floor must be well drained to provide proper cleaning of the area.

Regarding transport and unloading of live animals, waste products must be collected and eliminated in all soiled areas (S.L.36.38, 1995). Birds that are dead on arrival must be recorded, identified, and not permitted into the sacrifice area. Birds can only be sacrificed once their beaks are empty; that is, the beak must be inspected to make sure that no food is present.

A room or covered space that is suitably large and easy to clean and disinfect must be used for the premortem inspection of poultry; here the birds must be inspected before sacrifice, and those that do not pass inspection because of disease

must be culled. The slaughterhouse must have an inspection department headed up by a veterinary doctor with enough technical personnel to provide efficient service.

Slaughtering Line

Separate rooms that are easy to clean and disinfect must be provided exclusively for poultry suspected to be suffering from disease: a slaughter room large enough for stunning, another room for bleeding, another room for plucking, and still another room for scalding (S.L.36.38, 1995). In 1982, the Farm Animal Welfare Council highlighted the need for urgent reforms in order to reduce the number of birds slaughtered inhumanely. They expressed concern that large numbers of poultry may not be stunned before slaughter so that they will be insensible to pain until death supervenes. Specifically, they said that electrical stunning of poultry is not as reliable as it is claimed to be. They also stressed that when the neck is not cut properly, some birds will enter the scalding tank before they die and that this continues to happen even though some chickens on the way to scalding tank may display obvious signs of consciousness (Stevenson, 1993).

Keeping the last paragraph in mind, we have made a series of recommendations to comply with the animal well-being regulations, in this way guaranteeing the quality of the final product. We recommend that all poultry be stunned at the correct voltage and current, depending on the size and weight of the bird. The slaughter method must be as humane as possible, and the chickens must be bled about 90 s before they enter the scalding tank, which is designed to ease plucking. Clearly, only dead birds should be placed in the scalding tank. The slaughterhouse must have a bleeding area, which must have a hoist and sufficient room for personnel to bleed the animals. Blood must be eliminated properly and not in a public drain (NOM-194-SSA1, 2004).

Modern poultry slaughter is highly mechanized. The broilers are removed from the crates in which they have been transported and are hung upside down by their legs from shackles, which are on a moving line. This takes the birds to an electrically charged water bath through which their heads, necks, and upper thorax are dragged. This is designed to stun them (i.e., render them unconscious and insensible to pain). The shackle line then takes the broilers to the automatic neck cutters, the objective being that death will occur by bleeding for birds that don't die in the stunner (Stevenson, 1993).

However, a particular area of concern is the use of multibird water bath stunners with constant voltage. Current stuns a bird, not voltage. A multibird stunner with constant voltage will deliver the same current to each broiler only if each bird offers the same electrical impedance to current flow. However, in reality, bird impedance varies greatly, resulting in high-impedance birds receiving very little current (too little to stun them effectively) and low-impedance birds receiving too much. The industry should be encouraged to use a constant current, controlling each bird in multibird water bath stunners. Such a stunner would allow a current of 120 mA to be set for each bird without the wide variations in individual

current flow that occur in a constant-voltage stunner. This would prevent some birds from being stunned improperly and receiving too little current. It would also keep some birds from receiving a current flow so high that quality problems can occur (Stevenson, 1993).

A properly sized evisceration and preparation room must be far from other workstations, or separated by a wall so as to prevent contamination. Any communication between the evisceration–preparation room and the slaughter room, other than the narrow opening through which only slaughtered poultry may pass, must have an automatic closing door (S.L.36.38, 1995).

FACILITY REQUIREMENTS

Slaughterhouses must have at least two closed areas, one clean and the other for animal preparation, as well as corrals, a receiving area for animals, and a shipping area for carcass entrails (NOM-194-SSA1, 2004). The clean area is for the manipulation of products prepared for human consumption, specifically from evisceration to the refrigerated area where carcasses are stored (POEN, 1980). The animal preparation area is for handing animal bodies, organs, and their content, this area includes the premortem bath and the entrail cleaning area. For example, the scalding and defeathering area must be physically separated by walls. The processing room ceilings must be at least 3 m high.

Chiller Tank

Dressed poultry must be chilled to 4°C or below for at least 20 min. Water must flow in the opposite direction of dressed poultry in chiller tanks. Ice used for processing and chilling of dressed poultry must be manufactured from potable water.

Chillers and Freezers

The bird slaughterhouse must have adequate built-in chiller(s) and freezer(s) and must be provided for storage of poultry and its products. The temperature of the chiller must be maintained between 0 and 4°C, and the freezer must be −18°C or below. Every chiller or freezer must be fitted with temperature recorder charts and graphs and proper signage to indicate temperature. The slaughterhouse must be maintained in sanitary conditions at all times.

Cutting, Packing, and Storage Rooms

The temperature of the cutting room must be controlled at around 12 to 15°C. The material that is used to can and pack products must be sanitary, so that the product will not react to the packing or the physical characteristics of either chemical or sensorial substances. Ideally, the packing room (12 to 15°C) will be

located between the cutting room and the finished product cold room or delivery area. All food-packaging activities must be carried out on stainless-steel tables. The rooms for hazardous materials must be located away from any room where food products are handled. Just as in the handling of carcasses, the entrails and rejected products must be stored separately from the products used for human consumption.

Equipment and Utensils

Adequate equipment for cleaning and disinfecting hands and tools must be supplied in workrooms; such equipment must be as close as possible to the workstations, and taps must not be hand-operable; these facilities must have hot and cold running water, cleaning and disinfecting products, and disposable hand towels to cleanse instruments. The hot-water temperature must be at least 82°C (S.L.36.38, 1995). Instruments and any equipment that comes into contact with poultry during processing and storage must be made of noncorrodible material and must be easy to clean and disinfect. Cages for poultry delivery must be made of noncorrodible material, must be easy to clean and disinfect, and must have waterproof floors. They must be cleaned and disinfected each time they are emptied; equipment and instruments used for slaughtering and storing meat must be kept clean and in good condition. They must be cleaned carefully and disinfected several times during each working day, at the end of the day's work, and before being used again if they have been contaminated.

Waste Disposal

The area designated for rejected products and by-products must be physically separate from the rest of the slaughterhouse and must have a controlled temperature and a proportionate amount of clearly labeled plastic or anticorrosive metal containers with locking devices and a key under guard for security. Storage of poultry meat that has been detained temporarily, and unhealthy meat declared unfit for human consumption, must be kept under strict control if not removed from the slaughterhouse daily. Slaughterhouses must have an incinerator oven with sufficient capacity to dispose of the products rejected. A temperature-controlled room is required exclusively for the technical treatment or destruction of poultry meat and by-products declared unfit for human consumption, meat that is excluded from use in human consumption but is intended for industrial purposes. If such technical treatment or destruction is carried out on the premises, they must be separated from the processing area (S.L.36.38, 1995).

Rejected products must be marked with a special color that identifies them clearly. Rejected products that cannot be marked easily must be deposited in clearly marked containers. Effluent containing solid materials is directed through a separator, indirect waste separator, or save-all, which should effectively retain the solids prior to the discharge of effluent. Sewage must be disposed of in a separate sewage system that must be sufficient to prevent sewage backup in

processing areas where the product is handled or stored. Effluent or sewage lines must not pass directly over or through production areas unless they are controlled adequately.

PERSONNEL CARE AND HYGIENE

Employers have an obligation to train employees for equipment use and humane poultry handling. Owners of poultry operations have a responsibility to provide facilities and equipment that enable proper bird handling, loading, and unloading without causing injury or undue suffering to the birds. Correct building design, accessibility to transport, location, and appropriate design and use of cages and equipment greatly improve the humane handling of poultry. The driver of a road vehicle is responsible for the care and welfare of birds during transport unless an attendant or agent appointed by the owner travels with the consignment (CPTPWA, 2003). Personnel who have entered the unsanitary section of the slaughterhouse are not permitted in the clean area, unless they change aprons, robes, overalls, and boots as well as washing and disinfecting hands, nails, and forearms. Knife sterilizer(s) with hot water maintained at 82°C must be provided at the slaughter point, and the poultry killing knife must be sterilized regularly. Adequate hand-washing basins equipped with non-hand-operated taps, liquid soap, and disposable paper towels must be provided for food handlers. Bathrooms must not have direct access to the processing area. Adequate disinfecting facilities such as a foot bath must be provided at the entrance to the processing areas. The openings of the hoses that are used during operation must not come in contact with the floor or walls.

Staff members who slaughter animals and work on and handle meat must wash and disinfect their hands several times during each working day and each time they resume work. Persons who have been in contact with sick animals or infected meat must immediately wash their hands and arms carefully in hot water and then disinfect them. Smoking is forbidden in workrooms and storerooms (S.L.36.38, 1995). To prevent adulteration of product, all persons working in contact with products, food-contact surfaces, and product-packaging materials must adhere to hygienic practices while on duty. Personnel who handle products must use disposable or easily cleaned aprons, dresses, and outer clothing. Clean garments, head covers, and boots must be worn at the start of each workday, and garments must be changed during the day as often as necessary to prevent contamination or adulteration of product.

Any person who has or appears to have an infectious disease, open lesion (including boils, sores, or infected wounds), or any other abnormal source of microbial contamination must be excluded from any operations that could result in product adulteration until the condition is corrected. Personnel must clean their hands using foot-operated washing facilities and may not clean their hands in a sink used for food preparation or in a service sink or cleaning facility used for the disposal of mop water and similar liquid waste. Personnel must keep their

fingernails trimmed, filed, and maintained so that the edges and surfaces are cleanable and not rough.

Areas where slaughtering and inspection is carried out must be suitably lighted to detect entrails, bile, excrement, contamination, or damage to carcasses, with enough light to distinguish small injuries or petechiae (NOM-194-SSA1, 2004).

CONCLUSIONS

It is important to consider that the slaughterhouse must be designed to protect fundamental aspects such as the well-being of birds during unloading and the time present at the installation. Another fundamental aspect at the installation is the guarantee that good slaughtering techniques are used, assuring refrigeration of carcasses during the entire procedure as well as the presence of an on-site water treatment plant. It is also important to point out that the design of the bird slaughterhouse must include an expert veterinary doctor with experience in animal well-being and food production of innocuous carcasses. The objective of having a veterinary doctor on site at the slaughterhouse is to adjust to the regulations of each country, not the slaughterhouse regulations. We refer specifically to slaughterhouse establishments that slaughter, store, transport, and sell domestic birds and their products. Slaughterhouses must comply with regulations.

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6

SLAUGHTERING EQUIPMENT AND OPERATIONS

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Handbook of Poultry Science and Technology, *Volume 1: Primary Processing*, Edited by Isabel Guerrero-Legarreta and Y.H. Hui

INTRODUCTION

Globally, poultry meat production as well as trade in poultry products have shown a remarkable dynamic over the last four decades. Between 1970 and 2005, poultry meat production increased faster than that of beef, veal, or pig meat. The trade volume of poultry meat increased even faster than production (Windhorst, 2006). This increase in poultry meat production and trade is closely related to the rapid worldwide increase in poultry meat consumption. The reasons for this growth are the healthy image of the product, which is considered lean and rich in protein, the boom in processed products, and last but not least, the relatively low price of this type of meat (Uijttenboogaart, 1999). The appearance of the H5N1 strain of the avian influenza virus in the European Union (EU) in early 2006 has disrupted the market balance of poultry meat, weakening consumer confidence and export opportunities, and leading to falling prices and lower production. However, this short-term disruption is not expected to alter the medium-term outlook for poultry production, which remains relatively positive due to competitive prices with respect to other meats, strong consumer preference, and the increased use of poultry meat in food preparations. The poultry industry is the largest (in terms of animal numbers) and the most highly automated, vertically integrated, and intensified of all the animal production industries. As a consequence, public interest in the welfare of poultry has intensified. At the international level, animal welfare in general has assumed much greater importance in recent years. The European Commission (EC) has been developing animal welfare legislation for more than 30 years and has been at the forefront of initiatives to promote animal welfare internationally through its active participation in, and support for, initiatives of the Council of Europe. The poultry industry should therefore keep in mind that it is in their interest to be active and proactive in the field of animal welfare, since this will be one of the key factors for its positive image with consumers and subsequent development (AVEC, 2007).

POULTRY-SLAUGHTERING PLANTS

Large-scale poultry-processing plants exist worldwide. The plants are specifically designed to process poultry and incorporate slaughtering, defeathering, evisceration, inspection, chilling, and packaging operations. Although slight modifications might exist, the steps involved in a typical poultry (chicken, turkey, duck) plant are shown in Figure 1. All the stages are important from a hygienic point of view, although scalding, feather release, and evisceration are the most delicate (Capita et al., 1999). The operations can be automated to varying degrees, depending on required output, capital investment, labor costs, and so on. Some modern plants include automated evisceration and cut-up lines that can handle about 6000 birds per hour on a single line, while other manual operations handle only a few dozen birds per hour. New computerized machine-vision equipment is also finding its way to processing plants and is used for grading and, potentially, for inspection

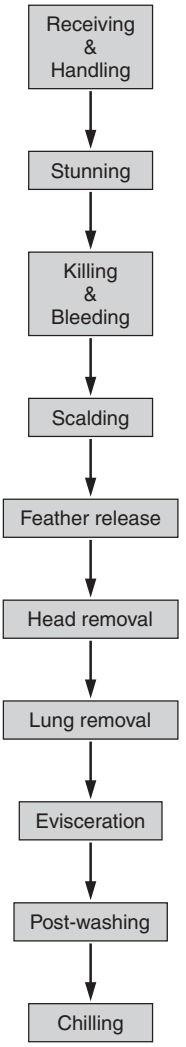

FIGURE 1 Flow diagram of the poultry-slaughtering process.

purposes. Such equipment can be useful for high-volume operations, and data can also be used for marketing purposes (Barbut, 2004).

OPERATIONS

Reception and Handling

Birds are usually transported to the processing plant in crates stacked on a truck or in cages mounted permanently on a truck. It goes without saying that transporting

vehicles and crates should be kept in a clean, hygienic, and safe manner. Upon arrival at the plant, a short rest period for the birds is usually recommended. The birds are then unloaded from the crates and placed on the shackle line manually. Automatic unloading systems have also been developed and are usually part of a modular crate system, which can be lifted and tilted slowly so that the birds can pass onto a conveyor belt. In plants where gas stunning is employed, the birds can be left in the crates, where they are stunned by the selected gas, and later removed from the crates.

Stunning

According to the 1958 Humane Method of Slaughter Act, all processors of food animals must render U.S. Department of Agriculture (USDA)–inspected animals insensible to pain before exsanguination. Even though this act excludes poultry, stunning is common in most plants, except when religious considerations are involved (e.g., the Jewish and Islamic laws do not permit stunning), to comply with the Poultry Inspection Regulations of 1984. This regulation states that poultry should be slaughtered in a manner that results in thorough bleeding of the carcass and that breathing must have ceased prior to entrance of the carcasses into the scalder (Alvarado et al., 2007). For stunning purposes, Regulation 1993/119/EC for the protection of animals during slaughter or killing only allows methods that cause immediate unconsciousness after application to the animal and ensure that the animal does not regain consciousness before death. In the case of poultry, stunning can be done using an electric current, gas, or mechanical means (Fletcher, 1999; Barbut, 2004).

Electrical Stunning The method most universally accepted and used for immobilizing poultry prior to slaughter in processing plants is electrical stunning (Bilgili, 1999; McKeegan et al., 2007). The industry justifies the use of electrical stunning systems because they rapidly immobilize a bird, reduce any struggle associated with slaughter, increase uniformity of heartbeat, and improve the bleed-out rate. Electrical stunning has always been considered an inexpensive, safe, and convenient method of slaughter (Bilgili, 1992; Fletcher, 1993). Electrical stunning is accomplished by passing a sufficient amount of electrical current through the central nervous system of birds for a given amount of time (Bilgili, 1992). The state of unconsciousness induced by electricity results from the inhibition of impulses from both the reticular activating and somatosensory systems (Heath et al., 1994). The stunning current reaching the brain must be sufficient to induce an epileptic seizure and is usually lower than that required for ventricular fibrillation and hence death by electrocution. Insufficient current may physically immobilize a bird but may not prevent the perception of pain, stress, or discomfort. Hence, if bleeding is not rapid, birds may regain consciousness prior to scalding (Fletcher, 1993).

Electric shock can be applied “dry” or in a water bath (the traditional and most used method of stunning poultry is to immerse the head in an electrified water

TABLE 1 Minimum Electric Current Root Mean Square per Bird Recommended in the EU for Poultry and Turkey Stunning

	Stunning in Water Bath	Stunning in Head (Dry)
Poultry	100 mA	240 mA
Turkey	150 mA	400 mA
Minimum time	4 s	3 s

bath). In both cases, the method involves the shackling of live birds to an overhead line, which has numerous negative aspects: poor animal welfare, considerable product damage, and difficult working conditions (Abeyesinghe et al., 2007). This method is used almost universally, and improvements are constantly being made in such areas as design, amperage, voltage, and frequency in an attempt to improve product quality.

High-voltage (ca. 120 mA) electrical stunning has been associated with a higher incidence of carcass damage, such as red wingtips, broken bones, and hemorrhages (Gregory and Wilkins, 1989). High voltages may cause approximately 90% heart fibrillation, resulting in inefficient bleeding; severe muscle contraction, causing increased hemorrhaging; and even death before exsanguination, again leading to poor carcass and meat quality. However, this high-voltage method is usually favored in the EU because it lowers the risk of birds regaining consciousness during the slaughter process (Raj et al., 1997; Lambooij et al., 1999; López and Casp, 2004; Alvarado et al., 2007). Table 1 shows the minimal electrical current recommended in the EU for poultry and turkey stunning. Use of an electric current of 100 mA produces stunning successfully in only 90% of animals, so that some authors have proposed that at least 120 mA be fixed as the minimum electric current (Lambooij et al., 1999; López and Casp, 2004).

Low-voltage (ca. 13 to 15 mA) electrical stunning is most often used in the United States to decrease carcass quality damage and the hemorrhaging associated with high-voltage electrical stunning, even though a bird may regain consciousness if not slaughtered within approximately 2 min of stunning. Low-voltage electrical stunning has been shown to affect early blood loss negatively but does not affect total blood loss after the 90- to 120-s exsanguination period (Gregory, 1993; Papinaho and Fletcher, 1995). However, despite its widespread use and improved methodology, electrical stunning has been criticized for reducing meat quality because of insufficient bleeding; the occurrence of blood blisters, especially in breast meat; and tougher or lower-quality meat if insufficient time is allowed for rigor mortis to develop before filleting (Summers, 2006).

Gas Stunning The use of gas (e.g., carbon dioxide, argon) for stunning poultry has been studied for many years. Stunning in a gas atmosphere can be carried out by increasing the carbon dioxide content of the gas mixture (hypercapnic

hypoxia), by oxygen depletion (anoxia), or by a combination of the two (hypercapnic anoxia) (Hoen and Lankhaar, 1999). Carbon dioxide has a unique property in that it reduces the pH of the cerebrospinal fluid of the bird, which results in an anesthesic response, whereas argon (or other inert gases) simply displaces air and leads to anoxia (Eisele et al., 1967; Alvarado et al., 2007). Carbon dioxide is an acidic gas and is pungent to inhale at high concentrations. It is also a potent respiratory stimulant that can cause breathlessness before loss of consciousness. The welfare implication is that birds might experience unpleasant sensations either during the initial inhalation of carbon dioxide or during the induction phase. Some studies have clearly indicated that chickens and turkeys can detect the presence of a high concentration of carbon dioxide and, given a free choice, will avoid it. However, presumably because argon is an inert gas with no taste or odor, birds would not detect it or feel any unpleasant sensations during the induction of anesthesia with this gas (Raj, 1998).

Stunning methods using carbon dioxide and argon gas mixtures also reduce hemorrhages in breast meat and accelerate aging, resulting in faster processing (Raj and Nute, 1995). From a welfare standpoint, behavioral and electrophysiological investigations into the time elapsing to loss of brain responsiveness in chickens and turkeys indicated that the first choice of gas should be 90% argon in air, leaving 8% nitrogen and 2% oxygen from air, and the second choice should be a mixture of 30% carbon dioxide and 60% argon in air, leaving 8% nitrogen and 2% oxygen from air. At this level of carbon dioxide, but no higher, the adverse effect is said to be low (Raj et al., 1991; Raj, 1997). The first atmosphere would have a gentler effect during the induction of anoxia, while the second atmosphere induces a more rapid anoxia. Birds showed no aversion to the presence of 90% argon or 30% carbon dioxide in a feeding chamber (Raj, 1997, 1998). Other studies have been developed to improve gas stunning systems. For example, Abeyesinghe et al. (2007) and McKeegan et al. (2007) recommend the use of a biphasic hypercapnic hyperoxygenation mixture in which an anesthetic phase with a gas mixture of 40% carbon dioxide, 30% oxygen, and 30% nitrogen is followed by a euthanasia phase with 80% carbon dioxide, 5% oxygen, and 15% nitrogen. These authors reported that use of this mixture has advantages, in terms of welfare and carcass and meat quality, compared with a single-phase hypercapnic anoxid approach using 60% argon and 30% carbon dioxide in air with less than 2% oxygen.

Gas stunning can be used for batch stunning or for stunning in transport crates. However, batch stunning eliminates preslaughter bird stress, allows easier suspension, and reduces damage and/or bruising due to suspension (Raj et al., 1990a,b). Gas stunning in crates may not be uniform, as some birds may put their heads under their wing, where air pockets may be found. Also, it is impossible to identify birds in crates that were dead before stunning. However, such problems are eliminated in the newly developed online gas stunning systems that are now being introduced (Summers, 2006).

Mechanical Stunning Mechanical means include the archaic method of "brain sticking" (piercing the brain) or concussion. Because of the logistical and welfare

difficulties of positioning the bird for mechanical methods under automated line conditions, there are at the present no commercial systems in use. This method is used only to slaughter ostriches, which some authors have compared with bovine slaughtering lines (Sáez, 2000).

Killing and Bleeding

After being stunned, general slaughter procedures are used to exsanguinate broilers. One method consists of cutting both the jugular and carotid arteries in the neck, to ensure rapid death. Failure to cut both carotids may add 2 min to the time taken for brain failure in birds (Stevenson, 2001). This method also leaves the windpipe and esophagus intact, which is important when automated equipment is later used to pull out the windpipe (Barbut, 2004). Less common methods include decapitation, which is accepted as a suitable means of killing chickens by the American Veterinary Medical Association (AVMA, 1993). Decapitation after low-voltage electrical stunning may be considered an alternative to the high-voltage stunning used in the EU, which, as mentioned above, may cause meat quality problems as a result of hemorrhaging. Decapitation causes a higher pH at 24 h postmortem and compared with other methods has no effect on color, water-holding capacity, or tenderness (McNeal and Fletcher, 2003; McNeal et al., 2003). The amount of blood in the body with respect to live weight is higher in birds (ca. 10%) than in other animals (3 to 4% in pigs). In any case, during bleeding only 40 to 60% of total blood is removed, the rest remaining in the body, where it is distributed within the viscera (20 to 25%) and carcass (15 to 20%; muscles, fat, bones, etc.). The duration of bleeding depends on the stunning method applied and the time elapsing between stunning and bleeding. If electric stunning is used, 40% of blood is eliminated in 60 to 90 s, while after gas stunning the bleeding period must be increased to 2 to 2.5 min. It is important to note that a poor bleed-out can increase the prevalence of carcass downgrading due to blood spots and, in particular, engorged or hemorrhagic wing veins (Hoen and Lankhaar, 1999).

Scalding

Scalding softens the skin and facilitates plucking. The tail feathers, remnant feathers, and skin color are the most important items for further processing. Two types of scalding system can be used: hot-water scalding or steam scalding. In turn, hot-water scalding may involve immersion of the carcass in the water or spraying water on the carcass surface. Standard scalding involves submerging the carcass in hot water when still on the slaughtering chain. Scalding temperatures should be determined by the type of poultry and plucking difficulty. For waterfowl and mature birds, a higher temperature and longer submersion time should be used, while younger birds need a lower temperature and shorter immersion time. Depending on scalding temperature, three types of scalding scheme have been defined (Table 2), the choice of which will depend on the relative degree of

TABLE 2 Recommended Scalding Schedules for Defeathering

Method	Water Temperature (°C)	Time (s)	Used for:
Hard scalding	>60	45–90	Waterfowl
Medium/subscalding	54–58	60–120	Mature birds
Soft/semiscalding	50–53	60–180	Broilers, young turkeys

difficulty in removing the feathers, the chilling method that is followed (water, air), and the age of the bird.

1. *Soft scalding/semiscalding* entails scalding for 60 to 180 s in water at 50 to 53°C. This method leaves the epidermal layer intact, which is why it is commonly used for young broilers and turkeys but still allows for relatively easy feather removal. Birds slaughtered for display should be scalded in this way to improve the appearance of the carcass, since water that is too hot will cause the outer layer of skin to loosen or be lost. Such loss also results in the loss of some yellow pigment from the skin.
2. *Subscalding/medium scalding* is used for mature birds, and involves using water at 54 to 58°C for 60 to 120 s. The epidermal layer is broken down by this time–temperature combination, and the feathers are usually much easier to remove.
3. *Hard scalding/full scalding* requires a water temperature above 60°C for 45 to 90 s. This method is faster and eliminates pinfeathers, but the birds tend to dry out and have a less desirable appearance. It is easier to remove the feathers from carcasses scalded at this temperature than from those scalded at lower temperature, but the flesh of such poultry is "doughy" and lifeless and the skin becomes discolored soon after processing. As a result, the carcass must be kept covered with a packaging material or moist with ice or water. Waterfowl may be scalded at this temperature because it is the only satisfactory way to release feathers, while the skin of waterfowl does not discolor as readily as do other species of poultry (Barbut, 2004).

During scalding, large numbers of bacteria are removed from carcasses, and many of them die in the hot scald water, although the process may also permit some bacterial cross-contamination between carcasses because the scalding process is a "community bath" (Mulder and Dorrosteijn, 1977; Mulder et al., 1978; Dickens et al., 1999). The fecal material from the grow-out houses and transport container on the feathers and feet of broilers and fecal material excreted from the intestinal tract can contaminate the scald water, thereby contaminating subsequent carcasses that pass through the scalder (Dickens et al., 1999). Lillard (1973) reported that when scald water contaminants enter the broiler's respiratory system during immersion scalding, they can be spread to the circulatory system and to the internal organs, and possibly throughout the entire carcass. Increasing scald water temperature to increase the death rate of bacteria may

not be a management option, however, because higher temperatures also affect the skin's appearance, color, and cooking characteristics (Jones and Grey, 1989). Any unnecessary heating of scald water also has an economic cost (Cason et al., 2001). To limit contamination, changes in scalder design have been introduced; for example, if the water flows in a direction opposite to the carcasses on the shackle line, they will generally move into progressively cleaner water. Other changes are the installation of multiple-tank scalders and electronic controls in poultry-processing plants, which permits management of scald water temperatures and the application of different water temperatures in the tanks, and the selection of hot-water spray scalding or steam scalder systems. Patrick et al., (1972) found that steam-scalded carcasses had significantly lower total bacterial counts than those of hot water–immersion scalded carcasses when sampled after scalding and plucking.

Feather Removal

Birds should be plucked immediately after scalding. In large processing plants, feather removal is done by mechanical pickers or pluckers equipped with rubber fingers that rub the feathers off the carcass. In a continuous operation, this is done while the carcass is hanging upside down and moved forward (by the shackle line) between two or three sets of rotating disks equipped with rubber fingers. In the early 1960s it was shown that scalding reduced feather attachment significantly. It was reported that scalding broilers at 50°C reduced feather pulling force by about 30% compared with pulling similar feathers from a nonscalder bird. When the scalding temperature was raised to 53°C, the force needed was reduced by about 50%; and when 60°C was used, 95% reduction was obtained (Klose et al., 1961). More recent studies have confirmed these results and also showed that the force required to pull the feathers was greater in the femoral area than in the pectoral area, with sternal feathers requiring the least force (Buhr et al., 1997; Barbut, 2004). Some authors have reported that this stage is the principal point of contamination (Mead et al., 1994). Experiments using marked microorganisms have demonstrated that the contamination of one bird can be passed to the next 200 birds in the slaughtering chain by the defeathering machine (Mead et al., 1994; Bremner and Johnston, 1996). In small-scale operations, hand picking may still be seen. Hand picking is also used if feathers are to be collected, as with ostriches (Figure 2). When pinfeathers are a problem, as with waterfowl, wax dipping is common after mechanical picking (i.e., suspending the carcasses in hot wax, followed by cold-water immersion and peeling off the wax); the wax can be reused after reheating and filtering. When only minor pinfeathers exist, singeing (the process of burning small feathers) is commonly used. The carcasses are then rinsed to remove soil left after defeathering and singeing (Barbut, 2004).

Head Removal

After defeathering and before evisceration, the head must be removed if decapitation was not used as the killing method. Automatic machines remove

FIGURE 2 Manual defeathering of an ostrich carcass.

the head, esophagus, and trachea, an essential stage for subsequent automatic evisceration.

Lung Removal

Lungs can be removed manually or by automated equipment. For turkey the tendons must also be removed in this step. The lungs must be cut at the tarsus joint (López and Casp, 2004), and it is important that the cut be made between the bones and not through a bone, since the latter will appear dark or red in a chilled bird and almost black in a cooked product (Barbut, 2004).

After removal of the legs, the carcasses are usually moved to another line. This can be done manually as the carcasses fall onto a sorting table, or by automatic transfer. When the birds are unloaded from the crates initially, they are placed on the line with their feet suspended from a shackle, so they need to be resuspended from the knee joint after their feet are cut. This also assists in reducing contamination since the dirty shackles used for live birds are replaced by clean shackles. The advantages of using automated re-hanging equipment include labor saving, better hygiene (since the birds are not piled onto a sorting table), and a more even rigor mortis process. The latter van is important since rigor starts to set in at this stage, but if the birds are re-hung without delay, all birds will be positioned in the same way (i.e., with equivalent tension on similar muscles) (Barbut, 2004).

Evisceration

This stage refers to opening the body cavity and withdrawing the viscera (i.e., intestines, gizzard, gallbladder, crop). Different operations form part of

evisceration: (1) repositioning on the conveying line, (2) cutting the neck skin, (3) cutting the cloaca, (4) opening the abdominal cavity, and (5) withdrawing the viscera (López and Casp, 2004). This can be done manually, semiautomatically, or fully automatically. In all cases, special care should be taken not to pierce the viscera and contaminate the carcass. Leakage of ingesta during evisceration is problematic because (1) the quality of the carcass is decreased; (2) production efficiency decreases because of the extra labor required to reprocess carcasses, with the corresponding loss of product quality and yield during trimming; and (3) there is a strong likelihood that the carcass will become contaminated with populations of pathogenic and spoilage bacteria (Russell and Walker, 1997). Several studies have demonstrated that cross-contamination frequently occurs during evisceration (Surkiewicz et al., 1969; Powell et al., 1995). The Canadian Food Inspection Agency recommends that farmers who supply birds to poultry-processing plants withdraw feeding 24 h before processing to minimize the possibility of accidental spillage of gastrointestinal contents onto the carcasses (CFIA, 1997).

Postwashing

Prior to refrigeration, a final internal and external washing of the carcass is necessary to remove debris and blood or fat clots. Remaining material in the intestinal crop due to problems during evisceration may also mean that the carcass must be washed. Washing involves spraying the carcasses (spray washing) in cabinet washers (Northcutt et al., 2005) with cold or hot water. When hot water (ca. 35 to 50°C) is selected, the washing process is more effective, due to the reduction in surface microbial counts (Thomas et al., 1974). The washing effect can also be improved by using brushes and rubber fingers. Where permitted, bacteriocidal rinses can be used. Research has investigated the antimicrobial effects of chlorine dioxide (Lillard, 1990), sodium chloride (Li et al., 1997), trisodium phosphate (Kim et al., 1994; Lillard, 1994; Hwang and Bauchat, 1995; Li et al., 1997; Xiong et al., 1998a,b), cetylpyridinium chloride (Kim et al., 1996; Li et al., 1997; Xiong et al., 1998a,b), hydrogen peroxide (Hwang and Bauchat, 1995), lactic acid (Mulder et al., 1987; Izat et al., 1990; Hwang and Bauchat, 1995; Li et al., 1997; Xiong et al., 1998a,b), and acidified sodium chloride (Kemp et al., 2000, 2001) in washing water. To date, chlorine remains the most widely used antimicrobial chemical in the poultry industry (Northcutt and Jones, 2004). The washed carcasses, with an internal temperature of approximately 30°C, now go to a refrigeration process.

Chilling

Carcasses must be chilled quickly to minimize microbial growth. The most common methods include water immersion chilling, air chilling, and spray chilling, all of which, together with the required equipment, are described in Chapter 17.

EQUIPMENT AND MACHINERY

Live-Bird Handling Systems

A substantial part of the overall efficiency of a poultry-processing plant is determined at the broiler house and during the journey to the plant. Application of the appropriate handling system yields efficiency gains long before the birds are hung in the shackles. These systems must be developed to try to reduce the risk of damage to birds during manipulation and loading, which will have an important effect on final product quality. In the EU the transport of animals for slaughter and the slaughter itself are regulated by EU Regulations 1991/628/EC and 1993/119/EC. Birds are usually transported in container systems because this obviates the need for manual handling, which leads to improved animal welfare (Uijttenboogaart, 1999). Different innovations in container design have been introduced. Stork Food Systems have developed a system based on a special container with an Air-Flo floor that offers many benefits as to ventilation, temperature control, and the collection of droppings. Unloading the birds from crates and placing them on the shackle line is usually done manually. Automated unloading systems have also been developed and form part of a modular crate system, which can be lifted and tilted slowly so that the birds can pass onto a conveyor belt. In plants where gas stunning is employed, the birds can be left in the crates, where they are stunned and then removed from the crates (this should assist in reducing the bruising of excited birds, as they are taken out of a cage, but unloading should be done immediately after stunning so that no time is allowed for the birds to regain consciousness) (Barbut, 2004).

Conveying Line

The high degree of automation involved in industrial poultry slaughtering implies the need for an elevated conveying line, which is used to hang the birds and convey them to the slaughter procedure. The speed can be adjusted according to the output (2000 to 4500 birds/h). The line is composed of stainless-steel chain and hooks.

Stunning Equipment

It is important to emphasize that stunning, neck cutting (killing), and bleeding operations are inseparable and interrelated steps in the slaughter process. The evolution of stunning technology in modern-day broiler plants has, for the most part, been driven by other factors in the slaughter process, such as the type of neck cut performed, bleed time, scalding and plucking efficiency, and the extent of automation in evisceration.

Electrical Stunners Although there are many makes of commercially available electrical stunners, their design and operation are similar. A fiberglass brine–water bath cabinet is positioned under the overhead conveyor line, from

which chickens are suspended on shackles. The cabinet is vertically adjustable and is usually set at a height that allows the heads of the birds to be submerged in a brine–water bath, with an electrified metal grate at the bottom. Although the shackle line is connected to earth, a ground bar contacting the shackles is often used to complete the electrical circuit. The birds pass through the stunner cabinet in a continuous procession, typically 140 to 180 birds per minute in the United States, depending on the inspection system used. When voltage is applied between the submerged electrode and the earth (ground), the current flows through the immersed chickens in the cabinet to complete the circuit. Chickens in this type of circuit represent a series of resistors connected in parallel. Although birds contacting each other in this circuit can create other resistive pathways, the significance of such pathways has not been well established (Kettlewell and Hallworth, 1990; Sparrey et al., 1992; Bilgili, 1999).

The current intensity flowing through each individual bird depends on the voltage applied and the electrical impedances of the birds in the brine–water bath. Woolley et al. (1986a, 1986b) have shown that the whole-bird resistance of broilers ranges between 1000 and 2600Ω. More recently, sex differences in resistance were also reported, with females exhibiting higher resistance than males (Rawles et al., 1995). As the birds enter and leave the stunner cabinet, they constantly change the total resistance of the system. At a given total voltage, the birds receive current in proportion to their own resistance. In addition, the resistance provided by the water or brine solution is also critical and has been shown to vary under commercial conditions (Bilgili, 1992). Commercial stunners provide a choice of alternating or direct currents, either low or high frequency, half or full rectified, sine or square waveforms, constant or pulsed currents (Ingling and Kuenzel, 1978; Griffiths and Purcell, 1984; Bilgili, 1992; Heath et al., 1994). The effectiveness of an electrical stunning system depends not only on the electrical variables used (i.e., current, voltage, waveform, frequency, and duration), but also on biological factors (i.e., size, weight, sex, composition, and feather cover) (Kettlewell and Hallworth, 1990). The development and implementation of low-voltage (10 to 14 V, pulsed direct current, 500 Hz, 10 to 12 mA per bird) stunning systems for broilers has been accomplished by significant changes not only in the electrical circuitry but also in the stunning process. The cabinets are designed with rump bars to limit the movement of birds and to prevent birds from avoiding the brine bath. The overflow of charged brine at the entry of the cabinet is eliminated by elevating a secondary entry ramp. This in-feed ramp is extended 4 to 5 cm over the primary ramp to allow quick capture of birds at entry into the brine solution. The feet–shackle contact is sprayed with water or brine solution to assist current flow. Ground bars are designed to ensure the continuous and uninterrupted flow of current through the system. The stunner control panels have also been redesigned for continuous display and monitoring of voltage and current levels. The low-voltage, high-frequency systems used in the United States are in contrast to the high-voltage, high-current systems used in the EU and in other parts of the world (Bilgili, 1999). In the EU, the minimum current per bird for water bath stunning is 100 mA. The voltage in a water bath

stunner in which more than one animal is stunned must be such that a current is obtained sufficient for stunning each individual animal. Furthermore, shackles are wetted to reduce electrical resistance between shackle and legs (Uijttenboogaart, 1999).

Controlled-Atmosphere Stunners The controlled-atmosphere method can be used in one of two ways: with crated birds, or with the birds unloaded and belt-conveyed through a gas cabinet. The first is more humane because the birds are taken directly from the transport vehicles in their crates or modules, which are inserted into a chamber where controlled-atmosphere killing occurs. Either a single gas or a biphasic combination of two gas mixtures can be used. In the two-stage system, the bird is introduced into an anesthetic atmosphere with a relatively low carbon dioxide content and a high oxygen content. In the second stage, the gas levels are switched to high carbon dioxide and low oxygen atmosphere. This system comprises two separate chambers through which crates are moved. The birds remain in the first chamber for approximately 75 s, which is defined as the first phase of exposure; the second phase lasts from 75 to 185 s (Abeyesinghe et al., 2007). The gas mixture must be controlled and monitored continuously (Figure 3). The atmosphere within the first chamber must be humidified to 60 to 80 $\pm$ 10% relative humidity, and windows must be fitted to the side of the chambers to allow the process to be observed.

Killers

Birds are killed manually (using knives) or by a mechanical rotary knife that cuts the jugular and carotid arteries at the neck. In the case of kosher and halal slaughter, only manual cutting of blood vessels is permitted. The automatic killing machines are designed for high efficiency and to avoid human manipulation. After the birds have been stunned, their heads are guided to a circular cutter by a bar directly in line with the overhead conveyor. In this process, the blood vessel in

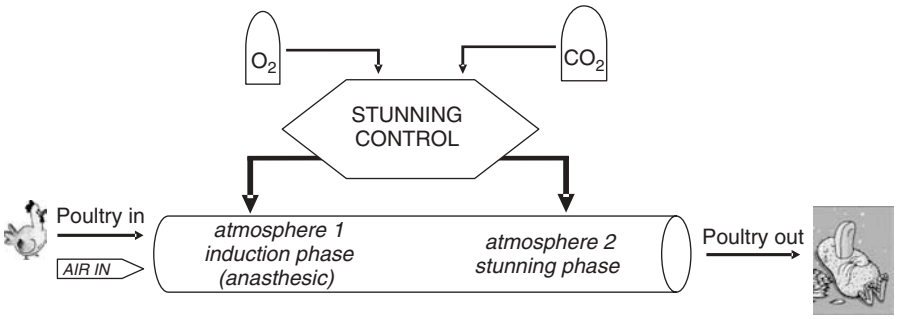

FIGURE 3 Controlled-atmosphere stunner. (Published with permission of Stork PMT BV in Boxmeer, The Netherlands, copyright © Stork PMT BV, 2008. All rights reserved. Any reproduction is prohibited.)

a bird's neck is opened without damaging the windpipe or gullet. The accuracy of the automatic killer is of most importance. Should the artery be cut inaccurately, the meat will take on a reddish hue. If damage is sustained by the windpipe or the gullet, the operating efficiency of the head puller and autocropping machine will be diminished. Kill line speeds are dictated by the number and speed of the evisceration lines. In the United States, each kill line typically supplies carcasses for two evisceration lines. Depending on the inspection system used, evisceration line speeds are limited to 70 or 91 birds per minute for the streamlined inspection system (SIS) and new enhanced line speeds (NELSs), respectively. A U.S. plant with four NELS evisceration lines will typically operate two kill lines, each at 180 birds per minute, which is in contrast to EU plants, in which each evisceration line is served by a separate kill line, usually operating at 100 to 140 birds per minute. The kill line speeds are important in terms of dwell time in the stunner (i.e., length of the stunner cabinet) as well as the efficiency of kill and bleeding operations (Bilgili, 1999).

In the United States, the blood vessels within the neck of the bird (both carotid arteries and jugular veins) are severed, usually by a deep ventral cut within 8 to 12 s of stunning. This methodology is accomplished by automatic neck cutters and by backup personnel (Heath et al., 1994). The ensuing rapid drainage of blood causes anoxia and often prevents birds from regaining consciousness during the subsequent 80 to 90 s bleed time. In the EU the neck cut is performed dorsolaterally or on one side only. Because the rate of blood loss is slower, the bleed times are usually extended to 120 to 180 s (Bilgili, 1999).

Scalders

Tank Scalders These are used for scalding by water immersion, the most commonly used systems in poultry-slaughtering plants. Scalding tanks or containers should be resistant to corrosion. The temperature of the scald water is maintained at approximately 60°C with a volume of 2.5 L per bird, depending on the scalding system selected. Air or steam can be used to agitate the water, which contributes to maintaining a constant temperature and guarantees optimal plucking results. The rate of flow of water into these tanks involves the continuous replacement of water to protect against a buildup of contamination, and where practicable the water should flow in the direction opposite to the direction of the line, so that the scalded poultry are pulled out on from the side of the tank where the hot water enters. Tanks should be emptied at regular intervals during the working day. Conventional scalders consist of a single tank which can be operated in one- or two-pass mode. To reduce water contamination, some innovations have been made in the scald process, such as including multiple-tank scalders (Cason et al., 1999) (Figures 4 and 5). In a commercial establishment, Veerkamp and Heemskerk (1992) observed reduced numbers of Enterobacteriaceae in the water of the last tank of a three-tank, two-pass counterflow scalder compared with numbers in a single-tank scalder previously operating at the same processing plant.

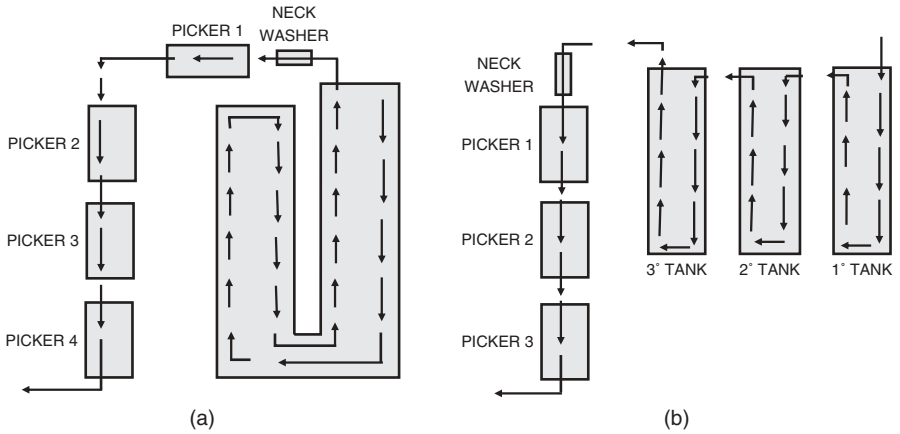

FIGURE 4 (a) Two-pass, single-tank scalder; (b) two-pass, three-tank counterflow scalder. (Published with permission of Stork PMT BV in Boxmeer, The Netherlands, copyright © Stork PMT BV, 2008. All rights reserved. Any reproduction is prohibited.)

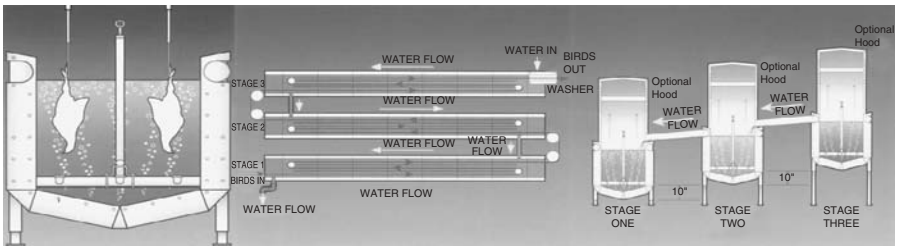

FIGURE 5 Scalding tank, water flow, and a three-stage scalding procedure. (Published with permission of Stork PMT BV in Boxmeer, The Netherlands, copyright © Stork PMT BV, 2008. All rights reserved. Any reproduction is prohibited.)

Spray Scalders These scalders are used to reduce problems related to water contamination. In this system the birds are sprayed with clean hot water, which avoids contamination, but a large amount of water is required. Because of this and high nergy costs, the system has little practical application.

Defeathering or Plucking Machines

Dry-Plucking Machines The suction developed at the plucking head draws the feathers into a set of rotating plates, where they are gripped and pulled from the body. They are then channeled through a suction unit and into a collection sack to await disposal. The grip on the feathers can be adjusted to obtain optimum plucking times for various species of bird. The finish of the plucked bird compares with that obtained by wet plucking. No special skill is required.

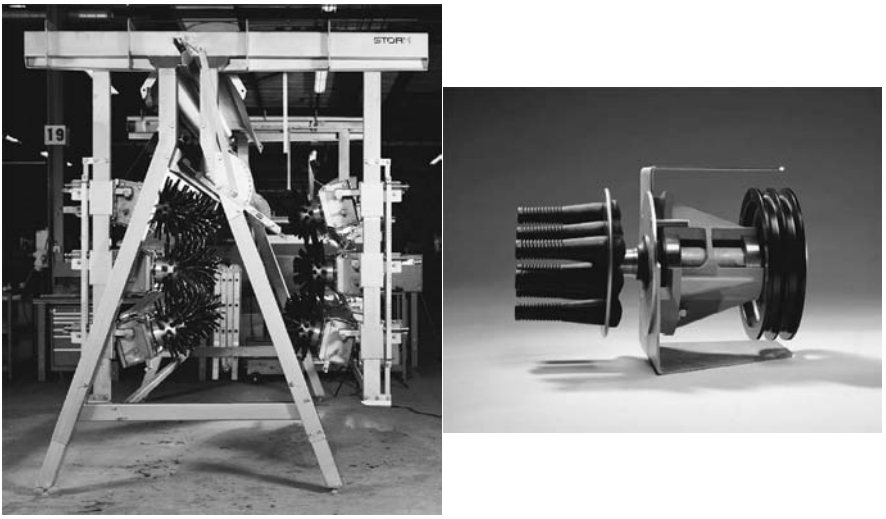

FIGURE 6 Defeathering machine, equipped with rotatable disks with rubber fingers. (Published with permission of Stork PMT BV in Boxmeer, The Netherlands, copyright © Stork PMT BV, 2008. All rights reserved. Any reproduction is prohibited.)

Wet-Plucking Machines Birds are defeathered mechanically using plucking machines in a wet procedure. For complete defeathering, two plucking machines in series are used. The first plucking machine is an automatic online rubber-fingered feather picker. The long fingers are located in rotatable plucking disks (Figure 6). At the top of the plucking machine, water sprayers help eliminate the shed feathers and skin. This first machine releases more than 70% of the feathers. The second plucking machine removes the remaining feathers located in different areas (Barbut, 2004; López and Casp, 2004). Plucking machines are designed to control the scatter of feathers as much as possible. Feathers should be stored in suitable clean containers, which must be removed at least once daily. Feathers conveyed by continuous running water should be removed from the water and the water preferably run to waste.

Head and Trachea Puller

This machine removes the head, trachea, and esophagus of a bird automatically. After proper positioning, the head and trachea puller breaks the spine at its weakest point, after which head, trachea, and esophagus are stretched out gradually and severed from the product. Their use represents an improvement in the efficiency of an eviscerator.

Evisceration Equipment

Evisceration can be done manually using a knife and a pair of scissors, semiautomatically, or fully automatically using a circular cutting blade and a scooplike

arm to withdraw the viscera. In a conventional manual operation, the abdominal skin is cut open along the midline (posterior part of the breast bone toward the cloaca), while the skin around the cloaca is usually cut in a circular pattern to minimize gut content spillage. In semiautomated or fully automated evisceration processes, the first step is to cut around the cloaca using a circular rotating blade. Thus, poultry evisceration equipment should be designed and adjusted to eliminate intestinal tearing during evisceration. Some of the newer devices are equipped with a vacuum device to reduce potential fecal contamination, and the cutting device is usually rinsed after each insertion. The viscera are then scooped out from the body cavity and remain attached to the body for inspection purposes (Barbut, 2004). Some of the new automated equipment allows total viscera separation immediately after withdrawal and placement on a parallel line. This can further improve the hygiene of eviscerated carcasses (Russell and Walker, 1997). Nu-Tech Nuova is a machine implemented by the Stork Food Company under this principle. This machine is suitable for use with almost all standard types of viscera shackles and their various ways of suspending a bird. The heart and lungs are positioned on top of the clamp of the viscera pack shackle and the liver and the rest of the viscera pack below it. If evisceration machinery is not designed or adjusted properly, the digestive tract of the bird may be torn during evisceration and its contents, or bile, may leak onto the inside cavity or outside the carcass.

Carcass Washer

Inside/outside carcass washers are traditionally used after evisceration machines. These washers consist of a stainless-steel cabinet equipped with various spray nozzles sited in different areas to provide strong water streams. The washing effect of water is improved by using brushes and rubber fingers. A pressure pump and a pressure regulator are provided with the cabinet to control the process (Northcutt et al., 2005).

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7

POULTRY CARCASS EVALUATION AND CUTTING

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INTRODUCTION

Poultry meat has been an important source of protein for human beings from ancient times. Today it is one of the most important foods in many cultures around the world, due to its nutritional characteristics. Poultry meat demands are increasing in relation to demographic growth. Apart from the quantities of meat that must be produced, the quality of the product must be observed to satisfy the demand under quality and health conditions (Uijttenboogaart, 1999). Carcass evaluation should be considered an important part of poultry-processing activities because it involves observation of standards of quality for the birds according to grading and expected yield. However, carcass composition can change under

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certain circumstances, such as stress, diet, preslaughter handling, the slaughtering process, genetic factors, and more. Genetics has been a major contributor to carcass yield increase, following advances in poultry nutritional knowledge (Bilgili, 1999; Thaler, 1999; Tankson et al., 2001; Havenstein et al., 2003; Gregory, 2005).

CHARACTERISTICS OF A POULTRY CARCASS

A poultry carcass is usually described as the dead body of a bird that has been slaughtered for meat purposes. A carcass includes muscles and other tissues, such as skin and fat. It is important to clarify that the word *muscle* is not, in fact, an exact synonym of *meat* because muscles must undergo a biochemical transformational process before being converted to meat. So this process is activated and carried out after slaughter and involves the presence of rigor mortis and pH changes in the carcass. These factors mainly determine the quality of meat (Sams, 1999). Conversely, it has been demonstrated that most poultry fat content is located in the skin (ca. 8 to 20% of the carcass weight) and abdominal region (Du and Ahn, 2002; Toledo et al., 2004; Fereidoun et al., 2007). Considering these characteristics but including marbling, poultry is recognized as a good source of lean meat if the skin is removed (Hennessy, 2005). As Bihan-Duval et al. (1999) have stated, the success of the poultry industry depends primarily on the possibility of increasing the most relevant parts of the carcass (e.g., the breast meat) and by reducing fat.

FACTORS AFFECTING POULTRY CARCASS QUALITY

Several conditions affect poultry carcasses, including diet, placement density, environmental conditions, preslaughter management, and genetics (Bilgili and Hess, 1995; Dransfield and Sosnicki, 1999; Fletcher, 1999; Havenstein et al., 2003; McNeal et al., 2003; Yamazaki et al., 2006; Murawska and Bochno, 2007). However, processing can be a major source of conditions that probably affect poultry carcass quality, as it is the characteristics of a carcass or its parts that determine its value on the basis of expected properties (USDA, 1998): color and appearance, flavor, tenderness, and yield. In this sense, stressor conditions such as poor handling and processing can result in PSE (pale, soft, and exudative) meat and consequently, affect quality (Tankson et al., 2001; Woelfel et al., 2002). So to understand how a carcass is affected, processing should be considered (Jones and Grey, 1989). Processing of birds includes receiving and weighing, stunning, bleeding, scalding, feather removal, evisceration, inspection, packing, chilling, washing, grading, cutting, and packaging (Buhr et al., 1997; Raj, 1998; Kang and Sams, 1999; Northcutt, 1997; Webster and Fletcher, 2001; Barbut, 2002; Zuidhof et al., 2004).

TABLE 1 Multiple Regression Equations for Estimation of Carcass and Breast Weights and Yields in Broiler Chicken Determined by Ultrasonic Measurements

Equation	r^2	S_y
Breast weight (g) $= 0.164X_1 + 0.386X_2 - 69.66$	0.9244**	17.31
Carcass weight (g) $= 0.543X_1 + 2.503X_2 - 11.88$	0.987**	26.38
Breast yield (%) $= 0.007X_1 + 0.024X_2 - 11.87$	0.520**	1.65
Carcass yield (g) $= 0.009609X_1 + 0.2X_2 - 70.1$	0.650**	1.80

Source: Silva et al. (2006).
** $p < 0.001$.

CUTTING AND YIELD OF POULTRY CARCASSES

Carcass yield represents the amount of the total bird, after processing and expressed as a percentage, that can be used for commercial purposes (Pollock, 1997). Its calculation is based on the proportion between an animal's live weight and its carcass weight; that is, yield expresses the percentage of edible products of a live bird. According to Muriel et al. (1997), one factor that affects carcass yield is sex. Males show higher yields than do females but also usually have higher levels of fat and differ in the yield of carcass parts. Other factors are associated with environmental conditions, breeds, and genetics, which cause modifications in fat-deposition patterns (Musa et al., 2006). In this sense, and considering the factors mentioned previously, it has been established that carcass yield is about 64 to 70% of a broiler, depending on its weight, and can change according to such factors as sex, age, and handling. Nevertheless, it has been observed that yield has improved over time and probably will continue to do so.

As carcass yield is such an important factor in the poultry industry from an economic point of view, many efforts have been made to predict it. Various methods of carcass yield prediction have been developed, including ultrasonic measurements and genetic parameters (Zerehdaran et al., 2004; Zuidhof, 2005). In fact, Silva et al. (2006) developed some equations for predicting carcass and breast yield of broilers (Table 1).

According to the U.S. Department of Agriculture (USDA, 1998), standards of quality demand a uniformity of parts and cuts in order to grade poultry. Cuts are sometimes made following joints or evident portions of a bird's body, such as wings or drumsticks, but portions may also be boneless. Independent of these considerations, any carcass cut is subject to inspection and grading according to quality.

POULTRY CARCASS GRADING

Grading involves the classification of a poultry carcass and its parts in groups according to different levels of quality as established by official standards and

grades. These levels are called A, B, or C by the USDA, depending on the quality as characteristics of the carcass or part evaluated, grade A being the highest-quality grade. The USDA calls for the following factors to be observed in grading a poultry carcass and its parts (USDA, 1998):

- *Conformation:* Meat distribution and amount, which determines the appearance of the carcass.
- *Fleshing:* Correlation between the covering and the amount of flesh on the carcass.
- *Fat covering:* The distribution of fat, especially under the skin.
- *Feathers:* Must not appear on the carcass.
- *Exposed flesh, cuts, tears, and broken bones:* Characteristics that result from bad premortem or processing handling and affect both the appearance of the carcass or its parts and grading. Location is relevant; for example, if the flaws occur in breast or legs, grading may be lower.
- *Skin discolorations, flesh blemishes, and bruises:* When pronounced, lead to lower grading. Discoloration occurs when a carcass is exposed to air and its surface dries. Discolorations are classified as slight (pinkish), lightly shaded (reddish), and moderate (dark red or bluish). The intensity of yellow color in chicken skin is not a quality grade.
- *Freezing defects:* Discoloration and dehydration of the skin during storage, called *freezer burn*. Affects the appearance of the product.

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8

OFFICIAL CONTROL OF SLAUGHTERHOUSES AND PROCESSING PLANTS

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Handbook of Poultry Science and Technology, *Volume 1: Primary Processing*, Edited by Isabel Guerrero-Legarreta and Y.H. Hui

INTRODUCTION

Slaughterhouses and processing plants are controlled so as to assure a high level of food safety in food production (EC, 2002, 2004b). In this chapter we describe the principles of official food control in such plants. Food legislation lays down challenges for official food control procedures such as assuring food safety in the entire food production chain and having methodical, high-quality, well-documented control procedures. At the same time, official control has to be impartial and equal (Pitkänen, 2006).

The first step for a food business operator in producing safe food is to adopt good manufacturing and hygiene practices. The next step is to draw up a functional in-house control system and implement it in practice. An important part of an in-house control system is the analysis and control of possible health hazards that are associated with production using the HACCP (hazard analysis and critical control points) principles. Official control has to verify that a food business operator's in-house control system covers all sectors of the business's activities and is able to observe deviations and anticipate possible health risks. Furthermore, since the requirements of food legislation are often associated with economical investments (EC, 2004b; Kaario et al., 2007a), one purpose of official control is to ensure that requirements laid down for food businesses are the same for the same size and type of business.

RESPONSIBILITIES OF OFFICIAL CONTROL AND FOOD BUSINESS OPERATOR

Various authorized agencies (authorities) are responsible for performing official control activities according to documented procedures (EC, 2004b; Pitkänen, 2006). For this purpose, the competent authority has to draw up and carry out a quality control system (Pitkänen, 2006). The food business operator is responsible for ensuring that the food produced is safe for consumers and does not have harmful effects on human health (EC, 2002). The business operator must address the person who is responsible for the in-house control system and has the competence and authority within the business to negotiate with the official authorities (Mäki-Petäys and Kaario, 2007). The responsibilities of the business operator and the authority are presented in Table 1.

CONTROL AUTHORITIES

Authorities act on different levels in different countries and have different tasks and powers. Although the system may vary from country to country, local authorities usually perform official control at a practical level and are responsible for the conformity of official control locally. Regional and central authorities carry out official control and audits at the regional and national levels. Regional authorities

TABLE 1 Responsibilities of Food Business Operator and Control Authorities

Business Operator	Authority
Constructing a food establishment that fulfills the requirements of food legislation	Approving the establishment
Drawing up an in-house control plan that fulfills the requirements of food legislation	Approving the in-house control plan
Observing and implementing changes in legislation into the in-house control plan	Verifying that the in-house control plan is in compliance with the legislation
Describing the activities of the business and in-house control in the in-house control plan	Verifying that the description is truthful
Following the in-house control plan in practice	Verifying that the business operator's practical procedures are in line with the in-house control plan
Documenting the in-house control procedures	Verifying that documentation is done
Taking corrective action when necessary and documenting it	Verifying that corrective action has been taken and documented when necessary
Focusing the in-house control system on relevant risks and targets	Evaluating if the in-house control plan is focused on the relevant risks and targets
Choosing in-house control methods that will enable the business to fulfill the requirements of the legislation	Evaluating if the methods are accurate and valid and are sufficient to identify noncompliances
Updating and validating the in-house control system	Approving the updates
Sampling to verify the food processes and to validate the in-house control system	Sampling to verify the food processes and audit the in-house control system
	Giving guidance and advice to business operators when necessary

guide and supervise the local official control in their region and are responsible for conformity in official control in all the establishments located in the region. The regional authority also performs audits of local authorities' offices to ensure the quality and equality of official control at the local level. The role of the central authority is to ensure uniform requirements and conformity of official control in different parts of the country.

Authorities performing official controls must ensure their impartiality and effectiveness (EC, 2004b). They should also have a sufficient number of suitably qualified and experienced staff and possess adequate facilities and equipment to carry out their duties properly (EC, 2004b). The authorities should ensure that they carry out their activities with a high level of transparency and make relevant information available to the public as soon as possible (EC, 2004b).

OBJECTIVES OF OFFICIAL CONTROL PROCESSES

Approval One of the objectives of official control is to verify that a food business fulfills the requirements of the food laws and that the business has a functioning in-house control system. For this purpose, the establishment and the in-house control system have to be approved by the appropriate authority, which must carry out an on-site inspection in the establishment to verify that it fulfills the requirements of legislation.

Regular On-Site Control Regular on-site control visits are carried out to ensure that the food establishment and the in-house control system are continuously in compliance with legislation and that the system is accurate and is operating properly. The frequency of regular official control should be planned on a risk basis (EC, 2004b). The frequency can vary from daily control at large slaughterhouses to less frequent on-site control visits to subsequent processing plants.

Import and Export Import and export of food products are significant functions of food businesses. Official control of imports and exports is essential in maintaining trust in food safety and reliability between trading partners. Official control of imports and exports includes, for example, identity checks, documentary checks, physical checks, sampling for analysis, and official certification. Information available to import control officers regarding business operators' food safety management systems is often limited. Documentary checks to verify approvals and sampling of individual batches are the main control tools for import control (EC, 2006b). In such cases the authority can establish its own sampling plans based on the risks associated with particular products, establishments, and countries of origin (EC, 2006b).

OFFICIAL CONTROL PLAN

Official control must be carried out regularly to observe noncompliances and deviations in time (EC, 2004b). The frequency of official control activities should be proportional to the risks (EC, 2004b; NFA, 2003, 2005). In large poultry slaughterhouses, for example, the controlling authority is present at all times during slaughtering (Anon., 2004a). In other processing plants, the authority makes on-site inspections according to a risk-based control plan (EC, 2004a, 2006a; NFA, 2003, 2005). Official controls should take place on the basis of documented procedures, to ensure that the controls are carried out uniformly and are consistently high in quality (EC, 2004b). This means that the risks of a certain establishment and its production processes are evaluated together with the food business's in-house control system. Official control procedures are then planned and targeted according to the results of the risk evaluation.

Risk factors that influence the control procedures are, for example, microbiological, chemical, and physical risks. These risks can be divided into more specific

categories, depending on production type, distribution area of the products, and product end use. When evaluating risks associated with poultry slaughtering and processing, a general risk factor is the nature of the automated industrial meat processes, where a certain level of cross-contamination is inevitable. The official control plan should be tailored separately for each branch and each establishment (Finlex, 2006; NFA, 2003, 2005). Official control has economic implications (EC, 2004b, 2006a; Kaario et al., 2007b), so it is necessary to be able to argue why some establishments must be visited more often than others.

When assessing a food business operator's in-house control system, an authority may find it necessary to take additional samples for official control, especially if it has concerns about the safety management systems. The extent of such official sampling depends on the business operator's analysis results and the authority's assessment of the operator's in-house control system. The in-house control system of a food business must be evaluated regularly by the relevant authority. In large establishments the evaluation should be carried out at least once a year (NFA, 2003, 2005). For convenience, the evaluation may be divided into sectors.

OFFICIAL CONTROL METHODS

The European Union's (EU's) goal for control methods is defined in EU legislation (EC, 2004b). Concepts regarding compliance may vary, but the principles are basically the same around the world, independent of the legislation or culture. The concept of appropriate control methods and techniques may include, for example, monitoring, surveillance, verification, audit, inspection, and sampling for analysis. Correct implementation of these techniques requires appropriate training of staff. The official control definitions according to EU legislation (EC, 2004b, 2006a) are as follows:

- *Audit:* a systematic and independent examination to determine whether activities and related results comply with planned arrangements, and whether these arrangements are implemented effectively and are capable of achieving objectives.
- *Inspection:* examination of any aspect of food to verify that it complies with the legal requirements of food law.
- *Monitoring:* conducting a planned sequence of observations or measurements with a view to obtaining an overview of the state of compliance with food law.
- *Sampling for analysis:* taking food or any other substance (including from the environment) relevant to the production, processing, and distribution of food, to verify, through analysis, compliance with food law.
- *Surveillance:* careful observation of one or more food businesses, business operators, or their activities.
- *Verification:* checking, by examination and through the consideration of objective evidence, whether specified requirements have been fulfilled.

OFFICIAL SAMPLING

Official laboratories in the field of food microbiology, together with relevant authorities, form an important structure in ensuring the safety of foods. The majority of sampling and testing to demonstrate compliance with the legislation is carried out by food business operators within their safety management systems. Official sampling can be carried out for a range of reasons (e.g., monitoring, surveying, and checking compliance with legislation). To benefit from sampling and testing of foodstuffs, the sampling must be well planned, also taking into account the intended purpose of the sampling.

The relevant authority should inspect and assess all the systems in place, including the sampling regime and any testing results, and may then carry out its own testing if it has concerns about the food business operator's approach. In many cases, where inspection and assessment are satisfactory, there will generally be no need for the authority to carry out additional testing (EC, 2006b).

Failure to meet microbiological criteria as set out in legislation could result in a number of responses by the food business operator, including withdrawal or recall of the product (EC, 2006b). It should always lead to an investigation of the process and procedures by the business operator to identify the reason for failure and corrective action to ensure compliance in the future.

TRANSPARENCY AND INDEPENDENCE

Authorities should adopt the appropriate measures to ensure that their control systems are transparent, taking any legal and other requirements into account. To demonstrate that official control is transparent, documented procedures should include clearly defined official control processes, official control criteria, and reporting procedures. To that end, authorities should adopt practices that improve the transparency of the process, such as balanced reporting, which means a proper mixture of verified compliance (positive findings) and areas for improvement (negative findings) (EC, 2006a). Official control must be free of commercial, financial, hierarchical, political, or other pressures that might affect the judgment or outcome of the control procedures. The control system and control personnel should be independent of the activity being controlled and free of bias and conflicts of interest (EC, 2006a).

CONTROL TARGETS IN POULTRY SLAUGHTER AND SUBSEQUENT PROCESSING

The nature of poultry slaughter and later processing is different from that of the red meat industry. Therefore, when discussing official control procedures, regard should be paid to the character of the poultry industry. Poultry processing in larger establishments is entirely automated, and carcasses travel on processing-line shackles at a speed of over 100 birds per minute and several thousands of birds per hour. The processing type and speed set challenges for the processing

facilities, equipment, and in-house control procedures as well as for official control. Despite the characteristics of the poultry industry with mass production and automated processes, the safety and hygiene of poultry carcasses cannot be compromised. Furthermore, the economic value of a single carcass is low, especially compared to the cost of the labor needed in ensuring the safety of the meat. Therefore, in the poultry industry, the area where food hygiene and safety and the production economy meet is especially challenging for official controllers.

Official controls on slaughtering and further processing include the following activities: examination of control systems of the business operator and the results obtained; inspections of surroundings, premises, offices, equipment, and machinery; raw materials, ingredients, processing aids, and other products used for the preparation of food; and transport (EC, 2004b). Official control must also cover the products, materials, and articles intended to come into contact with food, cleaning, and maintenance products, processes, pesticides, labeling, presentation and advertising, checks on the hygienic conditions, good manufacturing practices, good hygienic practices, and an HACCP program, as well as interviews of the food business operator and the staff. Authority personnel should not only read the measuring values recorded by the food business operator but also carry out controls with their own instruments to verify measurements taken by the business operator's equipment.

When carrying out on-site controls and observing possible noncompliances, official controllers should verify them by inspection and other control methods and techniques, and compare the results with the in-house control plan. When comparing the results, special attention should be given to the following: Does the business have procedures in place when deviations and noncompliances arise? Are the procedures documented in the in-house control plan? Is the in-house control plan specific enough? Are the corrective actions documented? Who is responsible for the corrective actions?

Control targets can be divided into general control targets that are common to all types of food-producing businesses, and specific control targets that are related to a certain type of food production and related activities. Examples of special control targets related to poultry slaughtering and subsequent processing are listed in Table 2.

ON-SITE CONTROL

On-site control visits are usually carried out when an establishment is in operation (Mäki-Petäys and Kaario, 2007). Staff members performing official control should be prepared for a visit by getting acquainted with the documents concerning the establishment. The food business representative should be present during the control visit so that the findings can be discussed jointly. This ensures that the representative is also able to give his or her view on-site. To avoid misunderstandings and situations developing to the point where enforcement measures are needed, both the authority staff and the business representative should document the findings and discussions (Mäki-Petäys and Kaario, 2007).

TABLE 2 Examples of Targets of Official Control in the Poultry-Slaughtering Process

Part of the Process	Typical Features	Official Control Targets
Animal reception and unloading	Birds in cages Cages piled Cages emptied and washed	In-house control system of animal welfare In-house control system of animal diseases Sanitation procedures of the cages Sanitation verification procedures Pest control procedures
Shackling or conveyor	Animal welfare Hygiene	In-house control system of animal welfare Sanitation procedures
Stunning	Electrical stunning and water basin or gas stunning	In-house control system of animal welfare Hygiene control procedures
Bleeding	Automated venesection	Venesection securing procedures
Scalding	Water basin Water temperature	In-house control system of water hygiene, water temperature, and water turnover
Plucking	Plucking machine	In-house control system of maintenance and repair of equipment
Feet cutting	Automated procedure	In-house control system for preventing carcass contamination
Evisceration; head and neck removal	Automated procedure Use of water	In-house control system for • Contamination prevention • Condensation water/ventilation • Maintenance and repair of equipment
Washing	Use of water	In-house control system for reducing cross-contamination risk In-house control procedures for water hygiene
Chilling	Air Water Convection	In-house control system for sufficient cooling capacity In-house control system for water hygiene
Storage	Racks Basins	In-house control system for sufficient and hygienic storage space, temperature

The approval documents and in-house control system of the establishment must be inspected during the control visit. When entering the production premises, the authority should verify that the activities and the premises correspond to officially approved activities. To avoid cross-contamination, the inspection round should be started in the area of greatest hygienic control and advance to areas of less control. In each room, an overview of the premises is made and the general hygiene and

condition of the production room are evaluated (Mäki-Petäys and Kaario, 2007). The structures, machinery, and equipment are evaluated as well as ventilation and illumination. Special attention should be paid to the surface material of walls, ceiling, floor, and doors. Attention should be given to routes used to transport raw material and end products, as well as to routes traversed by employees.

Official control should be able to evaluate if the in-house control system is directed to relevant targets. When inspecting the system, attention should be given to the control programs in place: Are they up to date, and do they match the actual activities? Furthermore, is the business operator executing the in-house control system efficiently, are the procedures followed in practice, and is documentation being carried out? The authority must verify the documentation and that the in-house control system is being followed. In addition to visual checks and control of documents, verification can also be by official sampling and analyses. To rely only on oral information from the business operator cannot be considered sufficient (Mäki-Petäys and Kaario, 2007).

At the end of the on-site control visit, a final meeting is held at which the findings and possible noncompliances are discussed together with the business representatives. During the meeting the necessary corrective action should be discussed and documented.

REPORT AND DOCUMENTATION

The authority must draw up a report of the official controls that it has carried out. The report should include a description of the purpose of the official controls, the control methods used, the results of the official controls, and if necessary, the corrective action that the business operator should take. The operator should be given a copy of the report, especially if noncompliances are found. The control targets should be documented even if no noncompliances were found.

The report should contain clear conclusions stemming from the findings of the control visit and, where appropriate, recommendations. Conclusions should address compliance with the planned arrangements, such as the in-house control plan, the effectiveness of the implementation, and the suitability of the planned arrangements to achieve the stated objectives. The conclusions should also be based on objective evidence (EC, 2006a). In particular, where conclusions are drawn as to the in-house control plan's suitability to achieve the stated objectives, evidence may be obtained from the results of several control visits. Recommendations should be based on sound conclusions and address the end result that should be delivered rather than the means of correcting noncompliance (EC, 2006a). If considered necessary, the business operator is asked to make a proposal as to the proper corrective actions, including a deadline for their completion.

Official control documentation includes instructions and guidelines, plans, inspection reports, and sampling results. Documentation can be in written or electronic form. In some cases, photographs can be added to the report, but a photograph alone is not sufficient for documentation (Mäki-Petäys and Kaario, 2007). Documentation helps toward recall of what has been discussed and agreed

or disagreed with the business operator. Also, it is easier to proceed with enforcement measures, if necessary, when the results of the negotiations have been documented.

FOLLOW-UP OF OFFICIAL CONTROL OUTCOME

Where appropriate, an action plan should be drawn up and delivered by the business operator. It should propose time-based corrective and preventive action to address any weaknesses identified by the controlling authority. The authority should assess the suitability of the plan. An action plan enables the authority to assess whether the corrective and preventive actions proposed are sufficient to correct the weaknesses identified.

Action plan should include risk-based prioritization and time frames for completion of corrective and preventive action. A wide range of action plans can be considered satisfactory; it is up to the authority to choose from the various options available. Corrective and preventive action should not be confined to addressing specific technical requirements, but should, instead, include systemwide measures, such as communication, cooperation, coordination, reviewing, and streamlining of control processes. An analysis of the cause any noncompliance should be conducted by the business operator to determine the most appropriate corrective and preventive action (EC, 2006a). Any differences of opinion between the business operator and the authority should be resolved. Mechanisms should be established to ensure that action plans are appropriate and that corrective and preventive actions are completed effectively and in a timely manner. Procedures for verifying the close-out of the action plan should be agreed to between the business operator and the authority (EC, 2006a).

ENFORCEMENT MEASURES

Enforcement measures are sometimes needed. When the authority identifies noncompliances, it has to take action to ensure that the business operator will remedy the situation. Carefully followed documentation procedures during routine controls are helpful when it becomes necessary to proceed with enforcement measures. Prior to enforcement, it is preferable to negotiate with the business operator (Mäki-Petäys and Kaario, 2007). When deciding whether to take enforcing action and which action to take, the authority should take account of the nature of the noncompliance and the operator's past record with regard to noncompliance (EC, 2004b).

EFFECTIVENESS OF OFFICIAL FOOD CONTROL

Official food control effectiveness entails fulfillment of legislative requirements and removal of noncompliances as a result of food control actions. Large quantities resources are spent in enforcement of regulations in the various steps of

the food chain, including slaughterhouses and processing plants, with the goal of improving and ensuring food safety. Although food control and the enforcement are cornerstones of food safety, there is only limited data on the effectiveness and congruence of official food control in slaughterhouses and processing plants.

Control of slaughterhouses is performed in principle when slaughter is under way (EC, 2004a), thus slaughterhouses are controlled more frequently than other food establishments. Nevertheless, it is difficult to find any scientific research describing the effects of official food control in slaughterhouses. The effectiveness of national control systems in enforcing food safety legislation in slaughterhouses and other food establishments is regularly audited by the competent authorities. The audit of food control systems brings audit-valuable information regarding the food control system, but in addition to audits, a scientific approach is needed. New information on the quality of the official food control and the effectiveness of control methods at the grassroots level is needed especially. It should be possible to demonstrate the effectiveness or ineffectiveness of official food control. However, measuring the effectiveness of such control is complicated, so reliable and easy-to-use indicators are sought. Quantitative indicators such as number of inspections performed or number of noncompliances are valuable as background information, but usually describe poorly the effect of inspections and official food control.

The effects of official food control are versatile, and indicators describing the effectiveness of official food control should therefore be innovative. According to the results of a research questionnaire issued in Finland in 2006, small and medium-sized food businesses especially considered official food control, notably on-site inspections, to be useful and to have improved safety management in food businesses (Jokela and Lundén, 2007a). Such effects of official food control are difficult to measure but are probably very important for food safety.

Food business operators often rely on the information provided by official control. Small and medium-sized food businesses especially consider food regulations difficult to understand and require information from local food control personnel concerning requirements (Kaario et al., 2007b). Such information is provided during on-site inspections. Improvement in in-house control systems have also been observed following recurrent inspections (Jokela and Lundén, 2007b). In the light of these results, on-site inspections appear to have a very important role in the implementation of regulations and food safety.

The frequency of on-site inspections varies between types of establishments. The amount and quality of the information and advice provided by food controllers may differ, due to differences in inspection frequency. Because control authorities are frequently present in slaughterhouses, slaughterhouse personnel have ready access to advice from authorities. Frequent control also enables rapid reaction to noncompliances in slaughterhouses, and the fact that these authorities are highly competent (EC, 2004a; Lundén et al., 2007) influences the quality of the control and possible also its effectiveness.

Possible outsourcing of particular official food control tasks (EC, 2004b) could also influence the effectiveness of food control. Outsourcing would create an

additional level of actors and an additional level of control tasks for controllers. Meat inspection is an example of an area where pressure exists toward outsourcing. Possible changes in management and food control methods should be subjected to research focused on the effects on food safety and economic effects due to organizational changes. The resourcing of official food control has been observed to have implication on food safety (Tähkäpää et al., 2008), and adequate resources should be secured. The motivation and competence of the performing party should be investigated as well as the functioning of further training, because these factors may influence food safety. Possible earlier experiences on alternative systems should be analyzed.

To enable investigating effectiveness and other control issues, the material produced in food control should be made as widely available as possible for research purposes. The amount of material is voluminous, and it should be utilized for the improvement of food control. The quality of food control material that is collected should be assessed by authorities and researchers, and possible new parameters introduced.

CONGRUENCE OF OFFICIAL FOOD CONTROL

By *congruence* we mean that all food business operators should be treated in a similar manner in a similar case. Business operators think that the requirements should be equal for all similar food businesses, but on the other hand, food businesses also think that there should be flexibility in enforcement of the regulations (Kaario et al., 2007b).

Congruent application of food legislation nationally is challenging, and it is even more challenging between countries. International food businesses acting in several countries are prone to comparing the application of legislation between countries, and understandably, they expect that the requirements are similar. However, the performing of official food control and inspections are influenced by many factors (Jones et al., 1994). The food control personnel should have a high degree of competence and be able to interpret the legislation similarly. Detailed legislation may increase congruence but decrease the possibility of flexible application of the legislation. Research results indicate that official food control and requirements may not always be congruent between authorities (Jokela et al., 2006). The reasons leading to incongruence should be investigated, and also whether the incongruence may lead to differences in the level of food safety or distortion of the competitive position.

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9

POULTRY PACKAGING

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INTRODUCTION

Packaging is the first and main form of commercialization for almost any raw or bulk foodstuff moving from production centers to distributors and consumers (Totosaus, 2006). Packaging of fresh poultry contributes to retaining its freshness by controlling microbial or chemical alterations during transport and display during retail sale, in home storage, and during preparation and presentation (Totosaus and Kuri, 2007). Poultry packaging is one of the most widely employed ways to extend shelf life and is normally employed in combination with other technologies (Woods and Church, 1999). Packaging of raw poultry meat limits the use of some processes, such as curing or heat, since changes produced by such treatments

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limit further processing of cured or cooked poultry meat. Modified atmospheres or vacuum packaging are more suitable alternatives (Totosaus, 2006).

There are two important aspects in the selection of packaging: the shape and form of a poultry carcass or cuts, and the material employed in packaging (Hotchkiss, 1994). The oldest method of packaging and distributing fresh poultry meat is via a *wet shipper*, a waxy-coated corrugated box in which whole birds are placed together with ice. A *dry shipper* is similar but without the ice. More recently, whole carcasses have been placed in polymer bags and sealed or clipped. Almost 90% of all chicken parts, including breast, thigh, drum, and wing portions, are packaged directly into consumer portions using highly oxygen permeable polystyrene foam trays with a highly oxygen permeable poly(vinyl chloride) (PVC) or polymer-based stretch-film overlap. Most of the remaining portions of poultry meat are packaged in bulk ice packs at the central processor, but end up in a similar stretch-wrap package at the retail level (Dawson, 2001).

The main concern in the packaging of raw poultry meat is the microbiological quality, as thermal or chemical processing can affect the properties of raw poultry. Preserving good microbiological quality is thus the main target when packaging raw poultry meat.

PACKAGING AND MICROBIOLOGICAL IMPLICATIONS

Raw poultry is highly perishable even when stored under chilled conditions. The growth of psychotropic spoilage bacteria is most often the cause of spoilage (Dawson, 2001). Hygiene and sanitation play a role in any effective disease control program for poultry production and processing premises. A microbiological risk assessment during production processing and treatment of food constitutes an important basis for judgment of the safety of food products. A poultry site must be prepared methodologically for the entry of each new batch (removal birds; litter and manure; vector and rodent control; dry and wet cleaning; disinfection; fumigation), and particular care should be exercised in the performance of sanitary procedures after a disease outbreak (Kašková et al., 2007). Poultry can be packaged whole before slaughtering or can be cut up. Handling operations increase microbiological counts, due to extra handling in the cutting process (Thomas et al., 1984). Cut-up poultry generally spoiled at a faster rate than did whole birds, and odor was more marked from cavities of whole carcasses than from cut-up chicken (Kraft et al., 1982). Besides packaging, alternative treatments to raw poultry can be employed to reduce microbial activity. These treatments can be chemical or physical (Table 1). Packaging materials employed in poultry packaging and other technologies may be reviewed in Totosaus (2006) and Totosaus and Kuri (2007).

CHEMICAL TREATMENTS

Chlorine Immersion in chlorine solutions (20 ppm) could help to enhance the microbiological quality of tray-packed stretch-wrapped packaging. Chlorine

TABLE 1 Chemical and Physical Treatments Employed for Raw Poultry

Treatment	References
Chemical	
Chlorine immersion	Kraft et al. (1982)
Potassium sorbate	Elliot et al. (1985)
Hypochlorous acid	Mokgatla et al. (1998)
Disodium ethylenediamenetetra-acetate and nisine	Cosby et al. (1999)
Trisodium phosphate	Capita et al. (2002)
Acid or alkaline solution	Okolocha and Ellerbroek (2005)
Peracetic acid and quaternary ammonium	Kašková et al. (2007)
Physical	
Vacuum packaging	Arafa and Chen (1975), Kraft et al. (1982), Thomas et al. (1984)
Modified atmosphere packaging	Jiménez et al. (1997), Nam and Ahn (2003a), Balamatsia et al. (2006)
Carbon dioxide	Bailey et al. (1979), Reddy and Kraft (1980), Gray et al. (1984), Thomas et al. (1984), Elliot et al. (1985), Kakouri and Nychas (1994)
Immersion in hot water	Göksoy et al. (2001)
Irradiation	Nam and Ahn (2003b)

decreased the incidence of *Salmonella* and coagulase-positive *Staphylococcus*, in both whole and cut-up poultry (Kraft et al., 1982).

Potassium Sorbate Potassium sorbate has also been employed to enhance the microbiological quality of raw poultry during packaging. However, the effectiveness of potassium sorbate depends on microorganism sensivity to this compound. *Pseudomonas* and lactic acid bacteria are not inhibited by potassium sorbate, creating premature souring of the poultry meat (Elliot et al., 1985).

Hypochlorous Acid Hypochlorous acid is used in poultry slaughter houses to ensure that all the *Salmonella* are eradicated, but since some strains isolated from different stages in a local poultry abattoir grow in the presence of this chemical, effective concentrations must be employed (Mokgatla et al., 1998).

Disodium Ethylenediamenetetraacetate and Nisine A combination of disodium ethylenediamenetetraacetate and nisine and vacuum or modified-atmosphere packaging has the potential to increase significantly the shelf life of raw processed poultry (Cosby et al., 1999).

Trisodium Phosphate Trisodium phosphate can be employed to assess the reduction of microbial populations on poultry: *Salmonella, Escherichia coli,*

Campylobacter, Pseudomonas, total counts, *Listeria, Staphylococcus aureus*, and *Lactobacillus* (Capita et al., 2002).

Acid or Alkaline Solution Dipping treatment with lactic acid (1%), sugars, foodstuff phosphates, ascorbic/isoascorbic acid, and 10% trisodium phosphate can be employed for the decontamination of poultry carcasses, achieving significant reductions of $\log_{10}$ CFU/mL for aerobic plate counts of Enterobacteriaceae, *Pseudomonas*, and *Lactobacillus* (Okolocha and Ellerbroek, 2005).

Peracetic Acid and Quaternary Ammonium Paracetic acid and quaternary ammonium can be employed as disinfecttants in poultry-processing plants, reducing the contamination of poultry carcasses (Kašková et al., 2007).

PHYSICAL TREATMENTS

Vacuum Packaging Vacuum packaging of poultry meat change microflora but will not inhibit bacterial growth, since some strains (*Aerobacter aerogenes, Escherichia coli*, and *Proteus mirabilis*) could survive and grow in vacuum-packaged sterilized poultry meat upon refrigerated storage. Moreover, many species of Enterobacteriaceae are primarily environmental saprophytes and scavengers; some of them are well known as pathogens (Arafa and Chen, 1975). On the other hand, although total bacterial counts were lower in cavities, off-odors were generally stronger and more objectionable from cavities than from the surfaces of chickens (Thomas et al., 1984). Compared with tray-packed stretch-wrapped packaging, whole poultry carcasses decreased bacterial counts, mainly mesophiles and psychotrophs, when vacuum packaging was employed (Kraft et al., 1982; Thomas et al., 1984).

Modified-Atmosphere Packaging Modified-atmosphere packaging (MAP) is a widely employed methodology in raw poultry packaging. Im one study, MAP (30% CO_2/70% N_2 or 70% CO_2/30% N_2) suppressed the growth of *Pseudomonas*, but the growth of Enterobacteriaceae and *Brochotrix thermosphacta* was not inhibited (Jiménez et al., 1997). Formation of biogenic amines are correlated with microbiological and sensory changes in MAP breast chicken meat (Balamatsia et al., 2006). Irradiation helps to control quality changes (color, lipid oxidation, and volatile compounds production) in MAP turkey meat (Nam and Ahn, 2003a).

Carbon Dioxide The inhibitory effect of carbon dioxide on the growth of psychotrophs, including *Pseudomonas*, which is the principal spoilage organism of refrigerated poultry, had also been employed as the basis of a dry packaging method. The gas flush in a bulk pack created a carbon dioxide atmosphere within the pack that successfully inhibited the growth of organisms throughout the package due to the ability of the gas to permeate the entire box (Thomas et al., 1984).

A carbon dioxide back-flushed vacuum pack, considered a dry packaging system, presents certain advantage over a standard iced storage system, a situation particularly important for the poultry processor and retail grocer. Another advantage is the elimination of short-weight problems and the ability to ship in mixed loads of product and meat from warehouse to store (Bailey et al., 1979). Carbon dioxide application could help as well to reduce the coliform counts in stretch-wrapped poultry (Thomas et al., 1984). Nonetheless, the use of carbon monoxide snow during raw poultry storage did not extend the shelf life of poultry samples during later display case storage under aerobic packaging conditions beyond that of control samples, with no evident difference in the incidental of potential pathogens such as salmonellae and coagulase-positive staphylococci (Reddy and Kraft, 1980).

Combining sorbate and carbon dioxide atmospheres has the potential to greatly extend the shelf life of fresh poultry, especially applicable for poultry parts waiting further processing, such as cured products or frankfurters, where the white color of the skin would not be important and sorbate could be used to partially replace nitrite salts. Use of this treatment is suggested as a support system in the refrigerated storage of poultry in case of mishandling, and application to large-volume storage of necks and backs prior to deboning and further processing (Gray et al., 1984; Elliot et al., 1985). Lactic acid bacteria and *B. thermosphacta* were the dominant organisms in samples stored in carbon dioxide/nitrogen; *Pseudomonas* grew only in oxygen–carbon dioxide packaging systems (Kakouri and Nychas, 1994).

Immersion in Hot Water Immersion in hot water is one of many potential methods for reducing levels of pathogenic bacteria on the surface of poultry meat. However, if the meat is to be sold in the raw state, reductions in microbial numbers need to be achieved without changing the appearance of the meat. Changes caused by this heat treatment can be identified visually, with greater changes at higher immersion temperatures and times (e.g., 120 s at 50°C or 1 s at 100°C). No heat treatments below 90°C are capable of reducing contamination with *E. coli* or similar thermotolerant microorganisms on poultry without causing adverse changes in the product (Göksoy et al., 2001).

Irradiation Irradiation is normally employed with another packaging technique. Since irradiation and aerobic packaging promoted lipid oxidation in raw turkey breast and thigh meats, the exposure of double-packaged irradiated turkey meats to aerobic conditions by removing outer vacuum bags a few days before the test was a more effective way to control lipid oxidation–dependent and radiolytic off-odor volatiles. When lipid oxidation and irradiation off-odor should be minimized without additional additives, double packaging is an excellent method to use for turkey meats employing 2.5 kGy (Nam and Ahn, 2003b).

TABLE 2 Main Microorganisms Associated with Raw Poultry Contamination

Microorganism	Contamination Characteristics	References
Listeria monocytogenes	Surface in resin or plastic rather than an uneven surface with organic residues, neutral pH, a low temperature, and high hygrometry	Chasseignaux et al. (2001, 2002), Soultos et al. (2003)
Campylobacter spp.	Cross-contamination of poultry carcasses during defeathering, evisceration, and carcass chillers	Harrison et al. (2001), Keener et al. (2004)
Salmonella spp.	Type serotypes and phage types detected are among those most frequently associated with human diseases	Kraft et al. (1982), Mokgatla et al. (1998), Harrison et al. (2001), Soultos et al. (2003), Capita et al. (2007)
Pseudomonas spp.	Principal spoilage organisms of refrigerated poultry	Thomas et al. (1984)
Brochotrix thermosphacta	Vacuum packs, carbon dioxide, and nitrogen	Kakouri and Nychas (1994)

MAIN PATHOGENS ASSOCIATED WITH RAW POULTRY

Chicken and chicken packaging is a potential vehicle for the introduction of pathogens in retail and domestic kitchens, in particular for the cross-contamination of *Campylobacter, Salmonella*, and *Listeria*. A high proportion of the bacterial flora on fresh chicken is resistant to a variety of antibiotics (Manie et al., 1998). Retail chicken had been considered as a potential source of *Listeria* and *Salmonella* spp. (Soultos et al., 2003). *Campylobacter* and *Salmonella* were isolated from 68% and 29% of retail chicken, respectively (Harrison et al., 2001) (Table 2).

Listeria monocytogenes *Listeria monocytogenes* is transmitted to humans primarily by the foodborne route. This bacterium is often found in the environment of food-processing plants. Work is ongoing to identify factors associated with *L. monocytogenes* contamination on working and nonworking surfaces in poultry-processing plants and to understand its survival in such an environment. Physicochemical risk profiles showed that a surface in resin or plastic, rather than an uneven surface, with organic residues, neutral pH, a low temperature, and high hygrometry was associated with *L. monocytogenes* contamination (Chasseignaux et al., 2002). Some *L. monocytogenes* strains persist for a long period in the plant environment, where different genotypes can be associated with poultry as well as with pork meat (Chasseignaux et al., 2001).

Campylobacter spp Epidemiological data suggest that contaminated products of animal origin, especially poultry, contribute significantly to campylobacteriosis.

Thus, reduction of contamination of raw poultry would have a large impact in reducing the incidence of illness. Contamination occurs both on farms and in poultry-slaughtering plants. Routine procedures on the farm, such as feed withdrawal, poultry handling, and transportation practices, have a documented effect on *Campylobacter* levels at the processing plant. At the plant, defeathering, evisceration, and carcass chillers have been documented to cross-contaminate poultry carcasses. Carcass washings and the application of processing aids have been shown to reduce populations of *Campylobacter* in carcasses by levels between $\log_{10} 5$ CFU/mL and $\log_{10} 8$ CFU/mL of carcass rinse (Keener et al., 2004).

Salmonella *Salmonella*-type serotypes and phage types detected are among those most frequently associated with human diseases. *Salmonella* strains were detected in 17.9% of carcasses collected from slaughterhouses. Isolates belonged to nine different serotypes, with *Salmonella enteriditis* being the most common. Three strains (5%) were resistant to one antibiotic and 40% were multiresistant to more than one antibiotic (Capita et al., 2007).

CONCLUSIONS

Most of the raw poultry processed in slaughterhouses is a main source of meat for further processing (e.g., curing, deboning, emulsified products manufacture) or for retail display (consumer selection). An adequate packaging system as well as good manufacture practices in this first stage of the poultry food chain ensure good microbiological quality and the control of pathogens in cross-contamination.

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10

KOSHER LAWS IN FOOD PROCESSING*

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*This chapter is a revised version of an original article by J. M. Regenstein, M. M. Chaudry, and C. E. Regenstein, 2003. The Kosher and Halal Food Laws, *Comprehensive Reviews in Food Science and Food Safety*, 2(3):111–127, 2003. Courtesy of Wiley–Blackwell (US/UK).

Handbook of Poultry Science and Technology, *Volume 1: Primary Processing*, Edited by Isabel Guerrero-Legarreta and Y.H. Hui

Preliminary note: The information in this chapter is as accurate as possible (as of September 1, 2007). However, the final decision on any application of the material rests with the religious authorities providing supervision. The ruling of the religious authorities may differ from the information presented here.

INTRODUCTION

The objective of this chapter is to describe the kosher laws as they apply in the food industry, with a particular emphasis on poultry. The focus is on practices in the United States. To understand the impact of kosher in the marketplace, one must have some understanding of how kosher foods are produced and how important kosher compliance is to consumers. To best appreciate the scope of kosher and how it affects the food industry, topics beyond those specifically related to poultry are covered. Many people in the food industry move between different segments of the industry, and it is worth having a more complete picture of kosher.

THE KOSHER LAWS

We start by focusing on the religious significance of the dietary laws for Jews. The kosher (kashrus) dietary laws determine which foods are "fit or proper" for consumption by Jewish consumers who observe these laws. The laws are Biblical in origin, coming mainly from the original five books of the Holy Scriptures, the

Torah, which has remained unchanged. At the same time that Moses received the Ten Commandments on Mount Sinai, Jewish tradition teaches that he also received the oral law, which was eventually written down many years later in the Talmud (the Mishnah). This oral law is as much a part of Biblical law as the written text, although other religions have only adopted the written Hebrew scriptures. Over the years, the meaning of the Biblical kosher laws have been interpreted and extended by the rabbis to protect the Jewish people from violating any of the fundamental laws and to address new issues and technologies. The system of Jewish law is referred to as *halacha*. The initial discussions of the law occur in the Talmud (the Talmudic commentaries known as the Gemmorrah, which contain the conflicting opinions of various rabbis who lived prior to the codification and which is written in a number of different languages). The most important relatively modern re-codifications of the laws occurred in the seventeenth century, through a religious text called the *Shulchan Aruch* ("set table") by Rabbi Joseph Karo and was shortly thereafter followed by a commentary by Rabbi Moses Isserles, known as the *Aruch Ha'Shulcan* ("tablecloth"). The latter texts remain the primary basis of the current practice of kosher laws. The text of Rabbi Isserles is followed by the Jews of Europe, the predominant sect of modern Judaism, especially in those cases where the recommendations differ from those of Rabbi Karo. Jews of African and Asian descent tend to follow the rulings of Rabbi Karo in all matters.

Why do Jews follow the kosher dietary laws? Many explanations have been given. The explanation below by Rabbi I. Grunfeld summarizes the most widely held ideas about the subject (Grunfeld, 1972) and serves to illustrate the fundamental importance of the kosher laws within the larger system of halacha.

> "And ye shall be men of a holy calling unto Me, and ye shall not eat any meat that is torn in the field" (Exodus XXII:30). Holiness or self-sanctification is a moral term; it is identical with ... moral freedom or moral autonomy. Its aim is the complete self-mastery of man.
>
> To the superficial observer it seems that men who do not obey the law are freer than law-abiding men, because they can follow their own inclinations. In reality, however, such men are subject to the most cruel bondage; they are slaves of their own instincts, impulses and desires. The first step towards emancipation from the tyranny of animal inclinations in man is, therefore, a voluntary submission to the moral law. The constraint of law is the beginning of human freedom .... Thus the fundamental idea of Jewish ethics, holiness, is inseparably connected with the idea of Law; and the dietary laws occupy a central position in that system of moral discipline which is the basis of all Jewish laws.
>
> The three strongest natural instincts in man are the impulses of food, sex, and acquisition. Judaism does not aim at the destruction of these impulses, but at their control and indeed their sanctification. It is the law which spiritualizes these instincts and transfigures them into legitimate joys of life.

The Kosher laws are viewed by the Jewish community as part of a group of laws given to the community without a need for explanation. Only in modern times have some people felt a need to try to justify them as health laws. For a discussion of why the kosher laws are not health laws, see an article by Regenstein (1994).

THE KOSHER MARKET

Why are we concerned about kosher in the secular world? Because kosher is an important component of the food business, especially in the United States but also in many other countries. Most people, even those in the food industry who may deal with some aspects of kosher in their work, are not aware of the breadth of foods that are under religious supervision. In this section we provide background on the economic aspects that make it important for the food industry to have a better understanding of kosher.

According to Integrated Marketing, an advertising agency specializing in the kosher food industry, the kosher market comprises almost 100,000 products in the United States. In 2005, about $200 billion in finished products was estimated to have kosher marking. However, deliberate consumers of kosher food [i.e., those who look specifically for the kosher mark (see below)] are estimated to be around 10 million Americans and they purchase almost $20 billion in kosher products. Fewer than one-third (possibly as little as 20%) of kosher consumers are Jewish (approximately 1 million year-round consumers). However, Jewish consumers keeping kosher obviously purchase all of their food as kosher and therefore represent a larger percentage of the dollar value of kosher. Their overall purchases annually are about twice the amount purchased by the average consumer. Other consumers, who at times find kosher products helpful in meeting their dietary needs, include Muslims, Seventh-Day Adventists, vegetarians, vegans, people with various types of allergies—particularly to dairy, grains, and legumes—and general consumers who value the quality of kosher products, even though there is rarely a one-to-one correlation between kosher and these consumers' needs. Hebrew National's slogans "We report to a higher authority" and "You don't have to be Jewish to love Levy's Rye Bread" are two of the more famous campaigns used to advertise kosher products to nonkosher consumers. *AdWeek Magazine* in the early 1990s called kosher "the Good Housekeeping Seal for the 90s." By undertaking kosher certification, companies can incrementally expand their market by opening up new markets. It should be noted that although many supermarkets define the kosher consumer in their scanning data as someone who purchases only products with kosher supervision symbols on the package, there are products that the rabbis accept that do not always need to have a supervision mark, as we describe later. We also include information that might assist kosher supervision agencies in addressing the specific needs of these other consumer groups.

The Muslim population in the United States is developing a stronger marketplace presence each year. Over the past 30 years many halal markets and

ethnic stores have sprung up, mainly in the major metropolitan areas. Most of the six to eight million Muslims in North America observe halal laws, particularly the avoidance of pork, but the food industry has, for the most part, ignored this consumer group. Although there are excellent opportunities to be realized in the North American halal market, even more compelling opportunities exist on a worldwide basis as the food industry moves to a more global business model. The number of Muslims in the world is over 1.3 billion people, and trade in halal products is about $150 billion (Egan, 2002). Many countries of South Asia, Southeast Asia, the Middle East, and Northern Africa have predominantly Muslim populations. Although only about 15% of India's population is Muslim, it is the second largest Muslim country in the world after Indonesia. In many countries halal certification has become necessary for products to be imported.

Although many Muslims purchase kosher food in the United States, these foods do not always meet the needs of the Muslim consumer. The most common areas of concern for the Muslim consumer when considering purchasing kosher products are the use of various questionable gelatins in products produced by more lenient kosher supervision and the use of alcohol as a carrier for flavors as well as a food ingredient. The details of both ideas are developed later in the chapter. The special issue of kosher and halal slaughter is taken up as a separate discussion.

With the agreement of the client company, kosher supervisors can address the needs of non-Jewish markets. A document establishing preliminary guidelines for making kosher appropriate for all of the groups mentioned above without violating Jewish law has been prepared (Regenstein, personal communication) and serves as a basis for a multicultural kosher dining program at Cornell University (dining.cornell.edu/docs/multicultural_doc.pdf). Other universities are also exploring kosher/halal and multicultural food options. Hopefully in the future, more kosher food producers will pay more attention to the needs of other user groups.

Although limited market data are available, the most dramatic data illustrating the impact of kosher certification in the marketplace is that of the Coors Brewing Company. According to their market analysis, their share of market in the Philadelphia market went up 18% when the company went kosher. Somewhat less dramatic increases were observed in other cities in the Northeast. Dannon Yogurt experienced a growth in sales when it switched from a "lenient" kosher certification to one that was normative mainstream (see the section on dealing with kosher and halal supervision agencies). A Northeast soda bottling company let its kosher certification lapse and as a result its sales dropped significantly. The company quickly got recertified!

In recent years, many large national companies have gone kosher. For some, the effort has been quite extensive. For example, when Nabisco took many of its cookie products kosher (see the section on equipment kosherization), it took over three years before its many bakeries around the country were kosherized and all its kosher products could finally be marketed in the United States. To consider

whether a company wants to participate in the kosher (or halal) market, its management needs to have some knowledge of the laws themselves to determine the potential profitability.

KOSHER DIETARY LAWS

The kosher dietary laws deal predominantly with three issues, all focused on the animal kingdom: (1) animals allowed, (2) prohibition of blood, and (3) prohibition of mixing of milk and meat. Additionally, for the week of Passover (in late March or April), restrictions on "chometz," the prohibited grains (wheat, rye, oats, barley, and spelt) in other than unleavened form—and the rabbinical extensions of this prohibition—lead to a whole new set of regulations, focused in this case on the plant kingdom. Ninety-two percent of American Jews celebrate Passover in some way, making it the most observed holiday in the Jewish calendar. It also accounts for about 40% of the sales of kosher products to the Jewish community. Although only 20 to 33% of the kosher market in the United States is Jewish, these consumers account for over half of the total dollar volume of the kosher market, since they purchase kosher food more consistently.

In this chapter we also discuss additional laws dealing with special issues such as grape juice, wine, and alcohol derived from grape products; Jewish supervision of milk; Jewish cooking, cheese making, and baking; equipment kosherization; purchasing new equipment from non-Jews; and old and new flour.

The kosher laws are an internally consistent logic system and have an implied "science" behind them—which may or may not agree with modern science. This system is the basis upon which rabbis work through problems (by responding to questions) and come up with solutions (by writing a response, a written document that sets out their position). Once their position is public, other rabbis have the right to accept or reject the position taken, which may be done simply by telling their followers or may be done in writing. Over time the broader community accepts and rejects many of these responses to the point where a position becomes normative. In general, once that happens, the rejected responses are no longer considered as a basis for decision making. This sorting process may be relatively fast, but in other cases it can take many years. In those cases where the religious texts do not define the religious "science," modern science can be helpful. However, where it disagrees with the texts, the texts of accepted response will often predominate.

Animals Allowed

Ruminants with split hoofs that chew their cud, the traditional domestic birds, and fish with fins and removable scales are generally permitted. Pigs, wild birds, sharks, dogfish, catfish, monkfish, and similar species are prohibited, as are all crustacean and molluskan shellfish. Almost all insects are prohibited such that carmine and cochineal, which are used as natural red pigments, are not permitted

in kosher products by most rabbinical supervisors. However, honey and shellac (lac resin) are permitted, as discussed later in this section.

Four classes of prohibited animals (mammals) are described specifically in the Torah. These are those animals that have one kosher characteristic but not both. For example, the rockbadger, the hare, and the camel chew their cud but do not have a split hoof; the pig has a split hoof but does not chew its cud. Neither category is more or less nonkosher, nor are those animals with neither trait; simply none are kosher, and these examples are listed specifically in the Torah only to clarify the text. In modern times, the prohibition of pork has often been the focus of both kosher and halal laws, since pork is such a major item of commerce in both Western and Eastern societies. Interestingly, the giraffe is a true ruminant and has a split hoof, rendering it kosher, with specific guidelines about its proper slaughtering procedures.

With respect to poultry, the traditional domestic birds (i.e., chicken, turkey, squab, duck, and goose) are kosher. Birds in the rattrie category (ostrich, emu, and rhea) are not kosher, as the ostrich is specifically mentioned in the Bible (Levitiens XI:16). However, it is not clear whether the animal of the Bible is the same animal as the one we know today as an ostrich. This is a problem that is often encountered with ancient texts—the Hebrew words for animals are difficult to determine in modern times.

There is a set of criteria that are sometimes referred to in trying to determine if a bird is kosher. The kosher bird has a stomach (gizzard) lining that can be removed from the rest of the gizzard. It cannot be a bird of prey. Another issue deals with tradition; newly discovered or developed birds (or other animals) may not be acceptable simply because there is no tradition of use. Some rabbis do not accept wild turkey, whereas others do not accept the domestic turkey. Others do not accept the featherless chicken.

The only animals from the sea that are permitted are those with fins and scales. All fish with scales have fins, so the focus is on the scales. These must be visible to the human eye and must be removable from the fish skin without tearing the skin. Cycloid and ctenoid scales found on traditional fish are generally considered acceptable, but the ganoid and placoid scales of sharks, gar, and so on, are not. A few fish remain controversial, probably the most controversial being the swordfish, whose scales do not seem to belong to any of the biologists' standard scale types. The Conservative movement permits swordfish and also permits sturgeon, which most Orthodox authorities consider nonkosher. A recent publication by both Orthodox rabbis and scientists/veterinarians has looked at the scalation of the swordfish (Govani et al., 2004). It is not clear if the juvenile scales are visible and removable without tearing the skin, as required by Jewish law. Thereafter the scales descend into the skin and certainly become nonremovable. Whether any Orthodox groups will accept swordfish (except for a few isolated groups that have accepted it historically) remains to be seen.

Most insects are not kosher. The exception includes a few types of grasshoppers, which are acceptable in the parts of the world where the tradition of eating them has not been lost. The edible insects are all in the "grasshopper" family,

identified as permitted in the Torah due to their unique "jumping" movement mechanism. Again, only visible insects are of concern; an insect that spends its entire life cycle inside a single food is not of concern. The recent development of exhaustive cleaning methods to prepare prepackaged salad vegetables eliminates a lot of the insects that are sometimes visible, rendering the product kosher and therefore usable in kosher food-service establishments and in the kosher home without requiring extensive special inspection procedures. Although companies in this arena go to a great deal of effort to produce insect-free product, some kosher supervision agencies remain unconvinced, and only certify those products (or particular production lots, e.g., one day the production may be acceptable and the next day it might not) that meet their more stringent requirements. The recent outbreak of locust in the Middle East were actually a kosher (and halal) species.

The prohibition of insects focuses on the whole animal. If one's intent is to make a dish where the food will be chopped up in a food processor, one may skip the elaborate inspection of fruits and vegetables for insects and assume that the presence of insect parts does not render the food nonkosher. There are guidebooks describing which fruits and vegetables in particular countries need inspection; recommended methods for doing this inspection are included. How well the procedures for removing insects work in practice has been a subject of controversy. Kosher consumers have appreciated the use of pesticides to keep products insect-free as well as the use of prepackaged vegetables that have been properly inspected. Modern IPM (integrated pest management) programs that allow for an increased level of insect infestation in fruits and vegetables can cause problems for the kosher consumer. Examples of problems with insects that one might not think about include insects under the "triangles" on the stalks of asparagus and under the "greens" of strawberries, and thrips on cabbage leaves. Kosher consumers and mashgichim, religious supervisors on site, are trained to inspect properly those fruits and vegetables that need to be examined. Because of the difficulty of inspecting them properly, many Orthodox consumers do not use brussel sprouts.

Honey and other products from bees are covered by a unique set of laws that essentially permits honey and beeswax. Other bee-derived materials (e.g., royal jelly) are more controversial. An article by Rabbi Z. Blech (2004) discusses this unique set of materials and the special laws surrounding bees and honey. Most rabbis extend this permission to the use of lac resin or shellac, which is used in candy and fruit coatings to provide a "shine."

Prohibition of Blood

Ruminants and fowl must be slaughtered according to Jewish law by a specially trained religious slaughterman (shochet) using a special knife designed for the purpose (chalef). The knife must be extremely sharp and have a very straight blade that is at least twice the diameter of the neck of the animal to be slaughtered. This knife, ironically, is not kosher, as it is used with both animals that will be declared kosher and some that are not. Also because of its

constant contact with blood, it remains in a special category. It is the process itself, and the strict following of the law, that makes a product kosher, not the presence or absence of a blessing over the food. However, prior to slaughter the shochet does make a blessing. The animal is not stunned prior to slaughter. If the slaughter is done in accordance with Jewish law and with the highest standards of modern animal handling practices, the animal will die without showing any signs of stress. The topic of kosher slaughter is discussed in more detail in Appendixes 1 and 2. In 1958, the U.S. Congress declared kosher slaughter and similar systems, (e.g., such as halal) to be humane, but included an exemption for preslaughter handling of the animal prior to kosher and halal slaughter. To deal with problems due to inappropriate preslaughter handling, the Food Marketing Institute, the trade association for many North American supermarkets, and the National Council of Chain Restaurants, are developing a set of basic animal welfare–based kosher/halal standards for upright slaughter based on the American Meat Institute's slaughter guidelines, which have existed for a number of years. Those aspects dealing with kosher slaughter, specifically poultry slaughter, will be discussed in more detail.

With respect to kosher, or kashrus, supervision, slaughtering is the only time a blessing is said—and it is said before beginning slaughter. The slaughterman asks forgiveness for taking a life. The blessing is not said over each animal, an issue we return to when discussing the Muslim concept of the meat of the "People of the Book." The rules for slaughter are very strict and the shochet checks the chalef before and after the slaughter of each animal. If any problem occurs with the knife, the animal becomes treife (i.e., not kosher). The shochet also checks the cut on the animal's neck after each slaughter to make sure that it was done correctly. If not, certain cuts can be made by the non-Jewish helper to aid in the rapid removal of blood. The animal welfare issues associated with religious slaughter are controversial, and it is often difficult to separate the impact of preslaughter handling from those aspects related directly to religious slaughter. Much of the current research has been done on systems that are not fully described. In many cases generalizations are made from very specifically poorly operating facilities. A paper describing some of the key components of reporting about kosher and halal slaughter is in preparation. Barnett et al. (2007) review one such poultry operation and do so with a very complete description of what happens at the particular plant during slaughter.

Slaughtered animals are subsequently inspected for visible internal organ defects by rabbinically trained inspectors. If an animal is found to have a defect, the animal is deemed unacceptable and becomes treife. There is no "trimming" of defective portions as generally permitted under secular law. The general rule is that a defect is religiously important if it would lead to a situation where the animal could be expected to die within a year. Some rabbis invoke these rules in dealing with issues related to veterinary practices (e.g., injections into certain parts of the animal's anatomy, such as the neck of a chicken). Again, the concept of a religious ability to live for 12 months more is not always

consistent with actual observations, as the basis is following practices prescribed previously.

Consumer desire for more stringent kosher meat inspection requirements in the United States has led to the development of a standard for kosher meat, mainly with respect to cattle, that meets a stricter inspection requirement, mainly with respect to the condition of the animal's lungs. As the major site of halachic defects, the lungs must always be inspected. Other organs are spotchecked or examined when a potential problem is observed. Meat that meets this stricter standard is referred to as *glatt kosher*, referring to the fact that the animal's lungs do not have any adhesions (sirkas). The word *glatt* means smooth, referring to the absence of sirkas (Figure 1) on the lungs. The bodek, or inspector of the internal organs, is trained to look for lung adhesions in the animal both before and after its lungs are removed from the lung cavity. To test a lung, the bodek first removes all sirkas according to a prescribed method and then blows up the lung using normal human air pressure or a bike pump! The lung is then put into a water tank and the bodek looks for air bubbles. If the lung is still intact, it is kosher. In the United States, a glatt kosher cow's lungs generally have fewer than two adhesions, which permit the inspection tasks to be done carefully in the limited time available in large plants. In some of these plants, those cattle that are not glatt are "reinspected" to determine if they are kosher. Some Jewish groups—particularly Jews who originated from countries under Muslim rule during the Dark Ages (i.e., Sephardim)—require a total absence of adhesions even in adult large animals (i.e., cattle). Such meat is referred to as "Beit Yosef" meat. Note that young (e.g., veal calves) and small (e.g., all sheep and goats) red meat animals must always be without adhesions. At this time we do not have a full understanding of what animal-handling practices lead to higher incidences of lung adhesions, although pneumonia in the calf is certainly one consideration. Preliminary research is being done on this issue to increase the success rate for kosher slaughter and to improve the economics of kosher slaughter. Lung inspections are not required for poultry.

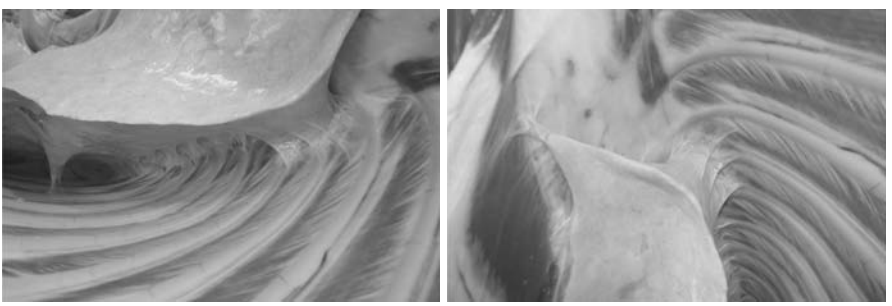

FIGURE 1 Sirchas (lung adhesions). (Courtesy of Judy Moses, Spirit of Humane, Boyceville, Wisconsin, www.spiritofhumane.com.)

Use of the word *glatt* for any other kosher product, including poultry, is only meant to convey the message that a higher standard is being used. It would be more accurate to the use the word *mehadrin*—meaning a stricter standard—and both of these words are used on some U.S. products and in other countries. However, there is also a company in the United States whose brand name is Mehadrin, leading to some confusion. Nonglatt meat and nonmehadrin poultry products encompass a larger percentage of the kosher marketplace (by volume), although the glatt community is probably the most strictly observant.

Meat and poultry must be further prepared by properly removing certain veins, arteries, prohibited fats, blood, and the sciatic nerve. The parts of the veins and arteries removed are high in blood, the prohibited fats are those mainly in the belly cavity that were used for sacrifices in ancient times, and the sciatic nerve commemorates Jacob's bout with the angel, leaving him to limp the rest of his life. This process is called *nikkur* in Hebrew and *treiboring* in Yiddish. The person who is specifically trained to do this is called a *Menacker*. In practical terms this means that only front-quarter cuts of kosher red meat are used in the United States and most Western countries because it is difficult to remove the siatic nerve, and the meat obtained ends up being in a lot of small pieces. Although it is very difficult and time consuming to remove an animal's sciatic nerve, necessity demanded that this deveining be done in parts of the world where the hindquarter was needed in the kosher food supply. In some animals (e.g., deer) it is relatively easy to devein the hindquarter. However, if there is no tradition of eating any hindquarter meat within a community, some rabbis have rejected the deer hindquarters for their community. This is an example of an issue where both sides of the argument are currently still accepted by various rabbis, as the process of determining a final stance on this issue has not been reached.

To further remove the prohibited blood, red meat and poultry must then be soaked and salted (melicha) within 72 h of slaughter. If this is not possible, nonglatt meat is specially washed (begissing), and this wash procedure may be repeated for up to two more times, each time within 72 h of the previous washing. The soaking is done for $\frac{1}{2}$ h in cool water; thereafter, the salting is done for 1 h with all surfaces, including cut surfaces and the inside cavity of a chicken, being covered with ample amounts of salt. The salted meat is then well rinsed three times. The salted meat must be able to drain throughout the hour and all the blood being removed must flow away freely. Shorter soaking and salting times are sometimes permitted (e.g., when there is not enough time before the Sabbath or a holiday to complete the process). In poultry, this step is often done between the prechilling (which most rabbis permit to double as the soak period) and the chiller. The chiller is then considered the third rinse and helps in removing the salt.

The animal's heart must be cut open and the congealed blood removed before beginning the overall soaking and salting process. Once the meat is properly koshered, any remaining "red liquid" is no longer considered blood according to halacha, and the meat can be used without further concern for these issues, including raw as steak tartare.

The salt used for koshering must be of a crystal size that is large enough that the crystals will not dissolve within the hour of salting and must be small enough to permit complete coverage of the meat. The salt industry refers to this crystal size as "kosher" salt. Although most salt is religiously kosher, the term *kosher* in this case refers to the grain size. The specific process of salting and soaking meat to make it ready for use is also referred to as *koshering* meat. The grain size and shape of salt from different salt companies will vary, and different rabbis will have different salt preferences.

Because of its high blood content, liver cannot be soaked and salted, but must instead be broiled until it is at least over half-cooked, using special equipment reserved for this purpose. The liver is then rinsed, after which the liver can be used in any way that the user wishes. Enough salt must be sprinkled on the liver to cover it. Koshering liver is one of the most complicated tasks to do in institutional settings. In theory any meat can be broiled instead of soaking and salting. However, this has not been done for so many years that some rabbis no longer accept this alternative.

Some concern has been raised about the salt level in kosher meat. Note that only the surfaces are salted, generally using primal cuts (i.e., 20 to 40-lb pieces of meat), and that the penetration of the salt is less than 0.5 cm in red meat (New York Department of Agriculture and Markets, personal communication). Many pieces of meat, as consumed, have therefore not been subjected directly to the salt treatment. If salt content in a diet is a very important consideration, one should cut off all surfaces (or learn to recognize those surfaces that have been salted) and not use any of the drippings that come out of the meat or poultry during cooking. Much of the salt that goes into the meat at the surface is lost during the cooking process.

Another issue that can arise when meat has not been soaked and salted is that of *kavoush*. For example, if meat trimmings sit in the blood released by meat for more than 24 h, the meat is considered to be pickled and cannot subsequently be soaked and salted. This meat is therefore not kosher. When large totes are used for shipping meat, it is almost impossible to prevent kavoush. These totes should be used only if the meat will be removed within 24 h or the meat has already been koshered.

Any ingredients or materials that might be derived from animal sources, such as tallow, are generally prohibited because of the difficulty of obtaining them exclusively from kosher animals. This includes many products that might be used in foods and dietary supplements, such as emulsifiers, stabilizers, and surfactants, particularly those materials that are fat-derived. Very careful rabbinical supervision would be necessary to assure that no animal-derived ingredients are included in kosher food products. Almost all such materials are available in a kosher form derived from plant oils. A possible practical and important exception to no animal ingredients might be a normative mainstream gelatin, which is now being produced from glatt kosher beef hides (see the section on gelatin). Also some rennet, the cheese-coagulating enzyme, is obtained from the dried fourth stomach of a kosher-slaughtered milk-fed calf, although most cheese, including

kosher cheese, is currently made using a biotechnology-derived chymosin (see the section on biotechnology).

There are a few concepts in Jewish laws that permit materials to alter their status. The first is *Dvar Hadash*, or new entity. If something undergoes a sufficient transformation, as defined rabbinically, it may become a new entity and not retain the identity of its source materials. Exactly what needs to be done to invoke this concept is quite controversial. Another concept that may help create flexibility for food manufacturers is the concept of "dry as wood," where the "drying" is defined as natural drying for over a year. The concept is used in part to justify use of the natural calf rennet discussed above; the extraction of a chemical from such a material permits its use when it would not otherwise be permitted. Finally, there is the concept of "not fit for either a person or, less critically, for a dog." If a material is unacceptable and would not even be eaten by a dog, the source is not considered a food, which means that anything derived from it could be kosher. Note, however, that some rabbis argue that if an identifiable object (e.g., a bone) is placed into such a mixture and then recovered, the item was not necessarily ever unfit for a dog.

Prohibition of Mixing Milk and Meat

"Thou shalt not seeth the kid in its mother's milk" (Exodus XXIII:19; Exodus XXXIV:26; Deuteronomy XIV:21). This passage appears three times in the Torah and is therefore considered a very serious admonition. As a result, the law cannot be violated even for nonfood use of such prohibited mixtures (e.g., in such uses as pet food). Neither can one derive benefit from such a mixture. Therefore, one cannot own a cheeseburger business. The meat side of the equation has been extended rabbinically to include poultry (but not fish), as both meat and poultry are warm-blooded animals and need to be slaughtered, inspected, deveined, salted, and soaked. The basis for this extension is found in the concept of not being seen to do something wrong (i.e., *maris ayin* in Hebrew). Poultry, especially dark meat, could easily be confused for lighter forms of red meat (e.g., veal). The dairy side of this prohibition includes all milk derivatives, or at least those that have not been declared a new entity.

Keeping meat and milk separate in accordance with kosher law requires that the processing and handling (including the status the processing and handling equipment) of all materials and products fall into one of three categories: (1) a meat product, (2) a dairy product, or (3) a neutral product called *pareve*, *parve*, or *parev*. Note that for words that are transliterations of Hebrew, such as *pareve*, multiple English spellings are acceptable. (All we usually ask is that the spelling be consistent within a single document!) The pareve category includes all products that are not classified religiously as meat or dairy. Secular classifications may be defined differently. All plant products are pareve, along with eggs, fish, honey, and lac resin (shellac). These pareve foods or ingredients can be used with either meat products or dairy products. However, if they are mixed with meat or dairy, they take on the identity of the product they are mixed with (i.e.,

an egg in a cheese soufflé becomes dairy). In the home or food-service kitchen, spices in containers that are added to foods while they are cooking may adsorb some of the steam and volatiles and would then take on the characteristics of the product. So a serious kosher kitchen will have separate spice containers for meat and dairy.

A special set of rules applies to fish. Fish can be eaten at the same meal at which meat is eaten, but it cannot be mixed directly with the meat. The dishes used with the fish are generally kept separate and rinsed (but not subject to the ritual of equipment kosherization) before they are used with meat, or vice versa. The original law in the Talmud speaks of a specific concern that one particular type of fish caused people to get sick when they mixed that fish with meat. Since we do not know what fish that is and have no modern evidence that such a problem exists, this rabbinical health concern is no longer valid or necessary according to the Conservative Jewish movement, whereas Orthodox rabbis extended the prohibition to all fish and meat mixtures. This is a very specific exception to the generalization that kosher laws are not health laws. Another exception with respect to handling fish: One of the very traditional Chassidic Orthodox groups, Lubavitch or Chabad, also has a tradition of not mixing milk with fish (e.g., so they would not permit a kosher fish gelatin to be used in yogurt). Most Orthodox communities do not follow this later strictness.

To assure the complete separation of milk and meat, all equipment, utensils, pipes, steam, and so on, must be of the properly designated category. If plant materials such as fruit juices are run through a dairy plant, they would be considered a dairy product under kosher law. Some kosher supervision agencies, but not others, would permit such a product to be listed as "dairy equipment (D.E.)" rather than "dairy." "D.E." tells the consumer that it does not contain any intentionally added dairy ingredients, but that it was made on dairy equipment (see the section on kosher and allergies). If a product with no meat ingredients, such as a vegetarian vegetable soup, is made in a meat plant, it may be marked "meat equipment (M.E.)." Although one may need to "wash" the dishes (much like the fish and meat separation discussed above) before and after use, D.E. food can be eaten on meat dishes and M.E. food on dairy dishes. For actual dairy and meat products, a significant wait is normally required to use a product with dairy ingredients after one has eaten meat. This can range from 3 to 6 h, depending on the customs (minhag) of the area from which the husband of each family came. With the D.E. listing, the consumer can use the D.E. product intentionally immediately before or after a meat meal but not intentionally *with* a meat meal. Following the eating of dairy, the wait before eating meat is much less, usually ranging from a "rinse of the mouth" with water to a 1-h wait. However, certain dairy foods do require the full wait of 3 to 6 h; for example, when a hard cheese is eaten, the wait for dairy to meat is the same as that for meat to dairy. A hard cheese is defined either as a cheese that has been aged for over 6 months or one that is particularly dry and hard, like many of the Italian cheeses. Thus, most companies producing cheese for the kosher market usually age their cheese for less than 6 months, although with proper package marking, indicating a longer

aging period, the quality of the cheese might be improved, and many kosher consumers might be happy to purchase these products. Traditionally, most Jews had dairy for breakfast and lunch and meat for supper. Now it is more likely that supper will sometimes be dairy, especially if high-quality cheese is available!

If one wants to make an ingredient or product truly pareve, the plant equipment must undergo a process of equipment kosherization (see the section on equipment kosherization). From a marketing standpoint, a pareve designation is most desirable since the product has the most uses for both the kosher and the nonkosher consumer.

SPECIAL KOSHER FOODS

Grape Products

To be kosher, all grape juice–based products can only be handled by sabbath-observing Jews from grape pressing to final processing. In manufacturing kosher grape juice, harvesting cannot occur on Saturday and only Jewish workers can press the grapes. If the juice is pasteurized (heated or *mevushal* in Hebrew), it can be handled by any worker as an ordinary kosher ingredient.

The actual pasteurization temperature is debated and different rabbinical groups use different temperatures. Some wineries do not pasteurize the product, preferring to hire only Jews to handle the wine, which then does not require heating. The traditional Jewish religious wines that are still often used for religious ceremonies were historically very sweet, often made from Concord grapes. Initially, these were actually made from raisins in some circumstances.

If a liquid bottling line (e.g., a soda line) uses a product with nonkosher grape juice, the line would have to be cleaned (rinsed) out before proceeding to make kosher products. The normal scheduling of light-to-dark products in many bottling plants during the course of the day, which is done so that the carryover from one product to the next is not observed by consumers, may need to be adjusted so that all grape juice–containing products are run at the end of the day. (*Note:* This practice of continuous production of certain types of products with changes in the composition is something about which people with allergies should also be aware.)

One controversial issue has been the status of marc alcohol. After the grapes are pressed, hot water containing cane or beet sugar is added to the pomace and a second-press juice is obtained. This is then fermented and a commercial (marc) alcohol obtained, whose kosher status remains controversial. Marc alcohol must be distilled before use, as it would otherwise contain unacceptable levels of methanol, an issue that may be relevant to the adjudication of its kosher status.

Jewish Cheese (Gevinas Yisroel)

Similar to the laws concerning kosher wine production, most kosher supervision organizations require the supervising rabbi or a Sabbath-observing Jew to add

the coagulating agent (i.e., the agent that makes the cheese form a curd) into the vat to ensure that the cheese is kosher. Any cheese that does not meet this requirement is unacceptable. This participation is required because a ripened cheese is considered a product fit for the table of nobility.

Kosher whey can be created more easily. If all the ingredients and equipment used during cheese making are kosher, the whey will be kosher as long as the curds and whey have not been heated above 120°F (49°C) before the whey is drained off. This is true even if a Sabbath observer has not added the coagulant. The necessity for Jewish participation in cheese-making is that the cheese is a product "fit for a king." Clearly, whey, which until recently was dumped into streams, does not fit into this category. Therefore, there is much more kosher whey and whey products available in the United States than kosher cheese.

Increasingly, the dairy industry is seeking to sell more whey and whey products to other food companies. Since many of these companies are kosher, there has been growing interest in assuring the kosher status of whey. For example, several manufacturers of Swiss cheese, which has a most desirable white whey, have reduced the temperature at which they work the curds under the whey. Instead of using the traditional 125 to 127°F (52 to 53°C), they are using a temperature under 120°F (49°C) to work the curds and to obtain a kosher whey. Without these changes most of the Swiss cheese whey and similar products actually end up being used as a feed ingredient rather than as human food. So sometimes the kosher status of a material, particularly an ingredient, can be affected very strongly by its kosher status. Obviously, all of these products cannot be used with meat and poultry.

There are also other challenges to overcome. Much of the whey is produced in spray driers, which are among the most difficult pieces of equipment to kosherize. The process of cleaning out the entire system is quite time consuming. Some spray driers also have an automatic shutoff device that does not permit hot water at 190°F (88°C) or hotter to be run through the system, which is what the rabbis require.

Another dairy problem deals with whey cream. Any cream that is separated from cheese at above 120°F (49°C) is subject to the restrictions that come with cheese and is generally not considered kosher. These types of creams have recently been used to produce butter, which is therefore not considered kosher. Most rabbis had traditionally accepted butter as kosher without supervision, as is still the case for most rabbis with respect to fluid milk. The transition to requiring kosher supervision of butter has been difficult, as it happened in a short time and the butter industry did not always understand what was happening to it. A more detailed article on this and closely related kosher dairy issues was published in 2002 (Regenstein and Regenstein, 2002a,b,c).

Jewish Milk (Cholev Yisroel)

Kosher-observant Jews are concerned about possible adulteration of milk with the milk of nonkosher animals such as mare's milk or camel's milk, and therefore

the tradition requires that the kosher milk be watched from the time of milking. This cholev Yisroel (Jewish milk) is required by some of the stricter kosher supervision agencies for all dairy ingredients. Rabbis who accept non-cholev Yisroel milk in the United States and other Western countries are able to do so for two reasons. First, they believe that the laws in the United States and many other countries are strong enough to assure that adulteration of milk by milk from prohibited species does not occur. Second, the nonkosher milks are usually worth more money than kosher milks, so there is no economic incentive to add nonkosher milk to the milk of kosher species.

A farm producing cholev Yisroel milk would have a Sabbath-observing Jew on the farm whenever milking is taking place, including the Sabbath and all holidays. Essentially, this requires that the Jewish supervisors live on or very near the farm, and often requires them to forgo communal celebration of the Sabbath and the holidays. The milk tanks on the farm and the tanker truck taking the milk to market would both be sealed by the on-site religious supervisor, and then the seal would be broken by the receiving religious supervisor at the milk plant.

Yashon (Old) and Chodesh (New) Flour

On the second day of Passover, Jews traditionally brought a grain offering to the Temple in Jerusalem. This served to bless all of the flour that was "growing" or had already been harvested on that day. Such flour has attained the status of *yashon* (old) flour. All wheat for flour that has not started to grow by the second day of Passover is considered *chodesh* (new) and should not be used until the next Passover. For all intents and purposes, the new grain would have been planted more than 14 days before the second day of Passover, the minimum time assumed necessary religiously for the seeds to germinate. All winter wheat from the northern hemisphere is considered yashon automatically, as it would have been planted in the fall. It is more difficult to assure the yashon status of spring wheat, which generally is harvested in August. Manufacturers may receive inquiries from consumers about the source and timing of their wheat and other grain purchases, particularly between August and the next Passover. The extent of observance of this law is increasing, so processors, including kosher poultry processors, may be asked about the status of the grains used, for example, in batters and breadings.

Early Fruit (Orleh)

Another kosher law concerning plants is the requirement that tree fruits not be harvested for human benefit until the fourth year. This has been particularly problematic with respect to papaya, a tree fruit that is often grown commercially for less than four years! Discussion and disagreement about what are "tree" fruits subject to this ruling remains at this time.

Passover Foods

The Passover holiday occurs in spring and requires observant Jews to avoid eating the usual products made from five prohibited grains: wheat, rye, oats, barley, and spelt (Hebrew: chometz) except in the limit form of matzos (or unleavened bread). Those observing kosher laws can only eat the specially supervised unleavened bread from wheat (Hebrew: matzos) that were prepared especially for the holiday. Once again, some matzos (e.g., schmura matzos) are made to a stricter standard than the normative product available in most Western countries, with rabbinical inspection beginning in the field at the time of harvest, especially to assure that the grain being harvest is so dry that no fermentation can take place. For other Passover matzos the rabbinical supervision does not start until the wheat is about to be milled into flour. Matzos made from oats and spelt are now available for consumers with allergies but are not supposed to be used by people without a health requirement for these products.

Special care is taken to assure that matzo does not have any time or opportunity to "rise." In some cases this literally means that products are made in cycles of less than 18 min (i.e., the entire process stops, everything is cleaned, and the 18-min cycle starts over again). This is likely to be the case for handmade schmura matzo. In continuous large-scale operations, the equipment is constantly vibrating so that there is no opportunity for the dough to rise, and this permits more continuous production.

Why 18 minutes? Note that the word for *life* is the two-letter Hebrew word *Chai*. Since the Hebrew alphabet is "mapped" to numbers (e.g., aleph = 1, bet = 2), the word *Chai* equals the number 18! Thus, fermentation, "life," is considered to require 18 min to occur. Anything made in less than 18 min has not fermented and has therefore not violated the prohibitions of Passover. Also, the drinking toast among Jews is *L'Chaim*, "to life."

In the Middle Ages, the rabbis of Europe also made products derived from corn, rice, legumes, mustard seed, buckwheat, and some other plants (Hebrew: kitnyos) prohibited for Passover. In addition to the actual "flours" of these materials, many contemporary rabbis also prohibit derivatives such as corn syrup, cornstarch, and cornstarch derivatives such as citric acid. Some rabbis will permit citric acid and similar materials to meet the new entity status. A small number of rabbis permit oil from kitnyos materials, or liquid kitnyos products and their derivatives, such as corn syrup. The major source of sweeteners and starches used for production of "sweet" Passover items are either real sugar or potato or tapioca-derived products such as potato syrup.

Rabbis are also concerned with other foodstuffs that are being raised in areas where wheat and other Passover grains are grown. Because of possible cross-contamination between these crops and the prohibited grains, some crops, such as fennel and fenugreek, are also prohibited for Passover. An interesting product is quinoa, a grainlike material grown in the Andes of Bolivia and Peru. This product is new to the rabbinate, and many rabbis have ruled that it is acceptable. However, because it would normally be handled in a plant handling other grain

and grainlike materials, the strictest rabbis require that the product's handling and packaging be supervised before permitting it for Passover.

During the Dark Ages, Jewish communities within Christian countries did not have regular contact with Jews living in Muslim countries. The laws governing these two communities began to drift apart. As a result, today's European or Ashkenazic Jewish community has significantly different laws and customs from the Sephardic Jewish communities, which included Spain, North Africa, and the Middle East. Sephardic custom, which is the default in Israel, includes, among other rules, no ban on all or some kitnyos materials (e.g., rice), a beit yosef meat standard of absolutely no lung adhesions on animals, and a willingness to use hindquarter that has been correctly subject to nikkur, or deveining. With a few exceptions, however, Passover foods in the United States are processed to Ashkenazic standards. Products from Israel may be marked specifically as "acceptable for those who use kitnyos."

Passover is a time of large family gatherings. The requirement for two separate sets of dishes specifically for Passover (i.e., one meat set and one dairy set) adds another element of resource usage and activity in providing hospitality. In previous generations, some kosher consumers limited themselves to meat products for the entire week of Passover. Overall, 40% of kosher sales for traditional "kosher" companies such as Manischewitz, Rokeach, and Kedem occur for the week of Passover. Stores generally begin to make Passover products available to consumers between 4 and 6 weeks prior to Passover. Consumers who regularly use products such as dietary supplements, and non-life-threatening drugs will be concerned about obtaining a version of their favorite and/or required product that is acceptable at Passover. For drugs, the prohibition of chometz is of special concern since many Jews do not want any manner of chometz in their home, including drugs, pet feeds, and nonfood items such as rubbing alcohol.

A violation of the laws of Passover is considered Biblical grounds for being "separated from the community." This is generally the highest level of prohibition and has led to extra strictness with respect to the production of kosher for Passover products. Thus, the decision to produce Passover products will lead a company into a more complex manufacturing territory.

The most stringent kosher consumers eat only "whole" (unbroken) matzos on the first seven days of Passover, the seven days observed by Jews everywhere, including Israel. Thus, any food prepared for those seven days (the Biblically commanded time) may need to be made without the use of any matzo meal or matzo flour [i.e., no gebruckts (broken matzos)]. However, on the eighth day, which is a rabbinical extension of Passover outside of the land of Israel, these people will also eat products made with less than whole matzos, including the traditional Jewish matzo ball soup.

With all the limitations of Passover, it is a challenge to make Passover food products that are tasty and have a decent texture. The kosher community welcomes the assistance of the food scientist and the food industry to develop more and better Passover products.

OTHER KOSHER PROCESSING ISSUES

Equipment Kosherization

There are generally three ways to make equipment kosher or to change its status back to pareve from dairy or meat. Rabbis generally frown on going intentionally from meat to dairy, or vice versa, directly (i.e., after some time as pareve, it might be possible to go to meat with a piece of equipment that was dairy way back when). Most conversions are from dairy to pareve or from treife to one of the categories of kosher. There are a range of process procedures to be considered, depending on the equipment's prior production history.

After a plant or a processing line has been used to produce kosher pareve products, it can be switched to either kosher dairy or kosher meat without a special equipment kosherization step. It can also be used subsequently for halal production (from pareve or dairy lines, but not always from meat lines), and then, finally, for nonkosher products. In many cases, a mashgiach (i.e., a rabbinically approved kosher supervisor) is needed on site for equipment kosherization, so it normally is beneficial to minimize the number of changeovers from one status to another.

1. The simplest equipment kosherization occurs with equipment that has only been handled cold. This requires a good liquid caustic/soap cleaning, the type of cleaning done normally in most food plants. Some plants do not normally do a wet cleanup between runs (e.g., a dry powder packing plant or a chocolate line), and these would need to seek specific rabbinical guidance for the changeover. Materials such as ceramics, rubber, earthenware, and porcelain cannot be koshered because they are considered not "capable" of releasing the flavors trapped within them during the equipment kosherization process. If these materials are found in a processing plant, new materials may be required for production.

2. Most food-processing equipment is operated at cooking temperatures generally above 120°F (49°C), the temperature that is usually defined rabbinically as "cooking." However, the exact temperature for cooking depends on the individual rabbi, in that it is the temperature at which he must immediately remove his hand when he puts it into hot water. Recently, through an agreement by the major four mainstream American kosher certifying agencies, most normative kosher supervision agencies in the United States have settled on 120°F (49°C) as the temperature at which foods are cooked, and this figure is used throughout this chapter (see the section on dealing with kosher and halal supervision agencies).

Equipment that has been used with cooked product must be thoroughly cleaned with liquid caustic/soap before being kosherized. The equipment must then be left idle for 24 h, after which it is "flooded" with boiling water, defined as water between 190°F (88°C) and 212°F (100°C), in the presence of a kosher supervisor. The details depend on the equipment being kosherized. In some cases, particularly with food-service establishments, a pogem (bittering agent, often ammonia) is

used in the boiling water in lieu of the 24-h wait. The absolutely clean equipment (e.g., silverware) is put into the ammonia-containing boiling water to pick up a "bad" flavor, which is removed by a second boiling with clean water. The 24-h wait accomplishes the same thing as the ammonia (i.e., it turns any desirable flavors attached to the equipment into undesirable flavors).

The principles concerning koshering by hagalah (boiling water) or irui (boiling water poured over a surface) are based on an ancient understanding of the movement of taam (flavor) in and out of solid materials. The concepts of taam and its movement between products are also used to analyze the many possible combinations of kosher meat, kosher dairy, and/or nonkosher products interacting accidentally [i.e., for analysis "after the fact" (b'de-eved)]. For real accidents, the rabbis are able to be more lenient than they might be for things that are done intentionally (l'chatchilla, i.e., planned ahead of time). In modern times, because kosher supervision in the United States is active (i.e., the rabbis are operating with a contractual agreement and ongoing inspections), there is less room to work with some of these after-the-fact leniencies. In Europe, where rabbis sometimes make only informal visits to plants and report on their visits to their congregants and the greater Jewish community, the rules with respect to after-the-fact issues are sometimes used more freely, since the rabbi cannot control, nor is he responsible for any changes that the processing plant may make once he has left the plant.

3. In the case of ovens or other equipment that uses "fire," or dry heat, kosherization involves heating the metal until it glows. Again, the supervising rabbi is generally present while this process is taking place. In the case of ovens, particularly large commercial ovens, issues related to religiously defined "odor/vapors" and "steam" must also be considered. Sometimes the same oven can be used sequentially for alternating pareve and dairy baking. The details are beyond the scope of this chapter and require a sophisticated rabbinical analysis to determine which ovens can be used for more than one status (at separate times) without requiring kosherization.

The procedures that must be followed for equipment kosherization, especially for hot equipment, can be quite extensive and time consuming, so the fewer status conversions, the better. Careful formulating of products and good production planning can minimize the inconvenience. If a conversion involving hot foods using "wet" heat is needed, it is often scheduled for early Monday morning, before the production week starts. Since rabbis observe the Sabbath on Saturday, they are available to travel to food plants all around the country on Sunday to start work on Monday morning at 3, 4, or 5 A.M.

Jewish Cooking and Baking

In cases where it is necessary for rabbis to do the cooking (bishul Yisroel), their contribution to the process must remain independent of the company's activities. Often, this means turning on the pilot light. As long as the pilot light remains

lit, the rabbi does not have to be present; if it goes out, he must return. With electrical equipment and appliances, it is possible to keep electricity on all the time, using the lowest setting when actual heating is not taking place. The most difficult situation for kosher operations is a gas stove with an electrical starter. Care in selecting equipment can minimize a number of problems.

Baking generally requires Jewish participation, pas Yisroel (i.e., the Jew must start the ovens). In addition, if the owner of the bakery is Jewish, there may be a requirement for "taking challah," a portion of the dough that is removed and needs to be specially handled. Again, the details need to be worked out with the supervising rabbi. Note that a company that is over 50% Jewish management or Jewish ownership is usually subject to these stricter rules (e.g., the taking of challah and the need to observe the sabbath and other Jewish holidays). To be accountable for the rules that apply to everyone, some owners sell their business to a Gentile for the period of concern, even a single day each week. This is a legally binding contract, and in theory the Gentile owner can renege on his or her informal agreement to legally sell it back at the end of shabbos, the end of the holiday. On Passover, the need to do this can be more critical: Any chometz in the possession of a Jew during Passover is forever prohibited in a kosher home. For example, if a "Jewish" grocery store receives a shipment of bread during Passover, that bread, even if marked as kosher, although obviously non-Passover, can never be used by an observant kosher-observing Jew.

Toveling (Immersing Equipment Purchased from a Gentile)

When a Jewish company purchases or takes new or used equipment from Gentiles, the equipment must be bathed in a ritual bath (mikvah) prior to undergoing equipment kosherization. Equipment from metal and glass requires a blessing; complex items that contain glass or metal may need to be toveled (i.e., immersed) but may not need a blessing. A mashgiach needs to be present for this activity. A natural body of water can be used instead of the indoor mikvah, which may be very helpful with large equipment.

Tithing and Other Israeli Agricultural Laws

In ancient times, products from Israel were subject to special rules concerning tithing for the priests, their helpers, the poor, and so on. These are complex laws that only affect products from Israel. There is a rabbinical process for doing the tithing that does not require some of the actual product to be removed from the lot. The land of Israel is also subject to the Sabbath (sabbatical) years (i.e., crops from certain years cannot be used). These additional requirements challenge kosher consumers in the United States who are interested in purchasing and trying Israeli products. Rabbis in Israel arrange for companies to tithe when the products are destined for sale in Israel, but rarely for exports. In 2002, at least one major U.S. kosher supervision agency has begun to arrange for tithing before the product

is offered to the consumer in the United States. The details of this process are beyond the scope of this chapter.

KOSHER AND ALLERGIES

Many consumers use the kosher markings as a guideline to determine whether food products might meet their special needs, including those with allergies. There are, however, limitations that the particularly sensitive allergic consumer needs to keep in mind.

1. When equipment is kosherized or converted from one status to another, the procedure may not yield 100% removal of previous materials run on the equipment. This became an issue some years ago when rabbis discovered that the special procedures being used to convert a dairy chocolate line to a pareve chocolate line led to enough dairy contamination that consumers who were very sensitive to dairy allergens were having problems. These lines are koshered without water: Either a hot oil or "pareve" chocolate is run through the line in a quantity sufficient to remove any "dairy" residual as calculated by the supervising rabbi. The problem, however, may be the dust from the handling of the nonfat dry milk used for milk chocolate. Airborne dust is not of any religious concern. Both Islam and Judaism do not permit practices that would endanger life. As a result, rabbis decided that none of the current religiously acceptable methods for equipment kosherization of chocolate are effective enough to move between dairy and pareve production, therefore, mainstream kosher supervision agencies no longer permit this conversion in chocolate plants.

2. Kosher law does permit certain ex-post-facto (after-the-fact) errors to be negated. Trace amounts of materials added to a food accidentally can be nullified if the amount of "offending" material is less than 1/60 by *volume* under very specific conditions (i.e., truly added by accident). However, some items, such as strongly flavored compounds that make a significant impact on the product, even at less than 1/60, can never be negated. In deference to their industrial client company's desire to minimize negative publicity when problems arise, many kosher supervision agencies do *not* announce when they have used this nullification procedure to make a product acceptable. When there is a concern about allergic reactions, however, many rabbis are more willing to alert the public as soon as possible for health and safety reasons, and they have definitely become more sensitive about this issue over time. Products that might be made in a dairy plant (e.g., pareve substitutes for dairy products and some other liquids like teas and fruit juices) may be produced in plants that have been kosherized but may not meet a very critical allergy standard. Care in consuming such products is recommended.

3. Labels that say "Dairy and Meat Equipment" are used on products when there are no intentionally added dairy or meat ingredients, but the product is produced on a dairy or meat line without equipment kosherization. The product

is considered pareve with some use restrictions on how and when it might be used in a kosher home, but the rules for these products are more lenient than for actual meat and dairy products. Again, the more sensitive the allergy, the more caution is advised.

4. In a few instances where pareve or dairy products contain small amounts of fish, such as anchovies in Worcestershire sauce, this ingredient *may* be marked as part of the kosher supervision symbol. Many certifications do not specifically mark this if the fish in the initial material (i.e., in the Worcestershire sauce itself) is less than 1/60. Someone who is allergic should always read the ingredient label.

5. At Passover, there is some dispute about "derivatives" of kitnyos materials, the nongrain materials that are also prohibited for Ashkenazic Jews. A few rabbis permit some of these items, such as corn syrup, soybean oil, peanut oil, and materials from these liquid products. The proteinaeous part of these materials is generally not used even by the more lenient rabbis. Consumers with allergies to these items can therefore purchase these special Passover products from supervision agencies that do *not* permit kitnyos derivatives. With respect to equipment kosherization: Supervising rabbis tend to be very strict about the cleanup of the prohibited grains (wheat, rye, oats, barley, and spelt), so these Passover products come closest to meeting potential allergy concerns; this may not be the case with respect to the extended kitnyos prohibitions.

Consumers should not assume that kosher markings ensure the absence of trace amounts of the ingredient to which they are allergic. It is a useful first screen, but products should be tested carefully before assuming that everything is acceptable; that is, the allergic person should eat a small portion of the product, and increase the amount consumed slowly, over time, to assure no adverse reaction. People with allergies should get into the habit of checking lot numbers on products and purchasing stable goods with a single lot number in sufficient quantity to meet anticipated needs within the shelf-life expectations of the goods. Every packaged product has a lot number, representing some unit of production. Some companies change lot numbers a few times a day, whereas others change it once a day. In any case, the same lot number represents a production run that can usually be expected to be more consistent than runs produced at different times with different lot numbers.

How thoroughly are dairy ingredients kept out of a pareve line? The current standard for kosher may not meet the needs of allergic consumers since the dairy powder dust in the air may be sufficient to cause allergy problems. A company might choose to use a special marking on kosher pareve chocolates produced in plants that also produce dairy products to indicate that these are religiously pareve but may not be sufficiently devoid of dairy allergens for very allergic consumers. Furthermore, they may also want to consider checking the chocolate using a modern antibody or similar test. For example, regular M&Ms are marked as containing peanuts to alert people who are very allergic to peanuts. The product

does not contain peanuts, but common equipment (cleaned between product runs) is used for both products. Also, peanut dust may be in the air.

MEAT OF ANIMALS KILLED BY THE AHL-AL-KITAB*

There has been much discussion and controversy among Muslim consumers as well as Islamic scholars about the permissibility of consuming meat of animals killed by the Ahl-al-Kitab (people of the book), meaning, among certain other faith communities, Jews and Christians. The issue focuses on whether meat prepared in the manner practiced by either faith would be permitted for Muslims.

In the Holy Quran, this issue is presented only once, in Sura V, verse 5, in the following words: "This day all good things are made lawful for you. The food of those who have received the Scripture is lawful for you, and your food is lawful for them." This verse addresses the Muslims and seems to establish a social context where Muslims, Jews, and Christians could interact with each other. It points toward two sides of the issue: first, "the food of the people of the book is lawful for you" and second, "your food is lawful for them."

In most discussions, scholars try to deal with the first part (food of Ahl-al-Kitab) and ignore the second part (food of Muslims) altogether, leaving that decision to the people of the book. As far as the first part of the ruling is concerned, Muslims are allowed to eat the food of the Jews and Christians as long as it does not violate the first part of this verse: "This day all good and wholesome things have been made lawful for you" (Quran V:6).

The majority of Islamic scholars are of the opinion that the food of the Ahl-al-Kitab must meet the criteria established for halal and for wholesome food, including proper slaughter of animals. They believe that the following verse establishes a strict requirement for Muslims: "And eat not of that whereupon Allah's name hath not been mentioned, for lo! It is abomination" (Quran VI:121). However, some Islamic scholars are of the opinion that this verse does not apply to the food of Ahl-al-Kitab and that there is no need to mention the name of God at the time of slaughtering (Al-Qaradawi, 1984). It is up to the regulatory agencies in halal food–importing countries, halal certifiers for export or domestic consumption, or individual Muslim consumers to decide how to interpret these verses. However, for clarity in understanding modern-day practices of Ahl-al-Kitab, we offer the following analysis.

1. Christians do not follow a strict food code.
2. Jews are divided into three major groups:
   a. Orthodox Jews, who slaughter animals (ruminants and poultry) in their prescribed manner and prepare all kosher meat currently being marketed commercially in the United States and most other Western countries.

*With special acknowledgment of the contribution of Muhammad Chaudry, president of IFANCA, to this section.

   b. Conservative Jews, who follow the kosher guidelines based on Jewish law but who tend to be more lenient than Orthodox Jews and are not usually involved in slaughter.
   c. Reform Jews, who do not generally consider kosher laws an essential concern for modern Jewish practice.
3. Orthodox Jewish slaughterers say a blessing at the beginning of a slaughter session but do not pronounce the name of God at the actual time of slaying of each animal. However, in recent years the Orthodox rabbinate has ruled that the saying of the Muslim takbir (i.e., the blessing "Allah is great" in Arabic) by the Jewish slaughterman (i.e., the shochet) is permitted. At least one sheep and goat slaughter of a truckload of animals occurred in 2007, with the shochet saying the takbir out loud in the presence of a Muslim witness.

For those Muslims who want to adhere strictly to the requirements of verse VI:121, meat (red meat and poultry) of the Ahl-al-Kitab may not meet halal standards. In addition, as discussed elsewhere in this chapter, dairy and pareve kosher products may contain alcohol (e.g., in flavors) and more lenient kosher supervision, as defined above, will permit products that contain animal-based ingredients that may also be unacceptable to the halal-observing consumer.

SCIENTIFIC CONTRIBUTIONS

Gelatin

Important in many food products, gelatin is probably the most controversial of all modern kosher and halal ingredients. Gelatin can be derived from pork skin, beef bones, or beef skin. In recent years, some gelatins from fish skins have also entered the market. As a food ingredient, fish gelatin has many similarities to beef and pork gelatin; it can have a similar range of bloom strengths and viscosities. *Bloom* is the number of grams of force needed to drive a specific probe, under very specific conditions, 4 mm into a gelatin gel. However, depending on the species from which the fish skins are obtained, its melting point can vary over a much wider range of melting points than beef or pork gelatin. This may offer some unique opportunities to the food industry, especially for ice cream, yogurt, dessert gels, confections, and imitation margarine. Fish gelatins can be produced as kosher and/or halal with proper supervision and would be acceptable to almost all of the mainstream religious supervision organizations. Most gelatins currently available, even if called kosher, are not acceptable to the mainstream U.S. kosher supervision organizations and to Islamic scholars. Many are, in fact, totally unacceptable to halal consumers because they may be pork-based gelatin.

A recent development from one plant has been the manufacture of kosher gelatin from the hides of kosher (glatt) slaughtered cattle. It has been available in limited supply at great expense, and this gelatin has been accepted by the

mainstream and even some of the stricter kosher supervision agencies. The plant produces gelatins of different bloom strength, and both soft and hard capsules of various sizes have been prepared from this gelatin. This is an important new development that should be of interest to the neutraceutical and drug markets. Vegetarian capsules are also available, made with starch, cellulose, or other vegetable ingredients. They are reported to be more difficult to work with. There are reports of efforts to prepare gelatin in a plant using biotechnology. This has been done successfully in the laboratory but has not yet been commercialized.

One finds a wide range of attitudes toward gelatin among the lenient kosher supervision agencies. The most liberal view holds that gelatin, being made from bones and skin, is not being made from a food (flesh). Further, the process used to make the product goes through a stage where the product is so "unfit" that it is not edible by man or dog, and as such becomes a new entity (D'var Hadash). Rabbis holding this view may accept pork gelatin. Most water gelatin desserts with a generic "K" on the package follow this ruling.

Other rabbis permit gelatin only from beef bones and hides. Still other rabbis accept only "India dry bones" as a source of beef gelatin. These bones, found naturally in India, are obtained from animals that fell and died in the fields (because of the Hindu custom of not killing cows), are aged for over a year, and are "dry as wood"; additional religious laws exist for permitting these materials. Again, *none* of these products is accepted in mainstream kosher or halal supervisions and are therefore not accepted by a significant part of the kosher and halal communities.

Biotechnology

Rabbis currently accept products made by simple genetic engineering; for example, chymosin (rennin) was accepted by rabbis about a half a year before it was accepted by the U.S. Food and Drug Administration. The basis for this decision involves the fact that a gene isolated from a nonkosher source is far below "visible." Following isolation it is copied many times in vitro and eventually injected into a host which is then reproduced many times. Thus, the original source of the gene is essentially totally lost by the time the food product appears. The production conditions in the fermenters (i.e., the ingredients as well as the fermenter) must still be kosher, and any subsequent processing must use kosher or halal equipment and ingredients of the appropriate status. A product produced in a dairy medium (e.g., extracted directly from cow's milk) would be dairy. Mainstream rabbis may approve porcine lipase made through biotechnology when it becomes available if all the other conditions are kosher. The rabbis have not yet determined the status of more complex genetic manipulations, so such a discussion would be premature.

PET FOOD

Jews who observe the kosher laws can feed their domestic animals pet food that contains pork or other prohibited meats but cannot feed their animals products

that contain a mixture of milk and meat. The meat component refers only to potentially kosher meats; that is, one cannot serve beef and milk, but one can serve an animal pork and milk. On Passover the pet food can contain kitnyos, but not chometz, as one cannot have chometz in one's home or possession.

HEALTH CONCERNS

As described above, many people believe that the kosher laws are considered to be among the laws that were given for people's benefit, but this is not the case. One of the few exceptions is the rule concerning the mixing of meat and fish, which was instituted rabbinically to avoid a problem with a particular fish which when eaten with meat made people sick. Because this is one of the few laws that are health laws, the Conservative movement recently saw fit to rule that it is no longer valid since modern scholars cannot identify the fish nor have any evidence currently of such a problem.

The most common "health" aspect of the kosher laws that is cited is the prevention of trichinosis in pork. This argument has three weaknesses. First, all flesh products can be a source of pathogens. The thorough cooking of flesh foods that is traditional in the Jewish community gives better pathogen control. There seems to be no religious law or custom (minhag) that mandates this practice. Second, the presence of trichinosis in mummified pork has not been demonstrated. Third, the incubation period for trichinosis (i.e., 10 to 14 days) makes it unlikely that the ancient Israelites would have figured out the correlation at that time.

REGULATORY CONSIDERATIONS

Kosher Supervisory Agencies

In practical terms, the food industry works with kosher supervisory agencies to obtain permission to use the agency's trademark symbol (or in a few cases the ethical right to use the generic K; see below) on their products. In this way, the industry can make claims in the marketplace that are legal and, more important, credible to those purchasing these products intentionally. This decision can provide a significant potential marketing opportunity. Kosher supervision is taken on by a company to expand its markets. It is a business investment that, like any other investment, must be examined critically in this era of total quality management, just-in-time production, strategic suppliers, and so on.

What criteria should a company use to select a supervisory agency? Supervision fees must be taken into account as well as the agency's name recognition. Other important considerations include (1) the responsiveness of the agency in handling paperwork, in providing mashgiachs at the plants as needed on a timely basis, and in doing routine inspections at a defined frequency during the year, anywhere from twice a year to every day (including continuous), depending on the

nature of the production; (2) the willingness to work with the company on problem solving; (3) the ability to clearly explain their kosher standards and their fee structure; and (4) if their religious standards meet the company's needs in the marketplace. Also, of course, one should be sure that the "personal" chemistry is right.

One of the most difficult issues for the food industry to deal with in day-to-day kosher activities is the existence of so many different kosher supervisory agencies. How does this affect food companies? How do Jewish kosher consumers perceive the various groups? Because there has not been a central ruling religious authority for many years, different rabbis follow different traditions with respect to their dietary standards. Some authorities tend to follow the more lenient standards, whereas others follow more stringent standards. The trend in the mainstream kosher community today is toward a more stringent standard, since some of the previous leniencies were considered less than ideal but were tolerated when fewer alternatives were available.

One can generally divide kosher supervisory agencies into three broad categories. First there are the large organizations that dominate the supervision of larger food companies: the OU (the Union of Orthodox Jewish Congregations, Manhattan), OK (Organized Kashrus Laboratories, Brooklyn), Star-K (Baltimore), Kof-K (Teaneck, New Jersey), and the CRC (the Chicago Rabbinal Council, all five of which are nationwide and "mainstream." The concept of a *normative mainstream U.S. kosher standard* was the outcome of surveys of kosher foods in the supermarket by a food science class on kosher and halal food regulations taught each year at Cornell University. Over 40% of the grocery products in the supermarket have a kosher certification, and almost all of these reflect the same normative U.S. standard. This de facto kosher standard in the United States is represented by the major national supervision agencies noted above. The only other kosher supervision agency found routinely in the marketplace is the Kosher Overseers (Half Moon K, Los Angeles), which is working its way toward mainstream status. Many of the smaller kosher supervisory agencies also use this standard. There are numerous trademarked kosher symbols; at last count, over 867 (*Kashrus* magazine, October 2006) are used around the world to identify the kosher supervisory agencies and, indirectly, their different, and sometimes controversial, standards of kosher supervision. Some are more lenient than the normative standard; others are stricter. The letter "K" cannot be trademarked; any person or company can put a K on a product for any reason. However, a number of the more lenient supervisions use it. A few normative mainstream products may also have the generic K (e.g., Pepsi, Kellogg). Symbol look-alikes sometimes occur both as kosher markings and as symbols used for other purposes (e.g., the circle-K of a convenience store chain).

Three of the major agencies, the OU, Star-K, and CRC, are communal organizations) (i.e., they are part of a larger community religious organization. This provides them with a wide base of support but also means that the organizations are potentially subject to other priorities and needs of the greater organization. On the other hand, Kof-K and OK are private companies, as is Half-Moon K. Their only function is to provide kosher supervision. Although they do not answer

directly to the community, like all kosher supervisory agencies, their reputation depends on community support.

In addition to these national agencies, there are smaller private organizations and many local community organizations that provide equivalent religious standards of supervision. As such, products accepted by any of the normative mainstream organizations will, with an occasional exception, be accepted by similar organizations. The local organizations may have a greater stake in the local community. They may be more accessible and easier to work with. Although often having less technical expertise, they may be backed up by one of the national organizations. For a company marketing nationally, a limitation may be whether consumers elsewhere in the United States and more recently around the world as we globalize know and recognize the local kosher symbol. With the advent of *Kashrus* magazine and its yearly review of symbols, this has become somewhat less of a problem. However, *Kashrus* does not try to evaluate the standards of the various kosher supervisory agencies, but simply reports their existence. It is the responsibility of the local congregational rabbi to inform the congregation of his or her standards. Local rabbis who do not know enough about the far-away organization may be uncomfortable recommending an agency without calling one of the national agencies for advice.

It is important to note that for local food processing (e.g., bakery, deli, restaurant, butcher shop), either continuous or fairly regular supervision is the norm, often with a local rabbi visiting almost every day. The symbols of the kosher supervisory agencies representing these local groups are not as widely recognized beyond these communities as those of the major mainstream agencies in the kosher world.

The second category of kosher supervision, more stringent than normative mainstream, includes individual rabbis generally associated with Hassidic communities. These groups are often affiliated with the ultra-Orthodox communities of Williamsburg and Borough Park in Brooklyn and Monsey and Monroe, New York, and Lakewood, New Jersey. There are special food brands that cater specifically to these needs (e.g., Hadar, Liebers). Many of the products used in these communities require continuous rabbinical supervision rather than the occasional supervision used by the mainstream organizations for production-line factory-produced products. Rabbis for the stricter agencies will often do special continuous supervisions of products using a facility that is normally under mainstream supervision—often without any changes, but sometimes with special requirements for their custom production.

The third level of supervision is composed mainly of individual rabbis who are more lenient than the mainstream standard. Many of these rabbis are Orthodox; some may be Conservative. Their standards are based on their interpretation of the kosher laws and related religious rulings. Employing a more lenient rabbi means that the food processor cuts out more of the mainstream customers and the stricter markets; this is a retail marketing decision that each company must make for itself. More lenient supervisions are sometimes the only ones that will certify a product with a special problem that causes other supervisions to reject

it. For example, since fish blocks, which are used for fish sticks and portions, are produced around the world, it is difficult to get proper on-site supervision to assure that all fillets in the block are really the species on the label. As a result, only a lenient rabbi will accept such blocks based on a rule of the majority and the assumption that governmental authorities are also monitoring this situation. Many consumers then make buy or no-buy decisions based on the specific supervision.

Some companies have used the generic "K", which cannot be trademarked and which is not trusted by many educated kosher consumers. They realize that the symbol is generally used by one of the more lenient supervisions. A few large national brands have used the generic "K" for many years, even though they have normative mainstream supervisions. Most kosher consumers are aware of these few companies, which although they do not seem to lose market share because of this decision, are still viewed suspiciously by some consumers.

In recent years we have begun to see products that have dual halal and kosher certification. The first were the military MREs (meals ready-to-eat), but the market has since expanded to other industrial (ingredients) and consumer products. Some civilian versions of MREs are available in long-term shelf-stable (nonrefrigerated) form, which makes them convenient for use (Jackson, 2000). Meat products are either glatt kosher or dhabiha halal; pareve and dairy products have the dual certification.

Ingredient companies should be particularly careful in selecting a supervisory agency. They should try to use a mainstream kosher or halal agency because most kosher or halal food manufacturing companies will require such supervision. The ability to sell the ingredients to as many customers as possible requires a broadly acceptable standard. Unless an ingredient is acceptable to the mainstream, it is almost impossible to gain the benefit of having a kosher ingredient for sale. Ingredient companies also need to pay attention to the status of the kosher product (i.e., a pareve product is preferred over a dairy product because it has broader potential use). A joint venture to make lactic acid from whey failed in part because the major users of kosher food-grade lactic acid, pickle and olive manufacturers, were all kosher-pareve; given that their products are often used at a meat meal, the use of a dairy lactic acid would have been counterproductive.

Food companies will have to pay increasing attention to halal standards. In many cases a few changes also make it possible to permit kosher products to serve the halal community, such as the true absence of animal products and care to assure that any residual alcohol in products is below 0.1%. Again, a supervisory standard acceptable in all or most Muslim countries is desirable. Note that the finished product standard of 0.1% alcohol is used by Islamic Food and Nutrition Council of America and seems to be acceptable to the leadership of most halal communities. However, many halal consumers are not familiar with this standard at this time, so further education will be necessary.

There is some amount of interchangeability of products between kosher supervisory agencies. A system of certification letters is used to provide information from the certifying rabbi concerning products he has approved. The supervising rabbi certifies that a particular facility produces kosher products, or that only

products with certain labels or codes are kosher under his supervision. To prevent fraud, it is helpful if the letters are renewed every year and carry both starting and ending dates. These letters are the mainstay of how food companies and other kosher supervisory agencies establish the kosher status of ingredients as they move through commerce. Consumers may also ask to see such letters. Obviously, an agency will only accept letters they find to be accurate. That decision depends on two components: the actual kosher standards of the other agency, and an assessment of how well they operate and enforce their supervision (i.e., both theory and practice have to be appropriate).

There are, of course, periodic recalls of specific products for various kosher defects that would prevent their use. *Kashrus* magazine and the Web sites www.kashrusmagazine.com, and www.kashrut.com try to provide up-to-date listings of problems in both consumer items and industrial ingredients working across many different kosher supervisory agencies. Most major agencies have their own sites, and some even offer e-mail announcements of any kosher problems.

The kosher symbol of the certifying agency or person doing the certification may appear on the packaging. In some industrial situations, where kosher and nonkosher products are similar, some sort of color coding of product labels and packages may also be used. Most of these symbols are trademarks; they are duly registered, and misuse of the symbol can result in secular legal action. In a few cases, multiple rabbis have used the same kosher symbol, causing consumer confusion. (Unfortunately, the trademark owner is not always willing to pursue secular or religious legal action. There are functioning religious courts in most countries for matters arising within the Jewish community even though their enforcement powers are obviously limited in the absence of secular enforcement.)

Three additional notes about kosher markings on products are important:

1. To ensure that labels are marked properly, it is the responsibility of the food company to show its labels to its certifying agency prior to printing. This responsibility includes both the agency symbol and the documentation establishing its kosher status (e.g., dairy or pareve). It is the responsibility of the kosher supervisory agency to review these labels carefully. Many agencies currently do not require that "pareve" be marked on products; others do not use the "dairy" marking. This causes consumer confusion, which could be avoided if every kosher product had its status marked. In addition to providing the proper information, having each product marked with its status would challenge everyone to pay more attention to the proper marking of products, avoiding recalls or announcements of mislabeled products. The letter "P" or "p" has been used for both Passover and pareve. We suggest using the letter "N" for pareve (for "neutral"), consistent with the "D" for dairy and the "M" for meat.

2. The labels for private-label products with specific agency symbols on them should not be moved between plants and cannot be used if supervision changes. This is why some companies, both private label and branded, use the generic

"K." Thus, if the kosher supervision agency changes, the label can still be used. The sophisticated kosher consumer, however, is more and more uncomfortable with this symbol. A major concern is that the labels may be moved too easily between plants, including plants that are not kosher. The Kashrus Council of Toronto (COR) requires that each label include a plant number. This prevents the movement of labels between plants, even of the same company. Currently, they are the only agency that requires this additional safeguard, although Kof-K appears to be introducing this requirement. In particular, if a company uses the generic "K," the customer service and sales departments of the company, and people representing the company at trade shows, need to know the identity of the certifying rabbi. But it is always a good idea for all sales and marketing staff to be comfortable providing information about the kosher and halal status of their products.

Federal and State Regulations

Making a claim of kosher on a product was a legal claim in the United States until fairly recently. The *Code of Federal Regulations* (21CFR101.29) used to have a paragraph indicating that such a claim must be appropriate, but this clause was removed a few years ago. Approximately 20 states, some U.S. counties, and some cities have laws specifically regulating the claim of "kosher." Many of these laws refer to "orthodox Hebrew practice" or some variant of this term (e.g., reference to specific Jewish documents), and their legality is subject to further court interpretation.

New York state probably has the most extensive set of state kosher laws. These laws, however, were recently declared unconstitutional by the Federal District Court for Eastern New York. The verdict was upheld by the Federal Court of Appeals for the Second District. The appeal to the entire Second District for "en banc" review was denied. Subsequently, the Supreme Court of the United States refused to hear an appeal, so the state of New York has developed a new law that will be constitutional. The original law includes a requirement to register kosher products with the Kosher Enforcement Bureau of the Department of Agriculture and Markets in Brooklyn and this has been retained in the new law, which is modeled on the New Jersey law.

The state of New Jersey also has relatively new kosher laws because the state's original kosher laws were declared unconstitutional by the New Jersey State Supreme Court. It was the same problem as in New York (i.e., requiring an "Orthodox" standard). The new laws focus specifically on consumer right to know issues and truth in labeling. They avoid having the state of New Jersey define "kosher." Rather, the food producer defines its terms and is held to that standard. Rabbis (or anyone else) providing supervision are asked to declare the information that consumers need to know to make an informed decision. The state will enforce the accuracy of the statements (i.e., if the rabbi and the company claim to do something, failure to do so is a violation). But it puts more onus on the buyer to be sure that the product meets his or her standard.

ANIMAL WELFARE

The largest fast-food chains in the United States are seeking to develop a set of animal welfare standards that determine the purchase of products they use in the United States and in many other markets. (Appendix 2 has a more detailed discussion of this project.) As it became clear that it was not ideal to have each supermarket chain and each chain restaurant come up with its own standards, the Food Marketing Institute (FMI; the trade association for many of the supermarkets in North America) and the National Council of Chain Restaurants (NCCR) appointed an animal welfare technical committee to come up with a single national animal welfare standard for each species as well as for animal and poultry slaughter. It is anticipated that these standards will be based predominantly on the animal welfare guidelines developed by the trade associations of the major production agriculture groups and of the American Meat Institute, representing the meat-processing industry. However, the FMI/NCCR effort has in some instances required the trade associations to strengthen their guidelines. The establishment of these standards in the marketplace will have a major impact on animal agriculture throughout the United States and eventually around the world. These standards generally raise the bar for animal welfare in the United States but are less aggressive than those currently being applied in Europe. The committee is trying to create conditions for significant improvement in how all animals are raised and slaughtered. Initially, the effort has focused on each of the trade associations associated with the major animals of production agriculture (beef, dairy, chicken, turkey, egg layers, and pigs), and with the slaughter process for these animals. The religious aspects are only a very small component of that effort. Many other issues are being negotiated. For instance, the egg-laying industry is committed to major increases in space per bird, currently suggesting a reduction of approximately 15% of installed capacity nationwide, with the changes in this case to be phased in over a 10-year period. Once work is completed on these large-volume commodities, the FMI/NCCR committee is likely to review standards for other animals, including sheep and goats, fish and shellfish (both wild caught and aquacultured), farmed game animals and game birds, ducks, honeybees, and rattries (ostrich, emu, rhea, etc.).

Animal welfare issues that arise in religious slaughter are incorporated in the FMI/NCCR committee work. A discussion of issues appears in an article by Regenstein and Grandin (2002) along with recommendations for auditable standards that will be used by the FMI/NCCR auditors. These standards are consistent with the American Meat Institute requirements. Religious slaughter should ideally be done with the animals in an upright position (for mammals), although the need to use an upside-down pen when required religiously is recognized. The standard shackling line is also permitted for poultry religious slaughter; that is, animals can be shackled prior to slaughter, although most kosher slaughter is done with the animals being held by the slaughterman or his helper. The animals are then put on the shackles or on a bleeding cone. For more information, see the FMI Web site (www.fmi.org).

Acknowledgments

We thank Muhammad Chaudry of the Islamic Food and Nutrition Council of America for his extensive input into this paper, especially for the sections dealing with Muslim issues. We thank Cornell University students Catherine E. Savage, Peng Zhou, and Andrew Rosenberg for assistance with the abstract, and Shawkat Toorawa of Cornell University's Near Eastern Studies Department for critical comments.

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APPENDIX 1: STANDARDS SUGGESTED FOR KOSHER/HALAL SLAUGHTER OF POULTRY*

As kosher slaughter from an animal welfare point of view focuses on the actual time of slaughter, all other activities related to poultry (chicken and turkey) welfare need to be in accordance with the applicable American Humane Association standards.

Handling and Caging With live bird slaughter, the birds are generally removed from the crates just prior to slaughter rather than being hung up on a rail, which permits time for the birds to calm down. These birds must be slaughtered immediately. Attention to the details of removing them from the crates is extremely important. The opening should be such that a worker can easily remove the bird by two legs even if the wings are flapping. An alternative is to grasp the bird properly so that both wings are held comfortably. It is recommended that this be done in a low-light area, possibly with a red light so that the birds are calm prior to removal from the cages. Noise must also be kept to a minimum to prevent disturbing the birds unnecessarily.

For turkeys, some facilities walk turkeys up to the point of slaughter. That is acceptable; catching and handling of the birds must follow the procedures recommended above.

Restraint for Slaughter Once a bird is removed, it should be brought to an upright position and supported under the keel (breast) by the person holding the bird. The wings must be held gently against the body, and the bird must be sitting comfortably in the holder's hand. The bird must be held that way throughout the process until slaughtered. This is for both chickens and turkeys.

Slaughter The slaughter knife for kosher (the chalef) has been designed specifically for that purpose.

- The knife must be twice the neck size of the bird.
- The knife must be very sharp.

*Prepared initially by Adele Douglass, Executive Director of Humane Farm Animal Care.

- The sharpness of the knife must be checked both before and after a series of slaughters.
- No more than eight birds are to be slaughtered at one time without a knife check.

The personnel doing the slaughtering and checking must be rabbinically certified and should provide a rabbinical certificate attesting to their skill. (If the rabbinical certificate is in Hebrew and not in English, an independent rabbinical verification should be sought.)

Halal For halal or other slaughtering of a live bird, a similar procedure is used. A knife similar to a chalef is used and the animal is cut so as to cut all blood vessels and the windpipe, but not the vertebrae. The only limitation of the current knife is that it was designed to kill a few animals at one time, not to be used all day. An ergometric knife (i.e., one whose handle is designed to be comfortable to hold) must be designed that would meet all rabbinical requirements.

Slaughter Speed The pace of the slaughter, even with each shochet (religious slaughterman) having the necessary helpers, should not exceed eight birds per minute. The job of slaughtering birds is tiring. Therefore:

- No shochet slaughters for more than an hour at a time without having an hour off. A maximum of 5 h of slaughter a day is considered acceptable.
- The off time can be used to do knife sharpening and checking.

For nonreligious slaughter, a limit of 5 h per day of slaughter with no more than 1 h at a time and a minimum of a half-hour break is required. In a well-run operation, the number of birds rejected because of shochet failure should be very small, less than 1% of the daily kill.

Post-slaughter Once a bird has been slaughtered, it is hung up on the rail to bleed or put into a bleeding cone. Birds must be completely dead before further processing, including not being put into the first water bath.. The time lapse must be at least 90 s.

APPENDIX 2: ANIMAL WELFARE REPORT*

Kosher Slaughter: An Update on the Supermarket/Chain Restaurant Program in the United States and the Farm Animal Welfare Committee of the United

*Prepared by Joe M. Regenstein, professor of food science and head of the Cornell Kosher Food Initiative, Cornell University, Ithaca, New York, based on the Religious Slaughter Report of 2002 of the Animal Welfare Committee of the Food Marketing Institute and National Council of Chain Restaurants, prepared by the author with the assistance of Temple Grandin, associate professor of animal science, Colorado State University, Fort Collins, Colorado.

Kingdom's Attack on Shechitah Animal welfare issues are back in the news. McDonald's recently announced a reduction in antibiotic use worldwide as a follow-up to its earlier efforts on establishing auditable animal welfare standards. Kentucky Fried Chicken announced that it would be following the new animal welfare guidelines being developed by a committee created and supported by the Food Marketing Institute (FMI; a trade association for supermarkets) and the National Council of Chain Restaurants (NCCR). New Jersey has major legislation pending on minimal animal welfare standards. The U.S. Senate and House are both considering a bill on downed animals (i.e., animals that cannot walk by themselves) on farms and related facilities. The U.S. Department of Agriculture has issued a memorandum of instruction to inspectors concerning humane handling of animals at slaughter.

How does this relate to Kashrus? Judaism clearly teaches the importance of respecting animals and treating them properly. Animal welfare and *Tsar Baalay Chayim* (avoiding harming animals) both accept the need to use animals for the benefit of people as long as the process is done with respect and consideration for the animal. Our goal is to inform readers of procedures used in the humane treatment of animals during kosher slaughter.

Animal welfare is not the same as *animal rights*. Many advocates of animal rights seek to change the status of animals in our society. They may desire to discontinue animal agriculture and other uses of animals, including their role as companion animals. Other humane societies may have a more limited agenda. Temple Grandin is one of the few experts on animal welfare, particularly religious slaughter, who has translated research information into practical applications, including significant improvements in religious slaughter consistent with religious requirements. She has designed and built most of the truly modern humane handling systems for all types of animals for many different slaughter systems. She is on almost every American-based animal welfare committee, including those of McDonald's, Burger King, and Kentucky Fried Chicken. Like the senior author of this paper, she is on the FMI/NCCR animal welfare committee (see www.fmi.org, topic: Animal Welfare). Grandin begins:

> Recently, I participated in a ritual kosher slaughter—in this ritual, the way it was meant to be done, I must say. This was at a plant where the management really understood the importance and significance of what they were doing, and communicated this to their employees—and to the animals as well, I believe. As each steer entered the kosher restraining box, I manipulated the controls to gently position the animal. After some practice, I learned that the animals would stand quietly and not resist being restrained if I eased the chin-life up under the animal's chin. Jerking the controls or causing the apparatus to make sudden movements made the cattle jump. … Some cattle were held so loosely by the head-holder and the rear pusher gate that they could easily have pulled away from the rabbi's knife. I was relieved and surprised to discover that the animals don't even feel the super-sharp blade as it touches their skin. They made no attempt to pull away. I felt peaceful and calm. (Regenstein and Grandin, 1992)

Notice how positive she is about kosher slaughter when it is done properly. The behavior of the animal suggests that death occurs without pain and suffering. In fact, there are various forms of anecdotal evidence that support the idea that opiate-type compounds called *endorphins* are released when an *Unstressed* animal is cut with a very sharp knife. These compounds cause the animal to die on a "drug high." That the animal dies comfortably is exactly the goal of kosher slaughter.

All of the preliminary steps to slaughter must be optimized to ensure that animals will be unstressed at the time of slaughter. Can this really be done? Grandin's testimonial suggests that it certainly can. Can it be done commercially? Definitely. Various systems and equipment are available. Some are actually quite simple and low cost; others can be designed to meet the most demanding high-speed production requirements. Is kosher slaughter being done using these systems? Definitely. Both glatt (smooth lungs, a more critical postmortem examination of the animal) and nonglatt operations that are commercially successful utilicize Grandin's methods in an integrated fashion to provide kosher meat that meets the highest animal welfare and kosher standards.

Not all kosher slaughter in the United States meets this standard. Companies must be motivated to invest in retrofitting equipment or buying new equipment. The kosher-observant community must care about how meat is slaughtered and convey this message to those involved in supplying kosher meat. What about kosher meat from other countries? The animal welfare standards are often lower (sometimes significantly so) than they are in the United States.

The U.S. Congress has declared religious slaughter, specifically kosher slaughter, humane. Congress exempted preslaughter handling of animals from the requirements of humane handling. The FMI/NCCR committee is working to provide information and standards that would help meat producers ensure humane slaughter. This committee is exploring significant improvements in how all food animals are raised and slaughtered. The initial effort has focused on each of the trade associations associated with the major animals of production agriculture (beef, dairy, chicken, turkey, egg layers, and pigs). In each case a dialogue has been initiated about each of these trade association's animal welfare standards. In many cases, without an independent audit, the organizations are adopting more stringent guidelines to achieve higher standards of animal welfare, despite increased costs. For example, the egg-laying industry is committed to phasing in major increases in the space allotted to each bird in cages. If the egg-layer standards were fully implemented instantly, it would probably represent a reduction of over 15% of our installed capacity nationwide!

As part of this process, the FMI/NCCR Animal Welfare Committee has adopted the guidelines developed by Grandin (1991a, 1997, 2002) for the American Meat Institute (AMI; a trade association for the slaughter and processing of meat). For over 10 years, the AMI slaughter standards have called for upright religious slaughter of animals, using one of the many restraining devices available for this purpose. For some groups within the Jewish community, upright slaughter may be unacceptable. It appears that sideways

(rather than upside-down) slaughter would meet their more stringent religious requirements. Humane equipment to meet this requirement can probably be built, although it will obviously be more expensive.

In all cases, all of the requirement of the slaughter that are not related directly to meeting the religious requirements can and should meet modern animal welfare requirements. In most cases, the religious requirements can be met completely by adopting equipment and handling procedures that also assure the highest level of modern animal welfare. The newer FMI/NCCR standards may be required as purchasing specifications by meat buyers for supermarkets and fast-food chains. Although they do not impose any regulatory-based requirements on kosher slaughter, we recommend voluntary compliance with these scientifically defensible kosher slaughter standards. We recognize that compliance with the FMI/NCCR recommendations would have a tremendous impact on the U.S. kosher meat supply. Below we have adopted portions of the FMI/NCCR report to offer readers basic information for their consideration of the critical issues of humane kosher slaughter.

I. Slaughter Pen Issues

"Recommended Ritual Slaughter Practices (Kosher and Halal) For both humane and safety reasons, plants which conduct ritual slaughter should install modern upright restraining equipment. The practice of hanging live cattle, calves, or sheep upside down should be eliminated. There are many different types of humane restraint devices available." (*AMI Meat Packer Guide*)

Handling systems that turn the animal upside down (although the most modern versions, properly operated, may be marginally acceptable if the rest of the animal handling is well done) and/or hang the animal by its legs are considered unacceptable. However, sideways slaughter in a modern restraining device may be acceptable if it is required to meet religious requirements. The cut should always be performed within 10 s after the animal is tilted sideways.

Examples of acceptable systems include:

"The ASPCA Pen This device consists of a narrow stall with an opening in the front for the animal's head. After the animal enters the box, it is nudged forward with a pusher gate and a belly lift comes up under the brisket. The head is restrained and lifted to the right tension level as determined by the religious authorities by a chin lift so that it is ready for the [shochet] prior to performing shehita.... Vertical travel of the belly lift should be restricted to 71 cm (28 inches) so that it does not lift the animal off the floor. (If lifting the animal off the ground is required for religious reasons, the belly lift should be modified, possibly by putting a double rail in place, so that the animal is comfortable off the ground with its body fully supported. The head restrainer will also probably need to be adjusted. An alternative is to life the whole pen or to tilt the entire pen so it is off the ground, although the animal's legs in this case would be on the pen floor.) The rear pusher gate should be equipped with either a separate pressure

regulator or special pilot-operated check values to allow the operator to control the amount of pressure exerted on the animal. The pen should be operated from the rear toward the front. Restraining of the head is the last step. The operator should avoid sudden jerking of the controls. Many cattle will stand still if the box is slowly closed up around them and less pressure will be required to hold them. Ritual slaughter should be performed immediately after the head is restrained." (*AMI Meat Packer Guide*) If animals are too large for the pen, the pen size may need to be adjusted. At the very least the rear pusher gate should probably not be used.

"This pen has a maximum capacity of 100 cattle per hour and it works best at 75 hear per hour. A small version of this pen could be easily built for calf plants." (*AMI Meat Packer Guide*)

"Conveyor Restrainer System Either a V restrainer or a center track conveyor restrainer can be used for holding cattle, sheep, or calves in an upright position during shechita. Conveyor systems must completely support the animal's body in a comfortable upright position. The restrainer is stopped for each animal and a head holder holds the head for the ritual slaughter man. Research in Holland indicates that the center track design provides the advantage of reducing bloodspots in the meat. In this case the animal's feet are off the ground.

"For cattle, a head holder similar to the front of the ASPCA pen can be used on the center track conveyor restrainer. A bi-parting chin life is attached to two horizontal sliding doors." (*AMI Meat Packer Guide*)

"Small Restrainer Systems For small locker plants which ritually slaughter a few calves or sheep per week, an inexpensive restrainer constructed, for example, from pipe, can be used to hold the animal in a manner similar to the center track restrainer. Animals must be allowed to bleed out and become completely insensible before any other slaughter procedure is performed." (We have a quote from a builder that the more recent version, developed by the authors, can be built for under $700.)

For medium-sized plants, including those in other countries, Grandin assures us that she can build an upright kosher pen at a reasonable cost that can be assembled and installed in a plant on a weekend and can be disassembled and removed on a weekend so that the plant is ready to go on Monday morning without any lost time for the transition to or from animal welfare appropriate kosher slaughter. She also believes that a side slaughter pen can be built to meet these practical specifications. However, this will definitely be a more expensive piece of equipment and may not be usable in all plants overseas, because this type of pen requires more space.

The Shochet and His Uniqueness "... In the case of the Jewish dietary laws, a specially trained person of known religiosity carries out the slaughter. This person, the 'shochet,' is specifically trained for this purpose. He is trained to use a special knife, called the 'chalef,' to rapidly cut the jugular vein and the

carotid artery without burrowing, tearing, or ripping the animal. The knife is checked regularly for any imperfections [that] would invalidate the slaughter. This process when done properly leads to a rapid death of the animal. A sharp cut is also known to be less painful." (Grandin and Regenstein, 1994)

Given the importance of religious slaughter . . . , it is important that scientists be absolutely objective when evaluating these practices from an animal welfare standpoint. There are three basic issues. They are stressfulness of restraint methods, pain perception during the incision, and latency of onset of complete insensibility.

Restraint A key intellectual consideration is separation of the variable of restraint stress from the animal's reaction to the slaughter procedure. Stressful or painful methods of restraint mask the animal's reactions to the throat cut. In North America some kosher slaughter plants use very stressful methods of restraint, such as shackling and hoisting fully conscious cattle by one rear leg.

"Observations of [Grandin] indicate that cattle restrained in this manner often struggle and bellow, and the rear leg is often bruised. . . . In Europe, the use of casting pens which invert cattle onto their backs completely mask reactions to the throat cut. Cattle resist inversion and twist their necks in an attempt to right their heads. Earlier versions of the Weinberg casting pen are more stressful than an upright restraint device (Dunn, 1990). An improved casting pen, called the Facomia pen, is probably less stressful than older Weinberg's pens, but a well-designed upright restraint system would be more comfortable for cattle. An even newer casting pen has been built in Ireland recently and is recommended for anyone doing a sideways cut. Another problem with all types of casting pens is that both cattle and calves will aspirate blood after the incision. This does not occur when the animal is held in an upright position.

"Unfortunately, some poorly designed upright American Society for the Prevention of Cruelty to Animals (ASPCA) restraint boxes apply excessive pressure to the thoracic and neck areas of cattle. In the interest of animal welfare, the use of any stressful method of restraint should be eliminated. A properly designed and operated upright restraint system will cause minimum stress. Poorly designed systems can cause great stress. Many stress problems are caused by rough handling and by excessive use of electric prods. The very best mechanical systems will cause distress if operated by abusive, uncaring people.

"In Europe there has been much concern about the stressfulness of restraint devices used for both conventional slaughter (where the bovid is stunned) and ritual slaughter. Ewbank et al. (1992) found that cattle restrained in a poorly designed head holder, i.e., where over 30 s was required to drive the animal into the holder, had higher cortisol [a measure of stress] levels than cattle stunned with their heads free. Cattle will voluntarily place their heads in a well-designed head restraint device that is properly operated by a trained operator (Grandin, 1992). Tume and Shaw (1992) reported very low cortisol levels of only 15 ng/mL in cattle during stunning and slaughter. Their measurements were made in cattle held in a head restraint (personal communication, Shaw, 1993). Cortisol levels

during on-farm restraint of extensively reared cattle range from 25 to 63 ng/mL (Mitchell et al., 1988; Zavy et al., 1992). Thus, some of the treatments given to animals on the farm were more stressful than the slaughter!

"... For ritual slaughter [or captive bolt stunning] devices to restrain the body are strongly recommended. Animals remain calmer in head restraint devices when the body is also restrained. Stunning or slaughter must occur within 10 s after the head is restrained." (Grandin and Regenstein, 1994)

Reactions to the Throat Cut "The variable of reactions to the incision must be separated from the variable of the time required for the animal to become completely insensible. Recordings of EEG or evoked potentials measure the time required for the animal to lose consciousness. They are not measures of pain. Careful observations of the animal's behavioral reactions to the cut are one of the best ways to determine if cutting the throat without prior stunning is painful. The time required for the animals to become unconscious will be discussed later.

"Observations of over 3000 cattle and formula-fed veal calves were made by [Grandin] in three different U.S. kosher slaughter plants. The plants had state of the art upright restraint systems. The systems have been described in detail by Dr. Grandin (1988, 1991b, 1992, 1993, 1994. The cattle were held in either a modified ASPCA pen or a double rail (center track) conveyor restrainer.

"This equipment was operated by [Grandin] or a person under her direct supervision. Very little pressure was applied to the animals by the rear pusher gate in the ASPCA pen. Head holders were equipped with pressure limiting devices. The animals were handled gently and calmly. It is impossible to observe reactions to the incision in an agitated or excited animal. Blood on the equipment did not appear to upset the cattle. They voluntarily entered the box when the rear gate was opened. Some cattle licked the blood.

"In all three restraint systems, the animals had little or no reaction to the throat cut. There was a slight flinch when the blade first touched the throat. This flinch was much less vigorous than an animal's reaction to an ear-tag punch. There was no further reaction as the cut proceeded. Both carotids were severed in all animals. Some animals in the modified ASPCA pen were held so loosely by the head holder and the rear pusher gate that they could have easily pulled away from the knife.

"These animals made no attempt to pull away. In all three slaughter plants there was almost no visible reaction of the animal's body or legs during the throat cut. Body and leg movements can be easily observed in the double rail restrainer because it lacks a pusher gate and very little pressure is applied to the body. Body reactions during the throat cut were much fewer than the body reactions and squirming that occurred during testing of various chin lifts and forehead hold-down brackets. Testing of a new chin lift required deep, prolonged invasion of the animal's flight zone by a person. Penetration of the flight zone of an extensively raised animal by people will cause the animal to attempt to move away (Grandin, 1993). The throat cut caused a much smaller reaction than penetration of the flight zone. It appears that the animal is not aware that its throat has been cut. Bager

et al. (1992) reported a similar observation with calves. Further observations of 20 Holstein, Angus, and Charolais bulls indicated that they did not react to the cut. The bulls were held in a comfortable head restraint with all body restraints released. They stood still during the cut and did not resist head restraint. After the cut the chin lift was lowered, the animal either immediately collapsed or it looked around like a normal alert animal. Within 5 to 60 seconds, the animals went into a hypoxic spasm and sensibility appeared to be lost. Calm animals had almost no spasms and excited cattle had very vigorous spasms. Calm cattle collapsed more quickly and appeared to have a more rapid onset of insensibility. Munk et al. (1976) reported similar observations with respect to the onset of spasms. The spasms were similar to the hypoxic spasms [that] occur when cattle become unconscious in a V-shaped stanchion due to pressure on the lower neck. Observations in feed-yards by [Grandin] during handling for routine husbandry procedures indicated that pressure on the carotid arteries and surrounding areas of the neck can kill cattle within 30 seconds." (Grandin and Regenstein, 1994)

"The details spelled out in Jewish law concerning the design of the knife and the cutting method appear to be important in preventing the animal from reacting to the cut. The knife must be razor sharp and free of nicks. It is shaped like a straight razor and the blade length must be twice the width of the animal's neck. The cut must be made continuously without hesitation or delay. It is also prohibited for the incision to close back over the knife during the cut. This is called "covering" (Epstein, 1948). The prohibition against covering appears to be important in reducing the animal's reaction to the cut. Ritual slaughtermen must be trained in knife sharpening. Shochets have been observed using a dull knife. They carefully obeyed the religious requirements of having a smooth, nick-free knife, but they had failed to keep it sharp.

"Further observations of kosher slaughter conducted in a poorly designed holder, i.e., one which allowed the incision to close back over the knife during the cut, resulted in vigorous reactions from the cattle during the cut. The animals kicked violently, twisted sideways, and shook the restraining device. Cattle that entered the poorly designed head holder in an already excited, agitated state had a more vigorous reaction to the throat cut than calm animals. These observations indicated that head holding devices must be designed so that the incision is held open during and immediately after the cut. Occasionally, a very wild, agitated animal went into a spasm [that] resembled an epileptic seizure immediately after the cut. This almost never occurred in calm cattle."

Time to Loss of Consciousness "Scientific researchers agree that sheep lose consciousness within 2 to l5 seconds after both carotid arteries are cut (Nangeroni and Kennett, 1963; Blackmore, 1984; Gregory and Wotton, 1984). However, studies with cattle and calves indicate that most animals lose consciousness rapidly; however, some animals may have a period of prolonged sensibility (Blackmore 1984; Daly et al., 1988) that lasts for over a minute. Other studies with bovids also indicate that the time required for them to become unconscious is more variable than for sheep and goats (Munk et al., 1976; Gregory and Wotten 1984).

The differences between cattle and sheep can be explained by differences in the anatomy of their blood vessels.

"Observations [by Grandin] of both calf and cattle slaughter indicate that problems with prolonged consciousness can be corrected. When a shochet uses a rapid cutting stroke, 95% of the calves collapse almost immediately (Grandin, 1987). When a slower, less decisive stroke was used, there was an increased incidence of prolonged sensibility. Approximately 30% of the calves cut with a slow knife stroke had a righting reflex and retained the ability to walk for up to 30 seconds.

"Gregory (1988) provided a possible explanation for the delayed onset of unconsciousness. A slow knife stroke may be more likely to stretch the arteries and induce occlusion. Rapid loss of consciousness will occur more readily if the cut is made as close to the jawbone as religious law will permit, and the head holder is loosened immediately after the cut. The chin lift should remain up. Excessive pressure applied to the chest by the rear pusher gate will slow bleed out. Gentle operation of the restrainer is essential. Observations indicate that calm cattle lose consciousness more rapidly and they are less likely to have contracted occluded blood vessels. Calm cattle will usually collapse within 10 to 15 seconds. Dr. Grandin recently scored time to insensibility (drop to the ground) in a glatt (a higher standard for kosher meat based on lung inspection) kosher plant in North America and found that 34/36 cattle were insensible in less than 10 seconds!"

Upright Restraint Equipment Design "Good upright restraint equipment is available for low stress, comfortable restraint of sheep, calves, and cattle (Giger et al., 1977; Westervelt et al., 1976; Grandin, 1988, 1991b, 1992, 1993). To maintain a high standard of animal welfare, a trained operator under close supervision of plant management must operate the equipment. Handlers in the lairage and race areas must handle animals gently and induce each animal to calmly enter the restrainer. Unfortunately, some very poorly designed restraint systems have recently been installed in Europe. The designers had little regard for animal comfort. Below is a list of specific recommendations."

All restraint devices must use the concept of optimal pressure.

1. The device must hold the animal firmly enough to provide a "feeling of restraint" but excessive pressure that would cause discomfort should be avoided. Many people operating pens make the mistake of squeezing an animal harder if it struggles. Struggling is often a sign of excessive pressure.

2. To prevent excessive bending of the neck, the bovine's forehead should be parallel to the floor. This positions the throat properly for ritual slaughter and stretches the neck skin, minimizing discomfort. There is an optimal tightness for the neck skin. If it is too loose, cutting is more difficult. If it is too tight, the Jewish rule [that] prohibits tearing may be violated, as the incision would have a tendency to tear before being cut by the knife. This also would be likely to cause pain. Some head restraints cause great distress to the cattle due to excessive

bending of the neck in an attempt to obtain extreme throat skin tightness. This is not necessary for compliance with religious law. One must remember that 4000 years ago hydraulic devices that could achieve such extremes of throat tightness were not available.

3. All head holders must be equipped with pressure-limiting devices. Pressure-limiting valves will automatically prevent a careless operator from applying excessive pressure. A 15-cm-wide forehead bracket covered with rubber belting will distribute pressure uniformly and the animal will be less likely to resist head restraint. The forehead bracket should also be equipped with an 8-cm-diameter pipe that fits behind the poll. This device makes it possible to hold the head securely with very little pressure.

4. The rear pusher gate of the ASPCA pen must be equipped with a pressure-limiting device. The animal must not be pushed too far forward in the head holder. The pressure must be regulated so that the animal stands on the floor with its back level. Arching of the back is a sign of excessive pressure. A calm relaxed animal will stand quietly in the pen and will not attempt to move its head. If the animal struggles, this is due to excessive pressure or being thrown off balance by the pusher gate.

5. The animal must not be lifted off the floor by the belly lift of an ASPCA pen because it does not fully support the body. Lifting devices that fully support the body in a comfortable upright position are permitted (e.g., the double rail adapter discussed earlier). In an ASPCA pen, the belly lift as designed is for restraint, not lifting. Lift travel should be restricted to 71 cm from the floor to the top of the lift. Other restrainers, such as the double-rail system, are designed to give full support under the belly. The conveyor slats must be shaped to fit the contours of the animal's sternum in systems where an animal straddles a conveyor.

6. All parts of the equipment should always move with a slow steady motion. Jerky motions or sudden bumping of the animal with the apparatus excites and agitates them. **Installing flow control valves or other control devices can eliminate jerky motion**. These valves automatically provide a smooth steady motion even if the operator jerks the controls.

7. All restraint devices must use the concept of optimal (not maximum) pressure. Sufficient pressure must be applied to give the animal a feeling of being held, but excessive pressure that causes struggling must be avoided. Animals will often stop struggling when excessive pressure is slowly reduced.

8. All equipment must be engineered to reduce noise. Air hissing and clanging metal noises cause visible agitation in cattle. Air exhausts must be muffled or piped outside. Plastic guides in the sliding doortracks will reduce noise further.

9. A solid barrier should be installed around the animal's head to prevent it from seeing people and other distractions in its flight zone. This is especially important for extensively reared cattle, particularly when they are not completely

tame. On conveyor systems the barrier is often not required because the animals feel more secure because they are touching each other.

10. Restraint equipment must be illuminated to encourage animals to enter. Lighting mistakes or air blowing back at the animals will cause cattle to balk (Grandin, 1993). **Distractions that cause balking must be eliminated**.

Some rabbinical authorities prefer inverted restraint and cutting downward because they are concerned that an upward cut may violate the Jewish rule that forbids excessive pressure on the knife. There is concern that the animal may tend to push downward on the knife during an upward cut. Observations indicate that just the opposite happens. [Italics added.] When large 800- to 950-kg bulls are held in a pneumatically powered head restraint, they can move easily. The animals pull their heads upward away from the knife during a miscut. This would reduce pressure on the blade. When the cut is done correctly, the bulls stood still and did not move the head restraint. Equal amounts of pressure were applied by the forehead bracket and the chin lift.

Upright restraint may provide the additional advantage of improved bleed-out because the animal remains calmer and more relaxed. Observations indicate that a relaxed, calm animal has improved bleed-out and a rapid onset of unconsciousness. Excited animals are more likely to have a slower bleed-out. The use of a comfortable upright restraint device would be advantageous from a religious standpoint because rapid bleedout and maximum loss of blood obeys the biblical principle ….

Rapid bleed-out and a reduction in convulsions provide the added advantage of reducing petechial hemorrhages [blood splash] and improving safety. Convulsing animals are more likely to injure plant employees. A calm, quiet animal held in a comfortable restraint device will meet a higher animal welfare standard and will have a lower incidence of petechial haemorrhages.

Restraint devices are used for holding animals both for ritual slaughter and for conventional slaughter where animals are stunned. The use of a head restraint will improve the accuracy of captive bolt stunning. In large beef slaughter plants without head restraint captive bolt stunning has a failure rate of 3 to 5%, i.e., a second shot is required. With such a high failure rate, many of the conventional methods can be quite inhumane to those animals that are not done successfully on the first try!

Captive bolt and electric stunning will induce instantaneous insensibility when they are properly applied. However, improper application can result in significant stress. All stunning methods trigger a massive secretion of epinephrine (Van der Wal, 1978; Warrington, 1974). This outpouring of epinephrine is greater than the secretion that would be triggered by an environmental stressor or a restraint method. Since the animal is expected to be unconscious, it does not feel the stress. **One can definitely conclude that improperly applied stunning methods would be much more stressful than kosher slaughter with the long straight razor-sharp knife**. [Bold added.] Kilgour (1978), one of the pioneers in animal welfare research, came to a similar conclusion on stunning and slaughter.

In some ritual slaughter plants animal welfare is compromised when animals are pulled out of the restraint box before they have lost sensibility. Observations clearly indicated that disturbance of the incision or allowing the cut edges to touch caused the animal to react strongly. Dragging the cut incision of a sensible animal against the bottom of the head-opening device is likely to cause pain. Animals must remain in the restraint device with the head holder and body restraint loosened until they collapse. The belly lift must remain up during bleedout to prevent bumping of the incision against the head opening when the animal collapses.

Since animals cannot communicate, it is impossible to completely rule out the possibility that a correctly made incision may cause some unpleasant sensation. However, one can definitely conclude that poor cutting methods and stressful restraint methods are not acceptable. Poor cutting technique often causes vigorous struggling. When the cut is done correctly, behavioral reactions to the cut are much less than reactions to air hissing, metal clanging noises, inversion, or excessive pressure applied to the body.

Discomfort during a properly done shechitah cut is probably minimal because cattle will stand still and do not resist a comfortable head restraint device. Observations in many plants indicate that slaughter without stunning requires greater management attention to the details of the procedures than stunning to maintain good welfare. Ritual slaughter is a procedure that can be greatly improved by the use of a total quality management (TQM) approach to continual incremental improvements in the process. In plants with existing upright restraint equipment significant improvements in animal welfare and reductions in petechial hemorrhages can be made by making the following changes:

- Training of employees in gentle calm cattle handling
- Modifying the restrainer per the specifications in this article
- Eliminating distractions which make animals balk
- Careful attention to the exact cutting method

There need to be continual monitoring and improvements in technique to achieve rapid onset of insensibility. Poor cutting technique, rough handling, excessive pressure applied by the restraint device, or agitated excited animals cause a high incidence of prolonged sensibility.

Kosher Slaughter: An Update on a Report Recently Issued in the UK

In 2003 in Great Britain, the Farm Animal Welfare Council (FAWC) recommended to Parliament that the exemption for religious slaughter (unstunned slaughter) be lifted. The FAWC report points out that many industry facilities for slaughter are outdated and need improvement. The report recognizes the need for other sectors to improve but does not give religious slaughter the same opportunity to improve, nor does it make suggestions that are necessarily consistent with kosher slaughter. For example, the report favors electrical stunning because

that kills the animal and requires less skill of the operator. In fact, the kosher slaughterman is a highly trained person, and most mainstream Jewish religious authorities specifically reject electrical stunning.

In the report's discussion of slaughter without prestunning, the FAWC authors refer to a 1985 report as being sufficient and do not present any new data or evaluate any new procedures or equipment to support their current recommendations. The FAWC authors report that some unidentified rabbis permit postslaughter stunning; FAWC recommends that if religious slaughter is permitted, postslaughter stunning should be used. Most mainstream Jewish religious authorities do not accept the postslaughter stunning process. The FACW suggests that all sheep for kosher slaughter in the UK are cradled upside down, which they consider unacceptable. In fact, upright equipment for rapid kosher sheep slaughter exists but was not evaluated by FACW for possible future adoption in the UK.

Other Issues Identified in the Current FACW Report

There is a superficial evaluation of equipment, and it is not related to vocalization scores, a major criterion in modern animal handling research. Grandin has determined that when the religious slaughter equipment is used properly, the vocalization scores are not excessive. Although vocalization is referred to elsewhere in the report, no effort appears to be made to indicate that low vocalization scores can be achieved with the proper equipment used appropriately for religious slaughter. The report discusses "pain" but does not include current data such as that associated with endorphin release, a possible mitigating factor in religious slaughter. Anecdotal observations of inappropriate behavior by one shochet appear to be used as the basis for policy, not scientific measurements.

1. *Insensibility*. It is suggested that monitoring be done and that some standard be adopted to limit the time to insensibility, but no suggestions are given. Grandin's data show that most animals killed kosher can be insensible in less than 10 s. The report focuses on the worst-case scenarios observed with equipment that may, in fact, be obsolete.

2. *Blood loss*. The report states that the differences between religious and nonreligious slaughter are insignificant, implying that a change of practice would be irrelevant. In fact, the difference between the two processes with respect to blood loss is neither a Jewish issue nor an animal welfare issue. Other unrelated issues are raised, such as the labeling of hindquarter cuts that might end up in the general meat supply. These issues are not animal welfare issues and only serve to cast doubt with respect to the sincerity of the FWAC report when dealing with religious slaughter.

The formal recommendation is "Council considers that slaughter without prestunning is unacceptable and that the Government should repeal the current exemption." And that "until the current exemption which permits slaughter without pre-stunning is repealed, Council recommends that any animal not stunned before slaughter should receive an immediate post-cut stun."

The FAWC report is not convincing because the authors have ignored a great deal of information currently available. The recommendations seem to be an anthropomorphic reaction to religious slaughter in an unwelcoming environment.

Acknowledgments

Originally written for the September 2003 issue of *Kashrus* Magazine. We thank Carrie E. Regenstein for her significant editorial assistance. (*Note:* Dr. Grandin was queried in the preparation of the FAWC report. However, she was not involved with the religious slaughter aspects of the report.) Dr. Yaakob B. Che Man, of the University Putra Malaysia, proofread the first of three drafts of this chapter.

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11

FOOD PRODUCTION FROM THE HALAL PERSPECTIVE

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Handbook of Poultry Science and Technology, *Volume 1: Primary Processing*, Edited by Isabel Guerrero-Legarreta and Y.H. Hui

INTRODUCTION

The word *halal*, like *kosher*, has become more common in the food industry in recent years, due to the greater consumer demand for halal products. In this chapter we discuss the various perspectives on halal food production according to the Islamic faith, with particular emphasis on poultry production. Standards and practices in Malaysia are used as an illustration.

Halal is a Quranic term meaning lawful and permissible; that is, there are no restrictions on such items or actions, so that their doing is allowed according to the lawgiver, Allah. *Haram* has the opposite meaning: that which Allah has absolutely prohibited, and anyone who engages in it is liable to incur the punishment of Allah in the hereafter as well as to receive legal punishment in this world. *Mushbooh* means suspected, doubtful, or questionable. If one does not know the halal or haram status of a particular food or drink, such a food or drink is doubtful, or mushbooh, and should be avoided. Another term that may be used is *najs*, which means religiously not clean. This refers to things that are not permissible, such as pork and all its derivatives, alcoholic drinks, and halal food that is contaminated or comes into direct contact with things that are not permissible (Chaudry, 1992; Al-Qaradawi, 1995).

The entire concept of halal is guided by the Shariah, which is the Islamic law, based on four sources: the Quran (the Divine Book), the *Hadiths* (the traditions of the Prophet Muhammad), *Ijma'* (the consensus of Islamic scholars), and *Qiyas* (deduction by analogy), according to various Islamic schools of thought or madzhabs of the Sunni traditions. The authors are not familiar enough with the Shi'a traditions to write about them. A particular food becomes halal, haram, or mushbooh by reference to any of the sources above (Hussaini and Sakr, 1984; Chand, 1995; Sakr, 1996).

It is obligatory for every Muslim to consume only halal food and avoid foods that are haram or food that contains najs. This is similar to the Jews, who consume only kosher food, or Hindus, Buddhists, and certain other groups who follow vegetarian tenets (Regenstein et al., 2003). In modern times, with the advent

of science and technology, food production undergoes many processes and is often marketed to all parts of the globe. This has raised concerns among Muslim consumers and has led to their desire to know whether a particular processed food contain any haram or mushbooh substances (Che Man et al., 2007a).

THE GLOBAL HALAL FOOD MARKET

The global halal food market is enormous and has averaged about $580 billion per year in recent years (MITI, 2006). There exists a huge market and many opportunities in the halal food business. The increasing awareness of Muslims worldwide to uphold the tenets of their religion along with the production of foods in more centralized facilities has opened up a demand for halal foods in compliance with their religious requirements. This trend of increasing demand for halal foods is expected to continue in tandem with the increasing Muslim population and globalization.

The demand for halal food products comes from Muslim and non-Muslim countries. However, the absolute demand comes from the 1.3 to 1.5 billion Muslims around the world, all of whom are potential consumers of halal foods. This number represents about 20% of the world's total population (MATRADE, 2005a,b). Furthermore, the birth rate of Muslims is reportedly the highest in the world. The world Muslim population is expected to grow at a rate of 3% annually (Islamic Population, 2007). The Muslim populations of highest density are located in Africa, the Middle East region, the Indian subcontinent, some of the new Commonwealth Independent States (CIS) of the former Soviet Republic, and the Association of South East Asian Nations (ASEAN). The Islamic awareness of halal food is expanding worldwide, especially in non-Muslim countries. This will create new markets for halal food products (Riaz and Chaudry, 2004a; AAFC, 2006).

It is estimated that there are more than 250 million Muslims in the ASEAN countries alone (Agri-Food Trade Service, 2002). ASEAN countries such as Malaysia, Indonesia, Thailand, and the Philippines, which are considered to be developing countries, have one of the highest potentials for the marketing of halal-processed food products, due to their rapidly growing number of Muslim citizens.

The growing purchasing power of Muslims in both the developing and developed countries will result in increased consumption of halal foods. In the United Arab Emiretes, for example, as the Muslim population continues to grow, the importation of food is expected to increase by 10 to 15% annually to meet the growing domestic market (MATRADE, 2005b; Che Man et al., 2007b). Food manufacturers, including the meat industry, who are keen to enter the halal food market must understand the basic concept of halal and haram to fulfill the requirements of their Muslim customers.

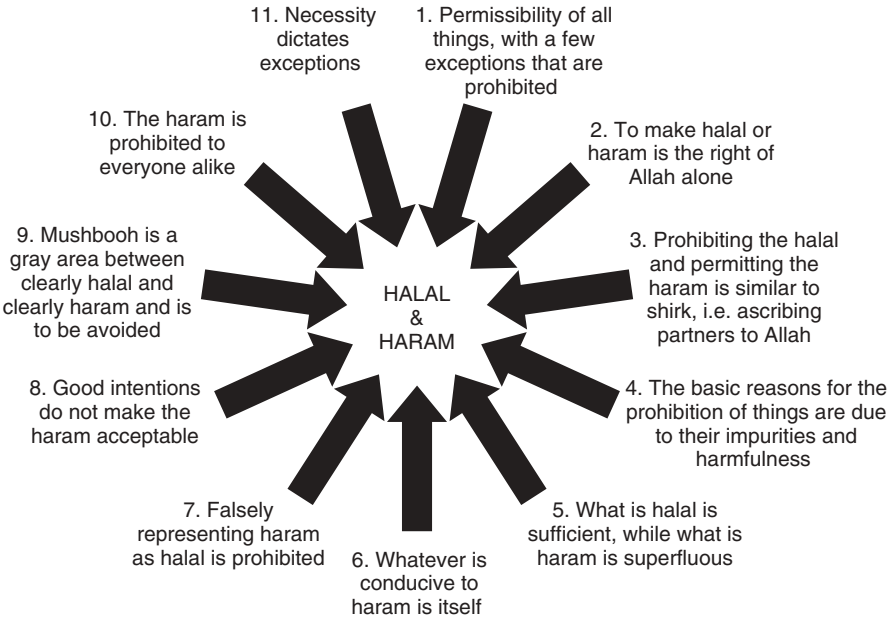

FIGURE 1 The 11 principles of halal and haram.

PRINCIPLES OF HALAL AND HARAM

Islam is a comprehensive religion guiding the lives of every Muslim. The life of a Muslim revolves around the concept of halal and haram. There are 11 general principles pertaining to halal and haram in Islam, as shown in Figure 1 (Al-Qaradawi, 1995; Riaz and Chaudry, 2004b).

1. The basic principle is permissibility of all things, with a few exceptions that are prohibited. Those exceptions include carrion, pork, blood, meat of animals that died of causes other than proper slaughtering, food that has been dedicated or immolated to someone other than Allah, intoxicants (*khamr*) such as alcoholic drinks, and drugs used inappropriately.

2. To make halal or haram is the right of Allah alone. No human being, no matter how pious or powerful, may take it into his or her hands to change it.

3. Prohibiting the halal and permitting the haram is similar to *shirk* or ascribing partners to Allah. This is a sin of the highest degree that makes one fall out of the sphere of Islam.

4. The basic reasons for the prohibition of things are due to their impurities and harmfulness. The reason for the prohibition is known only to Allah. However, some scientific explanations can be given as follows:

a. Carrion is unfit for human consumption.

b. Swine serves as an intermediate host for pathogenic worms to access the human body. Infestations by *Trichinella spiralis* and *Taenia solium* are not uncommon (Hussaini and Sakr, 1984).

c. Intoxicants have been considered harmful for the nervous system, as they can affect the senses and human judgment.

d. Immolating food to someone other than Allah may imply that there is somebody as important as Allah and this is considered as "shirk." This would be against the first tenet of Islam: "There is but one God."

These reasons and explanations, and others such as these, may be proposed, but the underlying principle behind the prohibitions remains the Divine order. What Muslims are required to say is: "We have heard and we shall obey."

5. What is halal is sufficient, whereas what is haram is superfluous. Allah prohibited only things that are unnecessary or dispensable, while providing better alternatives. People can survive and live better without consuming carrion, pork, blood, and the root of many vices—alcohol.

6. Whatever is conducive to haram is itself haram. If something is prohibited, anything leading to it is also prohibited. Islam intends to block all avenues leading to what is haram.

7. Falsely representing haram as halal is prohibited. It is haram to make flimsy excuses or to consume something that is prohibited, such as drinking alcohol for supposedly medical reasons.

8. Good intentions do not make the haram acceptable. Whenever any permissible action of the believer is accompanied by a good intention, his or her action becomes an act of worship. In the case of haram, it remains haram no matter how good the intention is or how honorable the purpose may be. Islam does not endorse employing a haram means to achieve a praiseworthy end. Indeed, the religion insists not only that the goal be honorable, but also that the means chosen to achieve it be halal and proper. Islamic law demands that the right should be secured solely through just means.

9. Mushbooh things are to be avoided. There is a gray area between clearly halal and clearly haram. This is the area of "what is doubtful." Islam considers it an act of piety for the Muslims to avoid doubtful things, for them to stay clear of the mushbooh. As narrated by Bukhari and Muslim in a hadith, Prophet Muhammad said: "Halal is clear and haram is clear. Between the two there are doubtful matters concerning, which people do not know, as to whether they are halal or haram. One who avoids them in order to safeguard his religion and his honor is safe, while if someone engages in a part of them, he may be doing something haram . . ." (Al-Qaradawi, 1995).

10. The haram is prohibited to everyone alike. Islamic laws are universally applicable to all races, creeds, and genders. In Islam there are no privileged classes; hence, the question of preferential treatment does not arise. This principle applies not only among Muslims, but also between Muslims and non-Muslims.

11. Necessity dictates exceptions. The range of things that are prohibited in Islam is quite limited, but emphasis on observing the prohibitions is very strong. At the same time, Islam is not oblivious to the exigencies of life, to their magnitudes, nor to human weaknesses and the human capacity to face them. A Muslim is permitted, under the compulsion of necessity, to eat a prohibited food to ensure survival, but only in quantities sufficient to remove the necessity and to avoid starvation.

HALAL AND FOOD QUALITY ACCORDING TO THE QURAN

The Shariah has given clear guidance with respect to the concept of halal and thoyyib (good and of high quality). They are declared through the Quranic injunctions, and Muslims are obliged to accept them as such (Abdullah, 2006).

Islam established the basic concept of natural use and the permissibility of things. Nothing is forbidden except what is prohibited in the Quran or mentioned in the hadiths of the Prophet Muhammad (Hussaini and Sakr, 1984). Some Quranic verses (Ali, 2001) related to Islamic dietary laws are:

> O ye who believe! Eat of the good things that We have provided for you, and be grateful to Allah, if it is Him ye worship. He hath only forbidden you dead meat, and blood, and the flesh of swine, and that on which any other name hath been invoked besides that of Allah. But if one is forced by necessity, without willful disobedience, nor transgressing due limits—then is he guiltless. For Allah is Oft-forgiving, Most Merciful. (*Surah* 2, Verse 172–173)

> Forbidden to you (as food) are: dead meat, blood, the flesh of swine, and that on which hath been invoked the name of other than Allah; that which hath been killed by strangling, or by a violent blow, or by a headlong fall, or by being gored to death; that which hath been (partly) eaten by a wild animal; unless ye are able to slaughter it (in due form); that which is sacrificed on stone (altars); (forbidden) also is the division (of meat) by raffling with arrows: that is impiety .... (Surah 5, Verse 3)

> Say: I find not in the message received by me by inspiration any (meat) forbidden to be eaten by one who wishes to eat it, unless it be dead meat, or blood poured forth, or the flesh of swine—for it is an abomination—or, what is impious, (meat) on which a name has been invoked, other than Allah. But (even so), if a person is forced by necessity, without willful disobedience, nor transgressing due limits—the Lord is Oft-forgiving, Most Merciful. (Surah 6, Verse 145)

As mentioned in many verses in the Quran the *Halalan Thoyyiban* concept must be viewed from a wider scope and in total perspective, including food production. It is not based on spiritual or religious aspects only but also encompasses quality, safety, and the wholesomeness of food as well. The concepts of quality and of seeking for the best are not new in Islam. This is true by the fact that Allah has specifically mentioned these concepts of quality and wholesomeness, or Halalan Thoyyiban, in several verses in the Quran (Ali, 2001), for example:

> O ye people! Eat of what is on earth. Halal and good; and do not follow the footsteps of the Evil One, for he is to you an avowed enemy. (Surah 2:168)
>
> Eat of the things which Allah hath provided for you, halal and good; but fear Allah, in Whom ye believe. (Surah 5:88)
>
> So eat of the sustenance which Allah has provided for you, halal and good; and be grateful for the favors of Allah, if it is He Whom ye serve. (Surah 16:114)

The categories of halal and haram are clear, but there are things in between which are of doubtful nature or a gray area. As a matter of piety, one should try to avoid them. On this matter, as narrated by Bukhari, Muslim, and At-Tarmizi, the Prophet said:

> The halal is made clear and the haram is also made clear, and in between lie the acts which are doubtful, about which most people do not know whether it is halal or haram. One who kept away from it in order to safeguard his religion and honor, he will remain in peace. But if one is involved in doubtful things, it is too remote to fall a victim to haram things. Like a shepherd who grazes his herds in forbidden ground, it is possible to enter into it. Remember that every king has a forbidden grazing ground, and beware that Allah's forbidden grazing ground means the haram things. (Doi, 1984; Abdullah, 2006)

In another Hadith, Prophet Muhammad said: "The halal is that which Allah has made halal in His book and the haram is that which He has forbidden, and that concerning which He is silent, He has permitted as a favor to you" (Al-Qaradawi, 1995; Abdullah, 2006).

SOURCES OF HALAL FOOD

Muslims are always concerned about the halal and haram status of their food. Islam takes into consideration the source of the food, its cleanliness, the manner in which it is cooked, served, and eaten, and the method of its disposal (Rajikin et al., 1997). They are taught to consume wholesome and safe (thoyyib) food. According to the Quran, the Islamic dietary laws laid down three general guidelines for halal food (Sakr, 1993; Abdullah, 2006):

1. Whether or not the consumption of the foodstuff is prohibited by Allah
2. Whether or not the foodstuff is obtained through a halal means
3. Whether or not the material is harmful to health

There are several sources of food that are considered as halal according to the Shariah and they are clearly mentioned in several verses of the Quran and many Hadiths of the Prophet. According to the Malaysian Standard MS1500:2004 (Department of Standards Malaysia, 2004), the sources can be divided into several categories:

1. *Animals*. Animals can be divided into two groups:

a. *Land animals*. All land animals are halal as food, except the following:

- Animals that are not slaughtered according to Shariah law
- Pigs and dogs and their descendants
- Animals with long pointed teeth or tusks that are used to kill prey, such as tigers, bears, elephants, cats, and monkeys
- Birds with talons or predatory birds
- Pests, such as rats, centipedes, scorpions, and similar animals
- Animals that are forbidden to be killed in Islam, such as bees (al-nahlah) and woodpeckers (hud-hud)
- Creatures that are considered repulsive, such as lice and flies

b. *Aquatic animals*. Aquatic animals are animals that live in water and cannot survive outside it, such as fish. All aquatic animals are halal, except those that are poisonous, intoxicating, or hazardous to health. However, animals that live both on land and water (amphibians), such as crocodiles, turtles, and frogs, are not halal. However, different madzhabs or schools of thoughts differ on this matter. For example, according to the Hanafi school of thought, mollusks and crustaceans are not halal.

2. *Plants*. All types of plants, plant products, and their derivatives are halal, except those that are poisonous, intoxicating, or hazardous to health.

3. *Mushrooms and microorganisms*. All types of mushrooms and microorganisms (i.e., bacteria, algae, and fungi) and their by-products and/or derivatives are halal, except those that are poisonous, intoxicating, or hazardous to health.

4. *Natural minerals and chemicals*. All natural minerals and chemicals are halal, except those that are poisonous, intoxicating, or hazardous to health.

5. *Drinks*. All types of water and beverages are halal as drinks, except those that are poisonous, intoxicating, or are hazardous to health.

6. *Genetically modified food*. Food and drinks containing products and/or by-products of genetically modified organisms (GMOs) or ingredients made by the use of genetic material of animals that are haram by Shariah are not halal. Even if the gene from a haram animal is sequenced and then a gene is synthesized in a totally halal manner, it will still be considered haram (JAKIM, 2001). It is not clear at this time whether this ruling will be accepted universally within the Muslim community.

Foods produced through biotechnology may increase the food supply and create new improved products. However, the use of modern biotechnology that uses recombinant DNA technique raises religious and ethical concerns. Some of the issues have been the use of enzymes derived from animals that have not been slaughtered according to Shariah and the use of porcine hormones to increase muscle mass in beef cattle. The GMOs that have raised concerns are where the foods or food ingredients are derived from plants that have been modified

genetically to express copies of animal genes, particularly if the genes are from prohibited animals (Napis and Abd. Karim, 1996).

In addressing the issue above, JAKIM (2001), the Malaysian government agency responsible for halal, issued a fatwa or religious ruling on biotechnology that "all animals treated with any product derived from haram sources (obtained through biotechnology or genetic engineering) become haram animals. Likewise any food or drinks derived from such animals are then deemed haram according to Shariah."

GUIDELINES FOR HALAL FOOD PRODUCTION

The production of halal food is no different than that from other food production activities that begin at the farm level and end on the consumer's plate. The activities include sourcing and handling of raw materials, including slaughtering of halal animals such as poultry, various unit operations, packaging, storage, transportation, and distribution.

Figure 2 illustrates the halal food supply chain from farm to consumers. The activities begin on the farm, continue to the abattoir in the case of animal products, then undergo processing and storage before distribution to consumers.

Sourcing and Handling of Raw Materials

Raw materials for the food industry are generally of either plant or animal origin. Raw materials from plant sources such as cereals, legumes, vegetables, fats, oils, sugars, fruits, and nuts are not critical as far as halal is concerned as long as they are not intoxicating, poisonous, or hazardous. However, raw materials from animal origin are more complex. The animals must be of a halal species. It must be handled and slaughtered according to the guidelines of Shariah as discussed in the preceding section. Looking further into animal breeding at the farm, all halal animals treated with any product derived from haram sources (e.g., from haram animals) or obtained through biotechnology or genetic engineering involving components from haram animals become haram animals. Similarly, any food or drinks derived from such animals are deemed haram according to Shariah.

Food ingredients and additives are components of processed food. The halal status of ingredients and additives from plant origins is rarely an issue, but doubts arise when the ingredients and additives are derived from animals. Any ingredient and additive derived from a haram animal is clearly haram. Some of the ingredients that are known to be haram, or at least mushbooh, are lard, pork extract, natural bacon flavor, some colors, some enzymes, some amino acids, some emulsifiers, and some gelatins. Although ingredients and additives in food must often be declared on the labels of food packages to provide informed choice to consumers, this does not provide enough information to make an informed halal decision. First, many ingredients can be derived from either animal or plant sources, and this information is not provided to consumers. Second, in

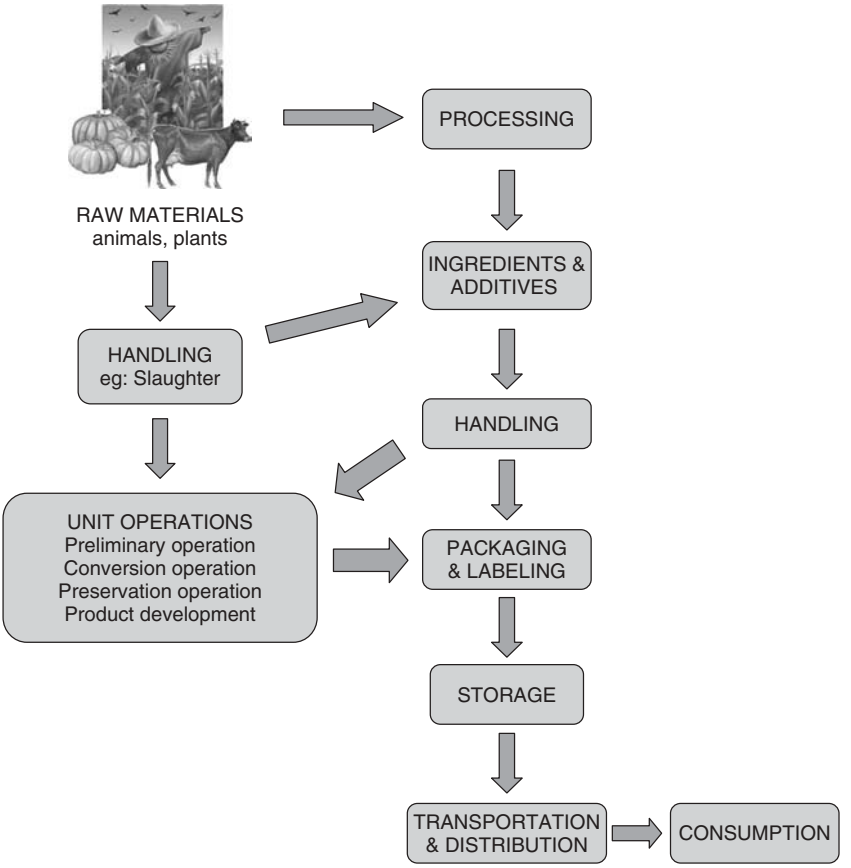

FIGURE 2 Halal food supply chain.

many cases, items may be grouped into a category such as "natural and artificial colors" without providing the components. Third, there are materials used during food processing that are not required to be labeled. Thus, in the modern world of food production, only a reliable religious supervision of the product will provide the halal consumer with assurance of the status of the product.

Handling of raw materials is done by either manual or mechanical means. Only some automation of raw material handling is currently the case. For halal food handling, it is important that food processors make sure that none of the equipment and machinery is in contact with foods that are haram or najs. If food establishments producing halal food carry out haram operations, they should expect to be required to carry out a mandatory ritual cleansing.

Unit Operations

There are various unit operations used normally in the processing of food. They can be classified into preliminary operations, conversion operations, and

preservation operations. Examples of preliminary food-processing operations include the cleaning of raw materials, and the sorting and grading of foods. Conversion operations encompass size reduction, screening, mixing, emulsification, filtration, membrane separation, centrifugation, solid–liquid extraction, expression, and crystallization. Preservation operations involve, among other processes, pasteurization, sterilization, drying, freezing, and irradiation. Each of these unit operations can make use of many different types of processing equipment that can yield products with different quality parameters. For example, the drying operation can be carried out using any of the following pieces of equipments: oven drier, forced-air drier, vacuum drier, spray drier, freeze drier, and foam mat drier. Again, whichever unit operation is selected for a given food-processing task in a plant, the food processor must make sure that halal foods are processed in such a manner as not to come into contact with foods that are haram or najs. Cumbersome cleansing is required if haram cross-contamination occurs. A halal-certified plant must be inspected by the halal inspector as well as quality assurance personnel from the appropriate halal authority.

Thorough cleansing must be done prior to halal processing. For non-pork-based food plants, the equipment used to produce halal food must be capable of being cleaned thoroughly and carefully with water and detergent, normally a part of good manufacturing practices. For a pork-based food manufacturing plant, the equipment in the plant can be changed to equipment that can produce halal food through ritual cleansing of the equipment. The procedure, called *dibagh*, has been used widely in the Southeast Asian region. This is almost impossible to do for machines that operate dry and cannot tolerate water washing. These may need to be replaced totally by new machines. According to Malaysian Standard MS1500:2004 (Department of Standards Malaysia, 2004), the dibagh procedure requires washing the affected areas seven times with clean water, one of which shall be water mixed with soil. Some opinions of Islamic scholars permit the use of soap or detergent in place of soil. Since the ritual cleansing procedure is cumbersome, it becomes a good manufacturing practice within a plant to separate halal and nonhalal operations, ideally so that they occur on different premises, especially pork-based products, at all times.

Packaging and Labeling

Appropriate packaging contributes to the success of any food product being marketed. The packaging materials should be halal in nature and must not contain any components that are considered najs according to Shariah. An example of critical packaging material is casings, which are used, for example, to contain processed meat products. Casings are of three types. Natural casings are made from animal intestines, collagen casings are currently made from finely ground cattle or pork skins (although fish collagen is being explored) and cellulose casings are made with cellulose (plant-based) and other ingredients, such as glycerin (which can be of animal origin). For the selection of casing materials for meat-based products, such as frankfurters, it is very important for manufacturers to source halal casings.

According to the Malaysian standard, packaging designs and labels, like production of nonalcoholic malt beverages in beer bottles or sparkling fruit juices in wine bottles, are not considered to be acceptable. Unfortunately, we are not familiar with the practice in other parts of the world. This is an example of an imitation of haram food products that may cause confusion and unnecessary repercussions among Muslim consumers. Therefore, it is very important for manufacturers to recognize that the careless or wrong choice of packaging materials and of packaging designs for food products may result in consumer concerns as to whether or not the foods are halal.

Storage

All food must be stored at some point along the production chain. In modern food industries, foods are stored in massive well-designed warehouses, large cold rooms, and walk-in freezers. Manufacturers should remember that in some countries, such as Malaysia, it is not permissible by law to store halal foods in the same storage compartment with haram foods (e.g., halal beef stored together with pork or fruits stored together with pork) (Ministry of Domestic Trade and Consumer Affairs, 1975). Cross-contamination with haram sources must be avoided completely (see also MS1500:2004, Sec. 4.3.2.2).

Storage of raw food materials and processed food products must be done under conditions that ensure no cross-contamination of any halal food stored in the production premise and that the storage space is always clean and hygienic. Dibagh or thorough ritual cleaning has to be done to convert storage facilities that have been used for haram food to halal status. Operators should also note that authorities in a country such as Malaysia do not hesitate to close down the storage premise if haram food is stored together with halal food.

Transportation and Distribution

Transportation may be under the control of the food manufacturers, or it may be carried out by independent operators (e.g., trucking, forwarding, or distribution companies). During transportation, halal foods must be handled properly so as to avoid cross-contamination with haram products. Food manufacturers using independent transport service must pay special attention in educating the operators about maintaining the conditions so that the food will not be rendered haram.

REQUIREMENTS FOR HALAL SLAUGHTERING OF POULTRY

Rationale

Humans have been consuming meat from very early times. During the Arab Jahiliah's time (before A.D. 570), all possible means were used to acquire the meat of animals. The flesh of dead animals was consumed. At times a part of a living animal's body would be cut and eaten. No consideration would be given to

preventing the pain and suffering of Allah's defenseless and innocent. However, the Jews on the Arabian continent were practicing their animal welfare–friendly Jewish law during those times. With the advent of Islam, the slaughtering of animals in the Muslim community has been carried out according to the Shariah. Animals that are declared halal are subjected to certain rules and regulations to ensure that the blood and other impurities come out from their body to the extent possible and that the slaughter be done in a manner that is the least painful and most merciful to the animal. The ritual nature of the slaughtering also serves as a reminder to humans of the tremendousness of the gift of life and the blessing of food in general and of meat in particular (Khan, 1991). Besides the earlier mentioned rationales, halal slaughter also emphasizes hygiene and sanitation (thoyyib), and this ensures that the meat obtained is not hazardous to health and of acceptable quality to consumers.

Conditions of Halal Slaughtering

Under the Shariah, there are four conditions or primary requirements (Figure 3) that must always be met by halal slaughter. The conditions are as follows:

1. *The slaughterer*. The slaughtering is performed only by a Muslim, either male or female, who is mentally sound (*aqil*) and mature (baligh), who fully understands the fundamental rules and conditions related to the slaughter of animals in Islam (*mumayyiz*). According to certain Islamic scholars (ulama'), Muslims are also permitted to eat meat or meat by-products from animals slaughtered by the People of the Book (*Ahl-al-Kitab*) (e.g., Jews), who are closest to Muslims in their beliefs concerning divine revelation, prophethood, and other fundamentals of religion.

2. *The animal slaughtered*. The animal to be slaughtered must be a halal species, healthy and alive (*hayat al-mustaqirrah*) at the point of slaughter. Any animal that dies of itself and is not killed expressly for food with the name of Allah pronounced over it is considered carrion. Animals slaughtered with the name other than Allah pronounced over it would be classified as that which is dedicated to other than Allah.

3. *The tools and equipment for slaughter*. The slaughtering lines, tools, and utensils should be dedicated to halal slaughter only. Beside that, the slaughtering knife or blade should be sharpened properly. The very sharp cutting instrument used in the slaughter should allow for a smooth and quick cut across the animal's throat. However, sharpening the blade of the knife either in front of the animal to be slaughtered or in front of other animals should always be avoided. The instrument should also be cleaned and an effort made to ensure that no blood from the previous slaughter is on the knife. Apart from the humane aspects, the regular cleaning of the knife prior to each slaughter indicates that strict hygiene is also being observed.

4. *The slaughter process*. The slaughtering should be initiated with *niyyah* (intention) that the slaughter is only for Allah and not for any other purposes.

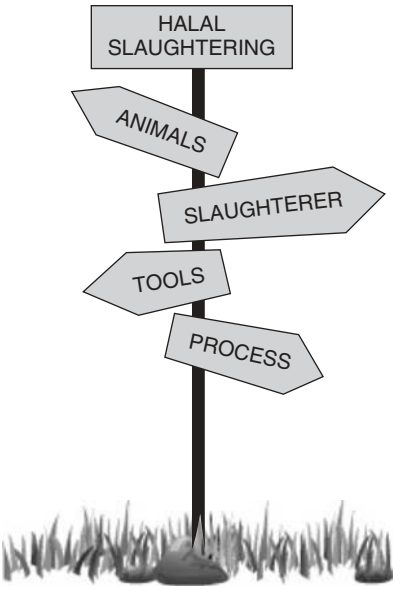

FIGURE 3 The four conditions for halal slaughtering.

As described earlier, the use of a sharp knife is extremely important to ensure that the killing is done perfectly, kindly, and least painfully. The act of slaughtering begins with the incision on the neck at some point just below the glottis (Adam's apple) and after the glottis for long-necked animals. In camels, the procedure of stabbing the neck and cutting downward to the top of the chest to sever the blood vessels while the animal is in standing posture is referred to as nahr. The cutting of the throat is done to sever the trachea (*halqum*), esophagus (*mari'*), and the two carotid arteries and jugular veins (*wadajain*), which will cause a rapid gush of blood and consequently will hasten the death of the animal (Figure 4). The slaughtering should not cut the spinal cord, as this could result in cardiac arrest and consequent stagnation of blood in the blood vessels. To ensure that the animals are properly slaughtered according to the Shariah, a trained Muslim inspector should be appointed to supervise commercial slaughter and to be responsible for assuring that the process is always done in accordance with Shariah.

According to the Quran (Surah 5: verse 3–4), there are strict rules when it comes to meat regarding what is allowed and what is forbidden.

> Forbidden to you (for food) are: dead meat, blood, the flesh of swine, and that on which hath been invoked the name of other than Allah; that which hath been killed by strangling, or by a violent blow, or by a headlong fall, or by being gored to death; that which hath been (partly) eaten by a wild animal; unless ye are able to slaughter it (in due form); that which is sacrificed on stone (altars); (forbidden)

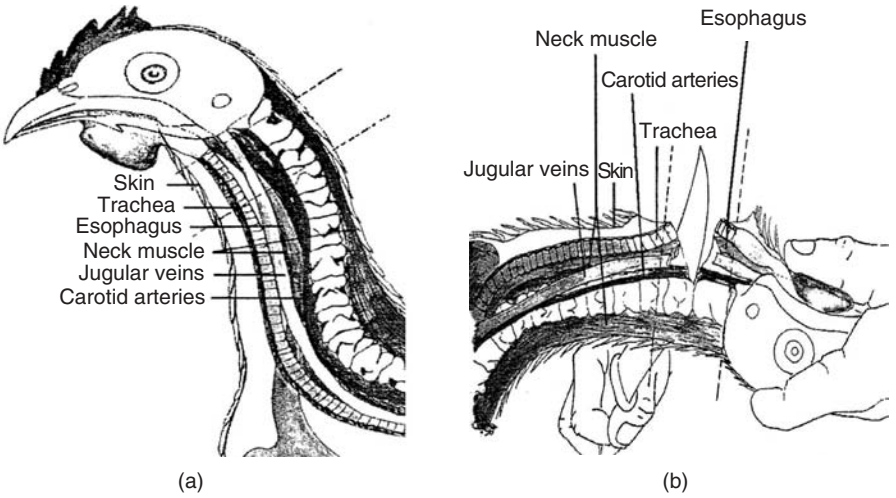

FIGURE 4 (a) Part of the chicken involved in slaughter; (b) proper point of cutting for the slaughter of chickens. (Adapted from Malaysian Standard MS1500:2004, Department of Standards Malaysia, 2004.)

> also is the division (of meat) by raffling with arrows: that is impiety. This day have those who reject faith given up all hope of your religion: yet fear them not but fear Me. This day have I perfected your religion for you, completed my favour upon you, and have chosen for you Islam as your religion. But if any is forced by hunger, with no inclination to transgression, Allah is indeed Oft-forgiving, Most Merciful. They ask thee what is halal to them (as food). Say: halal unto you are (all) things good and pure: and what ye have taught your trained hunting animals (to catch) in the manner directed to you by Allah: eat what they catch for you, but pronounce the name of Allah over it: and fear Allah for Allah is swift in taking account.

The Islamic slaughtering of animals is a blessing for both the animal and for humans. In this regard a prophetic tradition enjoins Muslims to show mercy when killing an animal for consumption: The Prophet Muhammad said: "Allah calls for mercy in everything, so be merciful when you kill and when you slaughter: sharpen your blade to relieve its pain."

Recommendations for Halal Slaughtering

Beside the mandatory requirements described earlier, there are also a number of secondary requirements that are actually recommendations. These include the health status and handling aspects of the animals or birds to be slaughtered which, according to the Shariah, should always be healthy and free from any diseases and defects. In Malaysia, the Department of Veterinary Services is the agency monitoring the practice by poultry farmers and processors. In addition, animals should be handled humanely and provided with rest and accessible drinking water

to overcome stress and the often agitated states experienced during transportation and lairage handling. For animal welfare reasons, it is highly recommended that a proper restraining and stunning method be employed provided that the animal is not dead before the slaughter. The carcass and its by-products become haram for Muslim consumption if the earlier interventions cause death prior to the actual slaughter. However, the issues of stunning is still debatable even within the Muslim community.

Abominable Acts in Halal Slaughtering

There are acts or procedures that should be avoided throughout the slaughtering process. Starving the animal by prolonged restriction to access feed and water is among those not recommended by Shariah. However, feed withdrawal for an appropriate amount of time with unlimited amount of drinking water is a common practice in the livestock industry, which when done properly will minimize contamination by gut content during evisceration. Use of an improperly sharpened or wrong-size knife should always be avoided, as this can cause more suffering and pain to the animals.

Applications of Stunning and Mechanical Blades in Halal Poultry Slaughtering

It is important to note that animals are sentient beings, rather than being agricultural products or commodities. Stunning before slaughter has been widely practiced, particularly by industrial halal poultry producers, who are always concerned about production efficiency, although this practice is not accepted by all parts of the Muslim community. In principle, stunning is used to induce insensibility and unconsciousness quickly in animals, so that the death process can occur through the bleeding, without pain, suffering, or distress. Additionally, stunning will immobilize the animals to allow neck cutting to be performed easily and accurately, and this will minimize the occurrence of bruises and broken bones (Figure 5) in the slaughtered birds besides protecting the abattoir personnel from occupational hazards (Gregory and Wilkins, 1989). However, it is a statutory requirement that no further carcass processing (e.g., electrical stimulation or scalding) begin until death has occurred. In this section we describe only use of the electrical water bath stunning system, as it is the most commonly practiced stunning method in halal poultry slaughtering, where large throughput rates are required.

Electrical Water Bath Stunning Stunning is usually carried out in an electrically charged water bath by moving the heads of the birds through water in which an electrode is submerged. Usually, conscious birds are hung upside down on a moving metal-shackle line (shackling) and passed through an electrified water bath such that the current flows through the entire body toward the shackle (Figure 6), which serves as the ground (earth). The effectiveness of the stunning

FIGURE 5 Bruises on the (a) wing and (b) leg; (c) broken bones, which are usually inflicted by the operator during preslaughter handling.

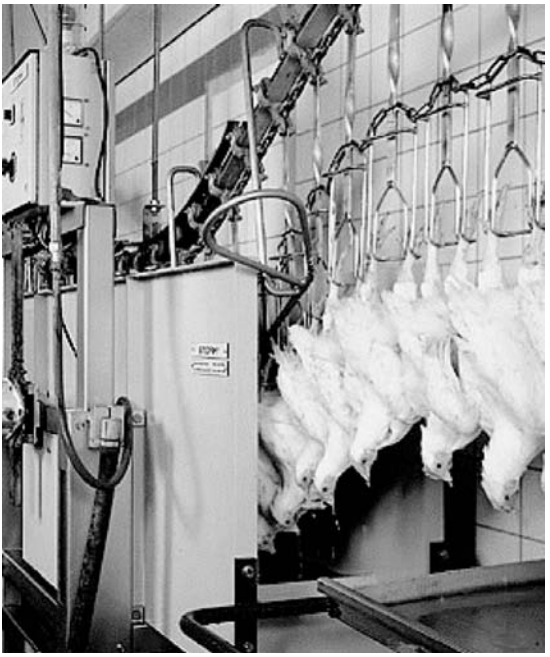

FIGURE 6 Shackled live birds being moved to the point where they will be submerged in an electrical water bath stunner.

method is determined primarily by the amount of current (amperage) received by individual birds rather than the voltage supplied to the equipment (Sparrey et al., 1992, 1993). The amount of current applied during electrical stunning must be sufficient to induce immediate loss of consciousness (Wilkins et al., 1998, 1999) but most not lead to death.

In the Malaysian context, the application of electrical water bath stunning should always abide by the halal requirements according to the Malaysian Standards MS1500:2004 (Department of Standards Malaysia, 2004) as follows:

- Slaughtering is to be carried out according to the requirements related to the slaughter of animals in Islam.
- The birds are to be alive (hayat al-mustaqirrah) at the time of slaughter.
- The use of stunning equipment is to be under the supervision of a trained Muslim and monitored periodically by a competent Islamic authority or halal certification authority.
- The stunning must not kill (i.e., it must be reversible) or cause permanent physical injury to the bird.
- Gadgets that are used to stun animals under the *mughallazah* (severe) najs category (e.g., pigs) are not to be used to stun animals for halal slaughter.
- The type of stunning that is recommended is electrical stunning or any other stunning that is permitted by the *fatwa* (religious) council.
- The electrical stunner is to be of the type allowed by the competent authority in charge of slaughter (e.g., the electrical stunning of poultry using a "water bath stunner").
- The strength of the current used is supervised by a trained Muslim and monitored by a competent Islamic authority or halal certification authority.

Mechanical Slaughter Industrial halal poultry slaughtering can be accomplished through the traditional manual method using hand slaughter (Figure 7) or by using a mechanical device (Figure 8), depending on the line speed, operation size, and facilities available at a premise. However, manual slaughter is still the most preferable method and is employed where Muslims control the abattoirs. With mass production, especially where Muslim slaughter is not the main goal, efficiency is of major concern. In these cases poultry are usually slaughtered using a machine. A mechanical slaughter machine is used to perform the act of cutting the throat and esophagus and severing the jugular veins and carotid arteries in the neck region (Gregory and Wilkins, 1989). Mechanical slaughter is gaining acceptance and becoming a widespread phenomenon in many abattoirs, plants, and firms controlled by Muslims (Wan Hassan, 2007). In relation to mechanical slaughter, one of the key issues is the birds that are missed by the machine. However, a halal checker may be assigned to slaughter missed birds manually.

The halal requirements for the use of mechanical slaughter of poultry in accordance with Malaysian Standard MS1500:2004 (Department of Standards Malaysia, 2004) are as follows:

- The operator of the mechanical knife (slaughterman) must be a Muslim.
- The operator must recite *Bismillah Allahuakbar* prior to switching on the mechanical knife machine and should not leave the slaughter area.
- Should the operator leave the slaughter area, he must stop the machine line and switch off the mechanical knife. To restart the operation he or another Muslim slaughterman recites "Bismillah Allahuakbar" again before switching on the line and mechanical knife.

FIGURE 7 Manual slaughtering of halal poultry.

FIGURE 8 Mechanical slaughter machine with a rotating blade.

- The knife used is to be of single-blade type and must be kept sharp at all times.
- The slaughter act must sever the trachea (halqum), esophagus (mari'), and both the carotid arteries and jugular veins (wadajain) to hasten the bleeding and death of the bird.
- The slaughterman is required to check that each bird is slaughtered properly. He or another Muslim slaughterman must slaughter manually any birds that are missed by the mechanical knife.
- The birds should be dead as a result of the slaughter before they progress to the scalding process.

Halal Control Systems in Poultry Slaughtering

The halal control or monitoring system is used to ensure continually that only halal meat and meat by-products reach the market regardless of location in the world. The system varies among producers but is commonly established through determinations of several control points for each operation from the farm to the final packaging stage. However, halal meat producers must always employ a sufficient number of Muslims to implement the halal control system effectively (MUIS, 2007).

Selection and Sorting of Live Birds First, the Muslim employees assigned have to check before slaughtering takes place that the poultry are still alive, as it is an important requirement for halal slaughtering. Dead poultry must be segregated and disposed of properly. The birds should be well rested and free of stress while held in crates prior to slaughter. In general, the preslaughter handling of birds should always be conducted properly.

Slaughtering of Birds The second stage of the control system requires qualified Muslim slaughterers to comply strictly with the halal slaughtering procedure, with the birds being killed by cutting the trachea, esophagus, and jugular veins and carotid arteries completely by using a sharp object (e.g., a knife) to inflict a precise cut. To maintain their full concentration during slaughtering, the slaughterers is to switch duties with other qualified slaughterers at a reasonable time interval set by management after discussion with the slaughterers. They must also ensure that the knife used for slaughtering is constantly sharp.

Live- and Dead-Bird Monitoring Before the birds are put into the scalding water or passed through the defeathering section, the third stage of control requires the responsible Muslim employees to monitor and make sure that the bird is dead and that the trachea, esophagus, and the jugular veins and carotid arteries were cut completely before it reaches this stage (Figure 9).

Labeling of Poultry The final control is done during the labeling of poultry. Only Muslim employees should place the halal label or tag on the product. The Muslim employees in charge of tagging must ensure that only properly slaughtered halal poultry are tagged.

According to the Malaysian Protocol for the Halal Meat Production (JAKIM, 2000), the halal checker must:

- Be a practicing Muslim
- Be authorized and be under the supervision of a recognized halal certifying organization
- Check the plant randomly to ensure that:
  a. Birds are not killed by the use of a stunner. Birds that are killed by use of the stunner are identified and all carcass parts are segregated as haram.

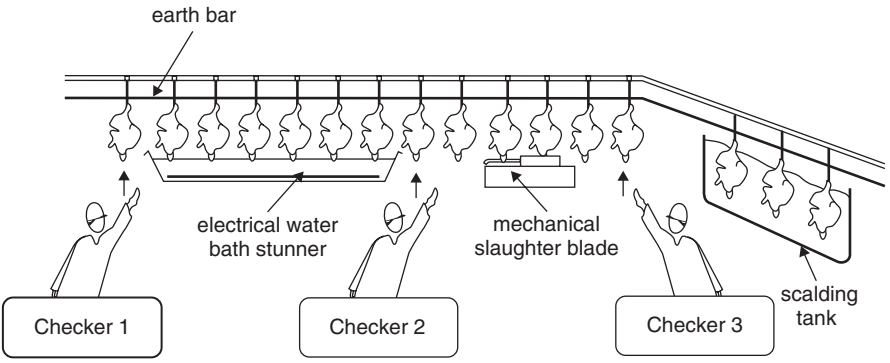

FIGURE 9 Part of the halal control system is conducted by Muslim checkers assigned to monitor each critical point from prestunning inspection to scalding of dead birds. Checkers 1 and 2 are to monitor that birds are still alive before and after entering the electrical water bath stunner, respectively, while checker 3 is to monitor that birds are dead before entering the scalding tank.

b. Birds are visually dead from the halal slaughter before further dressing procedures begin (using the criteria listed under "determination of visual death").
c. The segregation processes for all carcass parts, including offal, continue to be satisfactory in ensuring that only product eligible for use in Malaysia will be exported to that market.
d. The halal checker must supervise and certify the plant's halal record as follows:
   —*Antemortem* records
   —Stunner equipment verification and calibration
   —Stunning records
   —Slaughter records
   —Halal seal/stamp control
   —Chiller room records
   —Deboning activity records
   —Packaging and storage records

LEGISLATION, STANDARDS, AND GUIDELINES FOR HALAL PRODUCTS

International Documents on Food Legislation

Since its establishment in 1995, the World Trade Organization (WTO) Sanitary and Phytosanitary (SPS) and Technical Barriers to Trade (TBT) Agreements

recognized the Codex Alimentarius Commission (CAC) as the international reference for food standards for protecting human health and life and in resolving trade disputes between member countries. The other international reference bodies include the Office of International Epizootics (OIE), which addresses animal health and life, and the International Plant Protection Congress (IPPC), which looks into plant health and life.

The SPS agreement covers food safety, animal and plant health protection, and gives governments the right to give priority to health protection over trade. Trade restrictions need to be based on ensuring health protection. However, to qualify, they must be justified scientifically, on the basis of Codex standards, guidelines, or recommendations for food safety, or risk assessment. The TBT agreement covers mandatory technical regulations, voluntary standards, and conformity assessment procedures, with the right of governments to apply regulations needed to achieve legitimate objectives, including protection from deceptive practices. The five principles of the TBT agreement are nondiscrimination, harmonization, avoidance of unnecessary trade barriers, equivalence or mutual recognition, and transparency (Abdul Latif, 2003).

Codex Standard on the Use of the Term *Halal*

The Codex Alimentarius Commission, in short *Codex*, is an intergovernmental body established in 1962 by the Food and Agriculture Organization (FAO) and the World Health Organization (WHO) of the United Nations to implement the Joint FAO/WHO Food Standards Program. *Codex Alimentarius* are Latin words meaning food code or food law. Codex is a collection of internationally adopted food standards presented in a uniform manner. The objectives of Codex are to protect the health of consumers, to ensure fair practices in the food trade, and to coordinate all food standards work.

The issue of the use of the term *halal* with reference to specific labeling for processed meat was first raised at the second Session of the Codex Coordinating Committee for Asia (CCAsia) in 1979. Malaysia indicated that it was prepared to draft halal guidelines. Subsequently, these guidelines were further elaborated at the Codex Committee on Food Labeling in Ottawa. Finally, in 1997, Codex adopted general guidelines for use of the term *halal*. This guideline provides basic and general information on how food could be produced and claimed as halal in food labeling. It supplements Codex's general guidelines on claims (CAC, 1997).

Manual for the Slaughter of Small Ruminants in Developing Countries

Animal Production and Health Paper 49 (FAO, 1985) sets out guidelines for the slaughter of sheep and goats in developing countries. It outlined modern slaughtering procedures, taking into consideration the key aspects of religious and traditional observances, including halal slaughter (FAO, 1985; Che Man and Abdul Latif, 2002).

Islamic Ruling on Animal Slaughter: The Right Path to Health

In 1997, the FAO Regional Office for the Far East published the document identified in the title as part of a "health education through religion" activity. The document provides Islamic guidelines for animal slaughter in the eastern Mediterranean countries (WHO, 1977; Che Man and Abdul Latif, 2002).

Guidelines from the Halal Food Standard of Malaysia

Malaysia produced the following guidelines related to halal food as references for the food industries and consumers.

Guidelines on Foods, Drinks, and Goods Utilized by Muslims In 1984, JAKIM produced guidelines to elaborate on use of the term *halal* (e.g., *ditanggung halal* and *makanan orang Islam*) under a Trade Description (Use of Expression "Halal") Order, 1975 (Ministry of Domestic Trade and Consumer Affairs, 1975). The guidelines interpret and explain, to processors and the public, halal and haram aspects as stipulated in the Islamic dietary laws. Included are definitions, food and drink sources, slaughtering, processing and handling, cleanliness, labeling, and utensils used by Muslims.

General Guidelines on the Slaughtering of Animals and the Preparation and Handling of Halal Food This guideline on the slaughtering of animals and the preparation and handling of halal food was documented in May 2001 (JAKIM, 2001; Ab. Rahman, 2003). This guideline will have to be observed by all establishments involved in the processing of halal food for Malaysia. It serves as a basis for ascertaining the halal status of establishments by the competent authority in Malaysia. It also applies to all foreign establishments intending to export their products to Malaysia, and is to be used together with existing guidelines on good manufacturing practices (GMPs) and hygienic sanitary requirements.

Malaysian Standard MS1500:2004 Halal Food: Production, Preparation, Handling and Storage—General Guideline (First Revision) (Department of Standards Malaysia, 2004)

A. Scope This Malaysian standard prescribes practical guidelines for the food industry on the preparation and handling of halal food and serves as a basic requirement for food products and for the food trade and businesses in Malaysia. This standard must be used together with MS1480 and MS1514.

B. Normative References

- MS1480 [Food safety according to the hazard analysis and critical control point (HACCP) system]
- MS1514 (General principles of food hygiene)

- Guidelines on good hygiene practices for small- and medium-scale food industries toward HACCP: MOH/K/MAK/18.03(GU), Food Quality Control Division, Department of Public Health, Malaysia

C. Definitions

1. *Shariah law*. Shariah law comprises the laws of Islam in the Mazhab of Shafei, Maliki, Hambali, and Hanafi of the Sunni traditions. Thus, those following the Shi'a tradition may not find these guidelines appropriate.

2. *Halal*. Halal means things or actions permitted by Shariah law without punishment imposed on the doer.

3. *Halal food*. Halal food is food permitted under Shariah law and fulfills the following conditions:

a. Food/ingredients contain no nonhalal materials or products of animals that are not slaughtered according to Shariah law.
b. The food does not contain any ingredients that are najs according to Shariah law.
c. The food is not harmful.
d. The food is not prepared, processed, or manufactured using equipment that is contaminated with things that are najs according to Shariah law.
e. The food or its ingredients do not contain any human parts or its derivatives that are not permitted by Shariah law.
f. During its preparation, processing, packaging, storage, or transportation, the food is physically separated from any other food that does not meet the requirements stated in items (a) to (e) or any other things that have been decreed as najs by Shariah law.

4. *Najs*

a. Najs according to Shariah law are:
   (1) Pig (*khinzir*) and all its derivatives, blood, and carrion
   (2) Halal food that is contaminated with things that are nonhalal
   (3) Halal food that comes into direct contact with things that are nonhalal
   (4) Any liquid or objects originated from the orifices of human being or animal such as dogs and pigs
   (5) Carrion of halal animals that are not slaughtered according to Shariah law
b. There are three types of najs:
   (1) Mughallazah, considered as severe najs such as dogs and pigs, including any liquid and objects discharged from their orifices, descendants, and derivatives.
   (2) *Mukhaffafah*, considered as light najs. The only najs in this category is urine from a baby boy 2 years of age or below who has consumed no food except his mother's milk

(3) *Mutawassitah*, considered as medium najs not falling under severe or light najs: for example, vomit, pus, blood, alcoholic drinks (khamr), carrion, liquid and objects discharged from the orifices.

5. *Slaughtering*. According to Shariah law, the slaughter act should sever the trachea (halqum), esophagus (mari), and both the carotid arteries and jugular veins (wadajain) to hasten the bleeding and death of the animal.

6. *Competent authority*. The competent authority is the agency entrusted by the government to carry out specified work according to prescribed requirements.

7. *Islamic authority*. The Islamic authority is the government agency that is responsible for Islamic affairs in Malaysia.

D. Requirements

1. *Sources of halal food and drinks*

a. *Animals*. Animals can be divided into two categories:
   (1) *Land animals*. All land animals are halal as food, except the following:
      (a) Animals that are not slaughtered according to Shariah law
      (b) Pigs (khinzir) and dogs and their descendents
      (c) Animals with long pointed teeth or tusks that are used to kill prey, such as tigers, bears, elephants, cat, and monkeys
      (d) Birds with talons or predator birds
      (e) Pests, such as rats, centipedes, scorpions, and similar animals
      (f) Animals that are forbidden to be killed in Islam, such as bees (al-nahlah) and woodpeckers (hud-hud)
      (g) Creatures that are considered repulsive, such as lice and flies
   (2) *Aquatic animals*. Aquatic animals are animals that live in water and cannot survive outside it, such as fish. All aquatic animals are halal except those that are poisonous, intoxicating, or hazardous to health. Animals that live both on land and in water, such as crocodiles, turtles, and frogs, are not halal.

b. *Plants*. All types of plants, plant products, and their derivatives are halal except those that are poisonous, intoxicating, or hazardous to health.

c. *Mushroom and microorganisms*. All types of mushrooms and microorganisms (i.e., bacteria, algae, and fungi) and their by-products and/or derivatives are halal except those that are poisonous, intoxicating, or hazardous to health.

d. *Natural minerals and chemicals*. All natural minerals and chemicals are halal, except those that are poisonous, intoxicating, or hazardous to health.

e. *Drinks*. All types of water and beverages are halal as drinks, except those that are poisonous, intoxicating, or hazardous to health.

f. *Genetically modified food (GMF)*. Food and drinks containing products and/or by-products of genetically modified organisms (GMOs) or

ingredients made by the use of the genetic material of animals that are nonhalal by Shariah law are not halal.

2. *Slaughtering*

a. The halal slaughter must be physically separated from nonhalal slaughter according to the following requirements:
   (1) Slaughtering must be performed only by a Muslim who is mentally sound and fully understands the fundamental rules and conditions related to the slaughter of animals in Islam.
   (2) The act of slaughtering is done with niyyah (intention) and the slaughterman is well aware of his action.
   (3) The purpose of slaughtering is only for Allah and not for other purposes.
   (4) The animal to be slaughtered has to be an animal that is halal.
   (5) The animal to be slaughtered must be alive or deemed to be alive (hayat al-mustaqirrah) at the time of slaughter.
   (6) Animals to be slaughtered must be healthy and must have been approved by the competent authority.
   (7) The phrase *Bismillah irrah manirrahim* (in the name of Allah, Most Gracious, Most Merciful) has to be invoked immediately before slaughtering. The traditional statement at the time of slaughter may be different in other Muslim countries.
   (8) Slaughtering lines, tools, and utensils must be dedicated for halal slaughter only.
   (9) The slaughter knife and blade must be sharp.
   (10) Slaughtering is to be done only once. A sawing action is permitted as long as the slaughtering knife is nor lifted off the animal during slaughter.
   (11) Bones, nails, and teeth are not to be used as slaughtering tools.
   (12) The act of halal slaughter begins with an incision on the neck at some point just below the glottis (Adam's apple), and after the glottis for long-necked animals.
   (13) The slaughter act must sever the trachea (halqum), esophagus (mari), and both the carotid arteries and jugular veins (wadajain) to hasten the bleeding and death of the animal. Bleeding must be spontaneous and complete.
   (14) A trained Muslim inspector is appointed who is responsible for checking that the animals are properly slaughtered according to shariah law.

b. For poultry, scalding is only to be carried out on animals that are deemed dead as a result of halal slaughter.

c. Stunning is not recommended. However, if stunning is to be carried out, the conditions specified in Annex A of standard MS1500 must be complied with.

d. Slaughter of poultry by mechanical knife must be in accordance with the requirements specified in Annex B of standard MS1500

3. *Product processing, handling, and distribution*

a. All processed food is halal if it meets the following requirements:
   (1) The product or its ingredients does not contain any components or products of animals that are haram by Shariah law or products of animals that are not slaughtered according to Shariah law.
   (2) The product does not contain anything in any quantity that is decreed as najs by Shariah law.
   (3) The product or its ingredients are safe and not harmful.
   (4) The product is prepared, processed, or manufactured using equipment and facilities that are free from contamination with najs.
   (5) During its preparation, processing, packaging, storage, and transportation, the product must be physically separated from any other food that does not meet the requirements specified in items (1), (2), (3), and/or (4) or any thing else decreed as najs by Shariah law.

b. *Devices and utensils*
   (1) Devices, utensils, machines, and processing aids used in processing halal food should not be made of or contain any materials decreed as being najs by Shariah law and should be used only for halal food.
   (2) Devices, utensils, and machines used previously or in contact with najs al-mughallazah must be washed and ritually cleansed (dibagh) as required by Shariah law.
   (3) In the case of converting a najs al-mughallazah line or processing line containing najs al-mughalazah into a halal production line, the line should be washed and ritually cleansed (dibagh) according to Shariah law. This procedure must be supervised and verified by the competent Islamic authority. Upon conversion, the line should be operated for halal food only. Repetition in converting the line to a najs al-mughallazah line and back to a halal line should not be permitted.

4. *Product storage, display, and serving*. All halal products that are stored, displayed, sold, or served are to be categorized and labeled as halal and segregated at every stage so as to prevent them from being mixed or contaminated with things that are haram.

5. *Hygiene, sanitation, and food safety*

a. Hygiene, sanitation, and food safety are prerequisites in the preparation of halal food. This includes the various aspects of personal hygiene, clothing, equipment, and the working premises for processing or manufacture of food.

b. Producers should implement measures to:
   (1) Control contamination from air, soil, water, feedstuffs, fertilizers (including natural fertilizers), pesticides, veterinary drugs, or any other agent in primary production

(2) Protect food sources from pests, fecal material, contamination from microorganisms, and other forms of contamination

(3) Manage waste effectively

(4) Store harmful substances appropriately

c. Halal food must be processed, packed, and distributed under strict hygienic conditions in premises licensed in accordance with good manufacturing practices (GMPs) or good hygiene practices (GHPs) as specified in the guidelines on good hygiene practices for small- and medium-scale food industries incorporating HACCP and the public health legislation currently enforced by the competent authority in Malaysia.

d. Systems should be in place to prevent:

(1) Contamination of food by foreign matters such as plastic, glass, or metal shards from machinery, dust, harmful gas or fumes, and unwanted chemicals

(2) Excessive use of permitted food additives

In manufacturing and processing, suitable detection or screening devices should be used where necessary.

6. *Packaging and labeling*

a. The products should be suitably packaged. Packaging materials should be halal in nature and should fulfill the following requirements:

(1) The packaging materials should not be made from any raw materials decreed as being najs by Shariah law.

(2) The materials must not have been prepared, processed, or manufactured using equipment that is contaminated with things that are najs as decreed by Shariah law.

(3) During its preparation, processing, storage, or transportation, it should be physically separated from any other food that does not meet the requirements stated in item (1) or (2) or any thing else that has been decreed as najs by Shariah law.

(4) The packaging material does not contain raw materials considered hazardous to human health.

b. Packaging processes should be carried out in a clean and hygienic manner under sound sanitary conditions.

c. Labeling materials used in direct contact with the product must be nonhazardous and halal.

d. Each container must be marked legibly and indelibly, or a label attached to the container, with the following information:

(1) Name of the product

(2) Net content expressed in the metric system (SI units)

(3) Name and address of the manufacturer, importer, and/or distributor and any trademark

(4) List of ingredients

(5) Code number identifying the date and/or batch number of manufacture and expiry date
(6) Country of origin

e. For primary meat products, in addition to requirements specified in item d, the label or mark should include the following information:
(1) Date of slaughter
(2) Date of processing

7. *Legal requirements*. The product must in all other aspects comply with legislation, including other relevant requirements currently in force in Malaysia.

E. Compliance Products deemed to comply with this standard must comply with clause D above. This shall be verified through a site inspection as deemed necessary by the competent authority.

F. Halal Certificates The halal certificates are to be issued by the relevant Islamic authority in Malaysia.

G. Halal Certificate Mark Upon approval by the federal Islamic authority, each product may be marked with the halal certification mark of that authority provided that the product conforms to the requirements of this standard.

Malaysia does not have a specific law on halal foods. The regulations related to halal food in Malaysia are found in several documents, including the following:

Trade Description Act 1972 In this act, halal food is defined as follows:

1. It does not consist of, or contain, any part or matter of an animal that a Muslim is prohibited by Shariah law to consume or that has not been slaughtered in accordance with Shariah law.
2. It does not contain anything considered to be impure according to Shariah law.
3. It has not been prepared, processed, or manufactured using any instrument not free from anything impure according to Shariah law.
4. It has not in the course of preparation, processing or storage been in contact with or been in close proximity to any food that fails to satisfy conditions 1 to 3 or anything that is considered to be impure according to Shariah law.

With the provision of authority under Sections 10 and 11 of the 1972 act, the Minister proclaimed two orders related to halal food as follows:

Trade Description (Use of Expression "Halal") Order, 1975 Halal descriptions on food labels (including storage and trading areas for the ingredients) includes words and phrases that have the same meaning as halal (e.g., *ditanggung halal, makanan Islam*) or other symbol or emblem which indicates that the ingredient is halal.

Trade Descriptions (Marking of Food) Order, 1975 All food specified in the schedule that is halal according to Trade Description (Use of Expression "Halal") Order, 1975 must be marked by a label, tag, or any other form of mark indicating that such food is halal.

Food Act, 1983; Food Regulations, 1985 The Malaysian Food Regulations, 1985 under the Food Act, 1983, also has provisions in Part IV, Section 11 under particulars related to labeling (of haram/mushbooh food ingredients), whereby the following is stated:

> 11 (1) Every package containing food for sale should, unless otherwise provided in these Regulations, bear on it a label containing the following particulars, namely
>
> c) Where the food contains beef or pork, or its derivatives, or lard, a statement as to the presence in that food of such beef or pork, or its derivatives, or lard, in the form—"CONTAINS (state whether beef or pork, or its derivatives, or lard, as the case may be)" or in any other words to this effect.
> d) Where the food contains added alcohol, a statement as to the presence in that food of such alcohol, in capital bold-faced lettering of a non-serif character not smaller than 6 point, in the form—"CONTAINS ALCOHOL" or in any other words to this effect.

Animal Ordinance, 1953; Animal Rules, 1962 Within Animal Ordinance, 1953, the Animal (Importation) Order, 1962 applies to the importation of meat and livestock to Malaysia, whereby all meat and livestock must be halal, safe, and disease free. The Department of Veterinary Services and the Customs and Excise Department at all ports of entry in Malaysia should together enforce this law.

Custom Act, 1967; Prohibition of Imports/Export, 1988 The order requires that all beef, mutton, and poultry and their products imported into Malaysia be halal.

ASEAN General Guidelines on Halal Food At the regional level, the Association of South East Asian Nations (ASEAN) has taken steps to harmonize regulations on halal food trade, and in 1998 adopted the ASEAN Guidelines on the Preparation and Handling of Halal Food and in 1999, endorsed the ASEAN halal logo with the objective of facilitating trade in the region. The guidelines serve as a practical guide for the food industry during the production and handling of halal food by food-processing establishments. Upon compliance, it is permitted for companies to use a common ASEAN halal logo on the labels of their products as identifications that the products come from ASEAN-accredited food-processing plants (ASEAN General Guidelines on the Preparation and Handling of Halal Food, 1998).

Halal Food Laws in the United States In view of the increasing awareness of Muslims of their obligations to consume halal food, a halal food law was passed in New Jersey on March 6, 2000, the first such law in the United States. Eventually, more halal food laws were passed: in Minnesota in 2001, in Illinois in 2001, in Michigan and California in 2002, and in Texas in 2003. These laws are

intended to prevent fraud in the preparation, distribution, and sale of halal food products. The laws require vendors of halal food to disclose the basis upon which they claim that their food is halal. These laws have some serious limitations in ensuring the integrity of halal food products and building consumer confidence that the halal foods in the marketplace are authentic. The Illinois Halal Food Law passed in 2001 is unique in the sense that it is a new bill and not an amendment, whereas the New Jersey and Minnesota bills were modeled after the kosher laws but were separate laws. Additionally, Illinois law contains provisions providing for the regulation of a halal farm (Riaz and Chaudry, 2003).

Halal Food Regulations in Other Countries In Australia, the Export Meat Orders (EMO) Part 18 under the Export Control Act 1982 legislates the export of halal red meat, edible offal, and meat products. Halal labeling is mandatory if one wishes to describe one's food as halal, which is covered under EMO 323–339. The "pig scare" crisis in Indonesia in 1998 led to the formation of the Halal Certification Authority: the Majlis Ulama Indonesia (MUI), which enforces the Republic of Indonesia (RI) Act No. 23 of 1992 concerning health, RI Act No. 7 of 1996 concerning food, and Government Regulation No. 69 of 1999 concerning Food Labels. In Singapore, the government amended its Administration of Muslim Act (AMLA) in 1999 to regulate, promote, and enhance the halal food industry. Its main halal authority, acting as a government agency, is the Singapore Islamic Council (MUIS). In Thailand, the Statute for the Administration of Organizations of the Islamic Act (the AOI Act), 1997, regulates the halal food control and certification in the country.

In many Muslim-majority countries, such as those in the Middle East, a halal food act is deemed unnecessary, as every Muslim in the country assumes that all the food available in the market is halal. The onus of supplying halal food to the population lies with the government and the suppliers, who are also Muslims and would, hopefully, follow the required procedures.

Acknowledgments

Dr. Joe Regenstein, of Cornell University, reviewed the final draft of this chapter, giving some constructive suggestions.

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PART III

PRESERVATION: REFRIGERATION AND FREEZING

12

BIOCHEMICAL CHANGES DURING ONSET AND RESOLUTION OF RIGOR MORTIS UNDER AMBIENT TEMPERATURE

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Handbook of Poultry Science and Technology, *Volume 1: Primary Processing*, Edited by Isabel Guerrero-Legarreta and Y.H. Hui

INTRODUCTION

Fundamentally, the term *meat* includes muscular tissue along with nerve tissue, adipose tissue, connective tissue, blood vessels, and so on. For different reasons, the most important of these is muscle tissue, since this tissue, together with connective tissue, is what makes meat useful as a food and is also responsible for its characteristics. Because muscles are organs whose particular structure and function are used fundamentally for locomotion, they have a series of characteristics associated with this function which have to be modified when they are used as foods (Forrest et al., 1979). Muscle constitutes a very complex contractile system; its composition and structure have to be considered in order to understand the complex transformation that takes place during the conversion of muscle into meat. Muscle that functions as a motor tissue is converted into an important food, the principal component of meat.

The changes that take place in muscular tissue before being consumed are important to the final quality of the meat, which has led to studies about the causes of variations in quality with the aim of improving quality (Forrest et al., 1979). Many changes that occur after the death of the animal influence the final characteristics of good-quality meat. The death of an animal when slaughtered initiates metabolic processes in the muscle that change its in vivo nature. Animal muscles do not cease to have all their vital functions brusquely and suddenly become meat, but on the contrary, for a period of some hours or days a series of physical and chemical changes take place, all part of the conversion from muscle to meat. In chicken muscles these processes take only a short time (2 or 3 h after slaughter), in comparison to species with red muscles, such as pork, lamb, or beef. Furthermore, during this period chicken carcasses are often submitted to vey high temperatures during scalding (55°C) and very low temperatures during cooling (0°C), along with the decrease of pH from 6.90 to 5.90 (Wakefield et al., 1989; Dun et al., 2000), these changes in pH and muscle temperature have a negative influence on the tenderness of the meat (Dun et al., 2000). In the same way, the handling of birds before slaughter carries important quality defects, as is the case of the stress effect prior to slaughter, which increases the hardness and hardening of the breast. In this chapter we focus on the postmortem changes that take place in muscle tissue of poultry after slaughter, starting from a brief explanation of the muscular structure for its importance in the transformation from muscle to meat, all the chemical events that take place in the live animal and the alterations that this system undergoes after slaughter.

STRUCTURE AND COMPOSITION OF MUSCLE

Many of the properties of meat depend on the muscle structure and its postmortem changes, contraction state, the scale of degrading of structures, and so on, all of which have an important influence on the quality parameters of meat. The skeleton muscle is about 40 to 50% of body weight and has a very important

mechanical role in an animal's life, such as maintaining the shape of the body, and it is responsible for movement (Prändl, 1994). The average percentage of muscle in relation to live weight varies depending on the species, degree of fatness, and dressing method: 35% for beef, 32% for veal, 36% for pork, 25% for lamb, 50% for turkey, and 39% for broiler chicken (Toldrá and Reig, 2006). The muscle/bone ratio is also an important parameter representative of muscling: 3.5 for lamb, 2.1 for veal, 4.0 for pork, 2.5 for turkey, and 1.8 for poultry (Kauffman, 2001; Toldrá and Reig, 2006).

Muscle Structure

Skeleton muscle is made up of filament, long cylindrical cells that are slightly prismatic, also called *muscular fiber*, which are placed one on top of the other to form the muscles. They are recognizable for their marks or pattern of bands, and because their cells are multinuclear, with the nucleus situated peripherically under the membrane, are called *sarcoleme* (Cassens, 1994; Bowers et al., 1991). The muscular fibers are approximately 50μm in transversal diameter and are very long. The fibers are set and maintained in their place by means of components and connective tissue which acts as wrapping, covering the fibers and dividing the muscle into bundles of fibers (Davies, 2004).

Each muscle is surrounded by a thick wrapping of conjunctive tissue, called *epimysium*, which continues with the tendon, which is normally related to bone structures. A primary network of connective tissue goes deep into the muscle, dividing the muscle into bundles of fibers. This level of organization of connective tissue, called *perimysium*, in turn subdivides into thinner layers of connective tissue. The bundles can be grouped into different degrees of organization, called primary, secondary, and tertiary. Within the bundles, the individual muscular fibers are surrounded by a thin layer of connective tissue called *endomysium*. The blood capillars and nerve connections for muscular function in vivo are found in this covering of connective tissue (Cassens, 1994).

In poultry, the muscle fiber cross-sectional area increases with age. Geese selected for meat yield have larger fiber than birds selected for egg production, and fast-growing chickens have larger-diameter fibers than do slow-growing lines. This increase is also associated with an increase in the number of giant fibers, which typically have cross-sectional areas three to five times larger than normal, although these may also result from severe contraction (hypercontracted fibers) (Dransfield and Sosnicki, 1999).

Muscular fibers represent 75 to 92% of the total volume of muscle, and the remaining volume belongs to connective tissue, nerve fibers and extracellular fluid (Judge et al., 1989). Immersed in the sarcoplasm of the fibers, fiber structures called *myofibrils* are found lengthwise. The myofibrils, which are characteristics of muscle cells, are made up of fine protein fibers (filaments) and are directly responsible for the characteristic stretch mark pattern or bands of skeleton muscle. The myofibrils represent 80% of the total volume of muscle cells and are generally the contracting apparatus of the muscle and are able to shorten due to reversible chemical transformations, and so make muscle contraction possible.

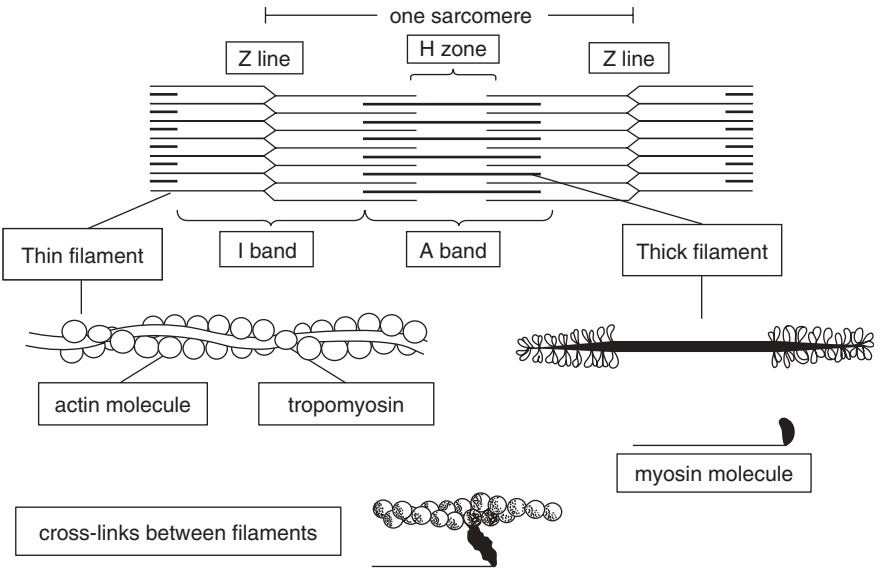

FIGURE 1 Schematic representation of muscle ultrastructure.

This aspect of the myofibrils is due to the presence of two types of thick and thin filaments which have an order, in that they overlap, forming a repetitive configuration of bands with identical characteristics. Each myofibril therefore contains a repetitive series of dark and clear bands. The wide bands of proteins of the muscular fiber, designated *A* (anisotropic) *bands*, contain a clear central area, an *H zone*, which in turn presents a dense *M line*. The clear bands, called *I* (isotropic) *bands*, are each divided in half by a *Z line*. The distance between two Z lines, known as a *sarcomere*, is considered the structural and contract unit of the muscle (Figure 1). The filaments that make up the myofibril consist of proteins known as *myofibrillar proteins*. Water is retained in the spaces between two types of filaments which are organized in a hexagonal network (Schreurs, 2000; Sayas-Barberá and Férnandez-López, 2006; Toldrá and Reig, 2006). Table 1 summarizes the most characteristic elements of a myofibril.

Types of Muscle Fibers

Chickens and, to some extent, turkeys display the largest differences in muscle color known to occur in a single animal. Breast muscle approaches the whiteness of some fish species; leg meat is comparable to pork and sometimes to beef in redness (Schreurs, 2000).

The activity of the muscles is divided into tonic and phasic types, although numerous muscles have mixed functions. Tonic-type muscles are slow to contract, whereas phasic type are fast to contract and are found in muscles with locomotor activity. A commonly used system is classification into three basic fiber

TABLE 1 Elements of a Myofibril

Bands

- *A band:* a region of thick (myosin) filaments
- *I band:* a region containing only thin filaments
- *Z line:* a dark thin line in the middle of the I band containing zigzag elements that anchor the ends of the thin filaments
- *M line:* a dark line in the middle of the I band containing the protein myomesin an *d* creatine kinase that connects the centers of the thick filaments

Sarcomere. An assembly of thick and thin filaments between adjacent Z lines forms the fundamental contractile unit of muscle.

Thick filaments

- Each is an assembly of myosin molecules.
- Each filament is 12 nm in diameter and 155 nm long.
- Each molecule has two heads, associated with the sliding of thick and thin filaments by forming cross-bridges between them. The enzyme catalyzing the splitting of ATP to achieve this is located in the heads.

Thin filaments

- Each is an assembly of several proteins, predominantly globular actin, supported by troponins T, C, I and tropomyosin (regulatory proteins).
- Each filament is 8 nm in diameter and 100 nm long.

Cytoskeletal framework. A distinct lateral component links adjacent myofibrils at the Z disk. The most prevalent proteins present here are titin and nebulin.

Source: Davies (2004).

types: red, white, and intermediate (Solomon et al., 1998). Another system of classification is based on contracting properties and levels of metabolic enzymes: show-contracting oxidative (SO), phase-contracting glycolytic (FG), and fast-contracting oxidative and glycolytic (FOG) fibers. Table 2 summarizes the characteristics of the types of fibers. Red muscles are dependent on oxidative processes for supplying energy, which is reflected in their high content in mitochondria and abundant blood irrigation.

The majority of the skeleton muscles, according to species, contain heterogeneous quantities of different types of fiber. With the exception of the pectoralis superficiales, the most important poultry breast muscle, this muscle contains only "phase" forms of myosin light and heavy chain contractile proteins, and has a predominantly glycolytic energy metabolism (e.g., mainly FG fibers) (Maruyama and Kanemaki, 1991; Solomon et al., 1998). In poultry, only fast-twitch (FG and FOG) fibers are focally innervated by *en plaque* motor end plates. The SO fibers in poultry are multiply innervated and are called *en grappe*. The en grappe end plates do not conduct action potentials (Solomon et al., 1998). With increasing growth rate, fiber becomes more glycolytic (fast twitch, glycolytic) (Dransfield and Sosnicki, 1999).

TABLE 2 Differences Between Muscle Fiber Types

Characteristic	Fiber Type		
	Slow Contracting; Oxidative	Fast Contracting; Oxidative and Glycolitic	Fast Contracting; Glycolytic
Size	Small	Intermediate	Large
Color	Red	Red	White
Myoglobin content	High	High	Low
Lipid storage	High	Intermediate	Low
Mitochondrias	Many	Many	Few
Metabolism	Aerobic	Aerobic/anaerobic	Anaerobic
Capillary density	High	High	Low
Contraction speed	Slow	Intermediate fast	Fast
Resistance to fatigue	High	Intermediate	Low
Contractile action	Tonic	Intermediate	Phasic

Source: Solomon et al. (1998); Schreurs (2000).

Muscle Composition

Meat is considered a protein food. Of the total content of muscle nitrogen, approximately 95% is protein and 5% comprises small peptides, amino acids, and other compounds. Compared with other products, chicken meat has exceptional qualities, since it is a source of high-quality protein that is low in fat with high levels of unsaturated acid fats and is a source of vitamins, which makes it a high-quality product in terms of nutrition and health (Table 3). One of the greatest reasons for the growth of chicken consumption may be the perception by the health-conscious that chicken is a low-fat source of healthy nutrition (Mozdziak, 2004).

Proteins constitute the most important component of the muscle and they have an important role in the structure, function, and integrity of the muscle. They

TABLE 3 Approximate Composition of Some Poultry Cuts

Data for 100-g Edible Portion	Protein (g)	Fat (g)	Cholesterol (mg)	Iron (mg)
Chicken breast meat, no skin, raw	23	1	58	0.7
Chicken breast meat and skin, raw	21	9	64	0.7
Chicken leg meat, no skin, raw	20	4	80	1.0
Turkey, fryer-roaster breast meat only, raw	25	1	62	1.17
Turkey, breast meat and skin, raw	22	7	65	1.2
Turkey leg meat, raw fryer roaster	20	2	84	1.8
Ostrich round, raw	22	2	71	3.5
Ostrich, tenderloin, raw	22	3	80	4.9

Source: Mozdziak (2004).

go through important changes during conversion from muscle to meat, which affects tenderness primarily. There are three groups of proteins in the muscle: myofibrillar protein, sarcoplasmic protein, and connective tissue proteins (Toldrá and Reig, 2006). Table 4 gives a summary of the main proteins, where they are found, and their function. Myofibrillar proteins are soluble in saline solutions of high molarity (about 0.6 M) and constitute approximately 60% of the total muscular protein. Sarcoplasmic proteins are soluble in water or in saline solutions of low molarity (<50 mM); they constitute approximately 30% of the muscular proteins and consist mainly of metabolic enzymes and endogenous proteinases, which we deal with below. Connective tissue proteins are mostly insoluble in either of the above-mentioned solvents and are made up of a very heterogeneous

TABLE 4 Main Muscle Proteins

Protein	Localization and Main Role in Muscle
Myofibillar protein	
Myosin	The main constituent of thick filaments
Actin	The main constituent of thin filaments
Titin	Throughout entire sarcomere; responsible for the longitudinal integrity of the sarcomere
Nebulina	Along thin filaments
Tropomyosin	Coiled around thin filaments in association with actin and troponin; regulatory protein
Troponin T, C, I	Coiled around thin filaments in association with actin and tropomyosina; regulatory protein
Vinculina	Attachment of myofibrils to sarcolemma
Filamin, synemin, Z nin, C,H,X,F I proteins	In the Z line; contributes to its high density
Desmina	In Z line; links adjacent myobibrils at the level the Z line
α, β, γ and eu-actinin	Proteins regulating the physical state of actin
Sarcoplasmic proteins	
Mitochondrial enzymes	Enzymes involved in the respiratory chain
Lysosomal enzymes	Digestive hydrolases (cathepsines, lipase, phospholipase, etc.)
Myoglobin	Natural pigment of meat
Connective tissue proteins	
Collagen	Protein giving support, strength, and shape to fibers
Elastin	Protein that gives elasticity to such tissues as capillaries, nerves, tendons

Source: Schreurs (2000); Toldrá and Reig (2006).

TABLE 5 Lipid Content and Acid Fat Composition in Chicken Thigh, Chest, and Skin

		Acid Fats (%)		
	Total Lipids (%)	Saturated	Monounsaturated	Polyunsaturated
Breast	0.9	33.5	34.5	32.0
Thigh	2.2	32.2	39.4	28.5
Skin	30.3	30.7	47.8	21.4

Source: Ratnayake et al. (1989); Barroleta and Cortinas (2002).

group of constituents which determine the structural integrity and attachment of the muscle to other anatomical elements (Schreurs, 2000).

Fat is a particularly valuable component of meat because of its influence on the flavors of cooked meat and its ability to improve meat's palatability. One of the nutritional advantages of consuming poultry meat, its low levels of fat, is considered a very important positive attribute in contrast to other types of meat (Sayas-Barberá and Fernández-López, 2000). Another positive attribute to be highlighted is its high content of polyunsaturated acid fats and carotenes (Pérez-Alvarez, 2006). With regard to the compositions of chicken acid fats, the majority are oleic, palmitic, and linoleic (Ratnayake et al., 1989; Barroeta and Cortinas, 2002; Cortinas et al., 2005). Table 5 gives the fat content and acid fat composition.

Carbohydrates are stored as glycogen in the liver and muscle. The changes that occur in energy metabolism, the conversion of glycogen to glucose and glucose to lactic acid, are complex; all such changes are controlled and mediated by enzymes and hormones.

PHYSIOLOGY AND BIOCHEMISTRY OF STRIATED MUSCLE

The chemical processes that take place in the muscle after an animal's death are very similar, except for the inability to synthesize or eliminate certain metabolites after physiological death. The contraction and relaxation pathways differ only slightly between those developed in the animal's lifetime and during rigor mortis. The muscle functions in living organisms lead to the execution of work, which is shown through a contraction. The energy needed in the contraction and relaxation process proceeds from hydrolysis of adenosine triphosphate (ATP). This energy uses the transport of active sodium and potassium in order to maintain the membrane potential for the transport system of calcium during relaxation and in the formation of activated myosin (Ponce Alquicira, 2006):

$$\mathrm{ATP} + \mathrm{H_2O} \rightarrow \mathrm{ADP} + \mathrm{H_3PO_4} + 20\ \mathrm{kJ/mol} \qquad (1)$$

The energetic efficacy of the muscle is very high, reaching approximately 35%. The rest is released as heat. Carbohydrates are an important source of energy. Fat is used with the same objective when the carbohydrate reserves have run out. Energy released from carbohydrates (or from fat) is stored in energy-rich compounds, ATP and creatíne phosphate, and is therefore available for muscle contraction (Prändl, 1994).

The muscle contains only enough ATP to maintain the contraction for a few seconds, so it is necessary to obtain energy from a cellular metabolism through the following pathways (Ponce Alquicira, 2006):

- Glycolysis from blood glucose or from muscle glycogen
- Oxidative phosphorylation
- From creatine phosphate
- From the condensation of adenosine diphosphate (ADP)

The carbohydrate stored in the muscle for use as energy is glycogen, and its degradation in the muscles is carried out through anaerobic mechanisms such as aerobias. The release of glucose from the glycogen depends on the glycogen phosphorylase enzyme, which is activated by Ca^{2+}, adrenaline, and adenosine monophosphate (AMP). Glycolysis is the principal pathway in the metabolism of glucose to synthesize ATP into aerobic or anaerobic conditions. The anaerobic degradation of glycogen leads to the production of pyruvic acid, which in turn leads to lactic acid. In certain intermediate points, only three molecules of ATP are synthesized by glucose. Aerobic degradation and the cycle of tricarboxilic acids, of which pyruvic acid is a principal product, lead to the final formation of CO_2 and water, generating 36 ATP molecules per glucose molecule.

Energetic balance:

$$\text{Anaerobic}: \quad \text{glycogen-glucose} + 3\text{ADP} + 3\text{P}_\text{i} \rightarrow \ 2\text{lactato} + 3\text{ATP} + 2\text{H}^+ + 3\text{H}_2\text{O} \tag{2}$$

$$\text{Aerobic}: \quad \text{glycogen-glucose} + 36\text{ADP} + 36\text{P}_\text{i} + 6\text{O}_2 \rightarrow \ 6\text{CO}_2 + 42\text{H}_2\text{O} + 36\text{ATP} \tag{3}$$

In the living animal the anaerobic and aerobic metabolic pathways are developed in synchronization, simultaneously and linked. However, when death occurs, only anaerobic processes are possible (Honikel, 2006).

MUSCLE CONTRACTION

Muscle contraction consists of the shortening of the length of the sarcomere as a consequence of the union between the actin filaments and myosin bonds, where the crossed myosin bonds pull the actin filaments into an A band

(Davies, 2004). The contraction of muscular fiber is initiated by a nervous impulse and requires the energy stored in the ATP. The reactions involved are initiated through the action of an enzyme capable of hydrolyzing the ATP of the muscle. The myosin has the capacity of ATPasa (myosin ATPasa) and therefore hydrolyzes ATP into ADP and phosphate, with the consequent release of energy for muscular contraction. The ATPasa of this protein is increased 100- to 200-fold by the presence of calcium ions and by F-actin (Ponce Alquicira, 2006). The formation of the complex between actin and myosin is due to a succession of multiple stages and includes a change of composition at the head of the myosin, hydrolysis of ATP, and movement of the actin filaments onto the myosin filaments, all of which generates a rush of strength which finally leads to movement (Ponce Alquicira, 2006).

In the relaxed muscle and in the absence of Ca^{2+} ions, the myosin can be associated to the actin, due to the fact that the points of interaction are sterically blocked by the position of troponine, which therefore prevents contraction. The free movement of the filaments is related to the presence of an Mg–ATP complex, which acts as a lubricant (Pearson, 1994). As a result of nervous stimulation, the sarcoplasm reticulum releases Ca^{2+} ions, which join the troponine and produce a change of the composition of its molecules and the movement of the tropomyosin molecule, leaving the G-actin places free, capable of interacting with the head of the myosin. Similarly, partial hydrolysis of ATP through ATPasa of the myosin takes place, forming the ADP–PI–myosin complex and adopting a high-energy state. Active myosin is joined to actin, forming an actin–myosin–ADP complex and the following release of P_i. It is then when a rush of strength takes place and the myosin head pulls the actin toward the center of the sarcomere. This actomyosin complex is separated when a new ATP molecule joins the head of the myosin, forming an actin–myosin–ATP complex. The union of ATP to the head of the myosin reduces the affinity of the myosin head through actin, leading to relaxation and formation of the myosin–ATP complex (Ponce Alquicira, 2006).

Relaxation begins before the reduction of the concentration of Ca^{2+} ions, when they move into the sarcoplasmic reticulum. In this way, troponine is no longer inhibited, and myosin–ATPasa is deactivated. With the deactivation of the ATPase capacity of the myosin, the separation of the actomyosin appears, and ATP–magnesium complex is formed, which relaxes and makes the contracting structure flexible (Prändl, 1994).

CONVERSION OF MUSCLES TO MEAT

The death of an animal when slaughtered initiates metabolic processes in the muscle which alter its in vivo characteristics, and a gradual transformation of the muscle into meat takes place. This process can be divided into three stages: *prerigor*, because the muscle is still elastic, *rigor mortis*, and *resolution* (Ponce Alquicira, 2006). The time this transformation takes depends on several factors, particularly the species of animal and the slaughter method. Oxygen and energy-rich compounds such as glucose are no longer transported to cells, and metabolic

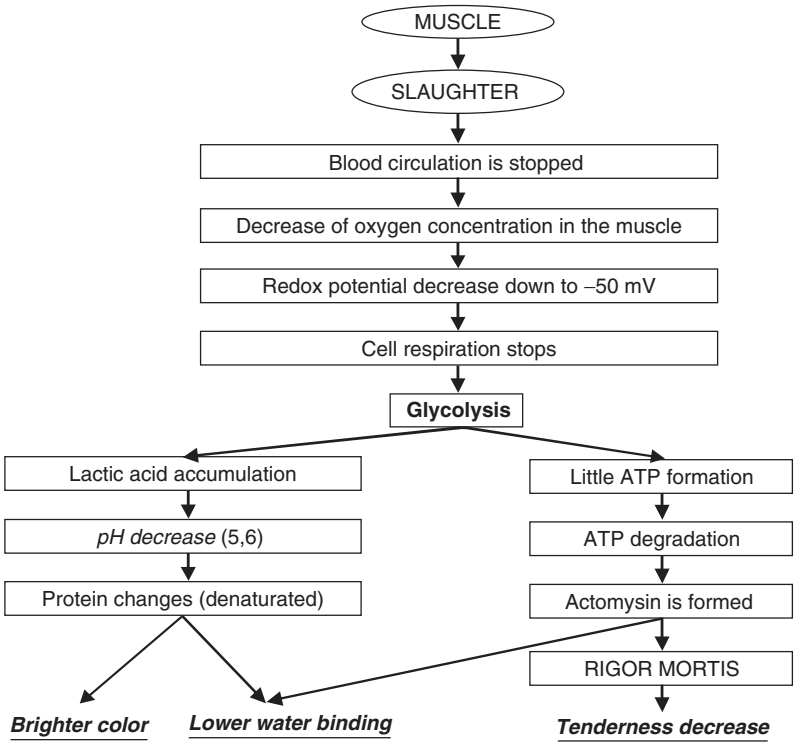

FIGURE 2 Changes during the conversion of muscle into meat.

products are not removed. These facts are the cause of the intense chemical and physical modifications, which give rise to the transformation from muscle to meat or postmortem changes in the muscle. The well-ordered cellular structure begins to disintegrate. Nerve cells cease to function 15 to 30 min after death. Fat cells break triacylglycerols down into fatty acids very slowly, but postmortem, the free fatty acids cannot be used for the formation of the other energy-rich compounds, such as ATP, because the two-carbon units ($-CH_2-CH_2-$) required for acetyl-CoA ($CH_3-Co-S-CoA$) need oxygen, which is not available postmortem. This is why fats remain relatively unchanged in the meat (Honikel, 2006). Figure 2 shows the principal changes that take place in muscle during conversion from muscle into meat. The contraction pathways and muscle relaxation in the in vivo animal differ very slightly from those that take place during rigor mortis, the most notable difference being the inability to eliminate or synthesize certain metabolites after physiological death.

Prerigor Stage

The first consequence of slaughter is that oxygen is no longer transported in the blood and muscles can no longer obtain energy through breathing. Since

mitochondrial activity stops with a decrease in internal oxygen, the only possible metabolic pathway is anaerobic. The muscles' oxygen content is too low to maintain oxidative phosphorylation of ADP to ATP. The only source of ATP is the anaerobic metabolism of glycogen, the main energy reserve of the muscle, which converts lactic acid into anaerobiosis through postmortem glycolysis. Muscle cells can still use glycogen as an energy source, but because of the lack of oxygen, the citric acid cycle and the oxidative phosphorylation pathway no longer function. Many processes need ATP as fuel and the generation of ATP is strictly necessary in the muscle to supply the energy required for muscle contraction and relaxation, membrane transport (drives the Na/K pump of the membrane and the calcium pump in the sarcoplasmic reticulum), metabolic processes, and so on. Glycogen is converted into dextrines, maltose, and finally, glucose through a phosphorolytic pathway. Glucose is then converted into lactic acid with the synthesis of 2 mol of ATP (Toldrá and Reig, 2006). The pyruvate is not decarboxylated (splitting off CO_2 to an acetyl group (CH_3-CO-) and is reduced to lactate, which is the endpoint of the anaerobic breakdown of glycogen in the muscle postmortem. This reaction provides the energy necessary in trying to maintain structural and functional integrity, and at the same time, important chemical changes take place: (1) decrease in ATP and glycogen, and (b) accumulation of lactic acid, which leads to a decreased pH value in muscle fiber. The extent of anaerobic glycolysis depends on the reserves of glycogens in the muscle.

At the initial postmortem period some ATP is regenerated through the conversion of creatine phosphate (CP) into creatine and the transfer of its phosphate to ADP. Some ATP can be generated through the adenylate kinase system, which converts two ADP molecules into one ATP molecule and the other into AMP. None of the postmortem formation mechanisms of ATP are able to maintain the ATP levels for more than a limited period. The main mechanisms of resynthesis are:

(a) $\mathrm{ADP} + \mathrm{CP} \rightarrow \mathrm{ATP} + \mathrm{creatine}$

(b) $2\mathrm{ADP} \rightarrow \mathrm{ATP} + \mathrm{AMP}$

(c) Gycolytic pathway

Postmortem Changes

Gycolytic activity finally stops, either because of the disappearance of the glycogen reserves, or more often because of the decrease in pH that accompanies glycolysis, from approximately 7.2 to values close to 5.3 to 5.7 according to species and handling. The rate of glycolysis varies among species and the muscles of a carcass (Table 6). Glycolytic fibers have a more rapid rigor mortis development. In beef, rigor would normally take about a day, whereas in pork, rigor is complete in several hours, and in chicken breast muscle it takes about 1 h (Dransfield and Sosnicki, 1999). The glycolytic enzymes are denaturalized progressively as the pH approaches 5.5 and at the isoelectric point of the proteins, and the degradation of glycogen ceases when 2 to 20% of the original

TABLE 6 Timing of Anaerobic Glycolysis in Various Muscle and Species

Species	Muscle	Time to Reach pH 5.5 to 5.7 (h)
Pork	Longissimus dorsi	
	Normal	6
	PSE	1
	Adductor	
	Normal	8
Chicken	Pectoralis	1.5
Beef	Longissimus dorsi	18
	Adductor	22
	Sternomandibularis	25
Lamb	Longissimus dorsi	16

Source: Honikel (2004).

amount remains (Ordoñez et al., 1998; Ponce Alquicira, 2006). A consequence of the termination of postmortem glycolysis and the decrease in the ATP level is the end of the contraction–relaxation cycle, so muscular elasticity gradually disappears and rigor mortis begins. At this point, actine and myosin interact to form inextensible actomyosin, since the levels of ATP are no longer enough to permit the rupture of the bonds between actine and myosin. At this moment, the muscle tissue is rigid and inextensible, known as rigor mortis, this state is irreversible.

Three stages of chemical changes are observable postmortem (Honikel, 2006):

1. A period of a few minutes to 30 min after slaughter when no pH decrease occurs. The ATP consumption is buffered by CP.
2. Decrease in pH (from around 7.0) and lactic acid production, with initially constant ATP concentrations (1 to 3 h).
3. Exhaustion of ATP, owing to the lack of glycogen and inactivation of glycolytic enzymes 1 to 30 h after death. In the end, when no ATP is available, the pH is around 5.5.

Chemical changes, decrease in pH, physical changes, and rigor mortis, are interrelated, although in this chapter they are studied separately.

Muscle pH Decrease Almost immediately after slaughter, the levels of muscle glycogen drop 5.5 to 6-fold in 24 h. The drop in the levels of glycogen depends on the species; in beef it is relatively slow, but in pork almost half the glycogen is used in the first 15 min postmortem (Ordoñez et al., 1998). Because the elimination of the products produced from the anaerobic metabolism does not function, lactic acid is accumulated inside the fiber. The pH of the muscle of a healthy and properly rested animal immediately before slaughter varies from 7 to 7.3. After slaughter, the pH decreases due to the degradation of ATP to values of

5.5 to 5.4, the speed of which is influenced by many factors, such as species of animal, muscle type, temperature during the postmortem process, and stress factors. In muscles where rapid-contraction fibers or white fibers predominate, the final pH reaches values of 5.5 in chicken and beef and 5.8 in turkey (Ordoñez et al., 1998). In muscles of slow contraction (principally red fibers), the pH reached by different species is 6.3 beef, 6.1 chicken, and 6.4 turkey. The temperature of the muscle has a great influence on the speed of postmortem glycolysis measured as a decrease of pH. High temperatures (around 40°C) accelerate the decrease of pH, while low temperatures delay the decrease and more time is necessary to reach pH values of 5.8.

At the time of slaughter, when the muscles have a high glycogen content, until rigor mortis appears, relatively high quantities of lactic acid are synthesized and pH decrease is greater than when the glycogen content is low. Therefore, the higher the glycogen content is at the time of slaughter, the lower the final pH value is. There is also a certain importance in the speed with which pH is reduced in meat. The pH fall during early postmortem has a great influence on the quality of poultry meat. Therefore, the rapid endogenous decrease of pH after death leads to meat having defective characteristics (e.g., PSE and DFD meat). The final value of pH influences the conservation and technological properties of meat (Prändl, 1994). Adequate acidification of meat means pH values between 5.4 and 5.8; in this interval, acidophobic microorganisms are inhibited, especially the proteolytics.

Structural Changes: Rigor Mortis At the time of death, the muscle is soft and extensible, but in a few hours it becomes an inextensible and relatively rigid structure, which is known as *rigor mortis*. This stiffness is due to contraction and loss of the ability to relax the muscles, because the source of energy has disappeared. If ATP is used up, the fibrillar structure changes with the formation of permanent bonds across the fibers. With the formation of cross-links between filaments, the meat becomes tough. The onset of rigor mortis marks the most rigid interaction in muscle and its toughest state. This process is basically irreversible, except for when the channels are old and with time certain inherent enzymes can cause degradation of the contracted structure. The biochemical process up to the start of rigor mortis can be divided into the following phases:

1. The flexibility and elasticity of the muscle remain unaltered. The meat is elastic and soft. This phase has a duration variable (1 to 20 h), depending on the reserve of glycogen and CP as well as on the temperature of the muscle. The hydrolysis of ATP increases as a consequence of a progressive drop in pH, but is compensated by the ATP resynthesis.
2. Extensibility and elasticity gradually decrease (2 to 3 h) as a consequence of the reduction of the concentration of ATP.
3. ATP disappears and there is a sharp decrease in the extensibility of the muscle. At this moment rigor mortis is said to be unsaturated.

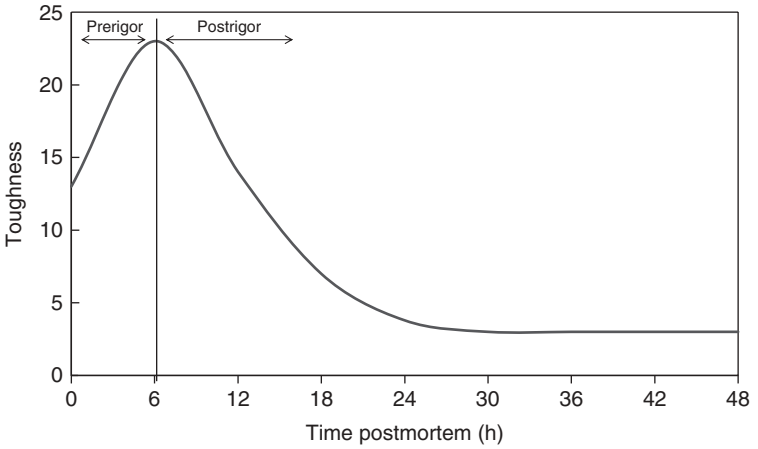

FIGURE 3 Development of muscle toughness in chicken breast. (From Schreurs, 2000.)

The development of the phenomenon of rigor mortis, as with the drop in pH, is influenced by many factors, such as species of animal, muscle type, muscle temperature, and the glycogen reserves and CP of the muscle at the time of slaughter. The higher the glycogen and CP content, the longer it takes for rigor mortis to appear, and vice versa. Temperature is another decisive factor in the development of stiffness and glycolysis, and consequently, the drop in pH is slower when the meat temperature is lower. The biochemical processes stop completely when the meat is frozen. Avian and mammalian muscles show similar postmortem alterations but in contrast to the postmortem physiology of "red meat," this period is shortened in poultry (Schreurs, 2000). The time that passes until rigor occurs in normal process conditions is less than 0.5 h in chicken, less than 1 h for turkey, 0.25 to 3 h in pork, and 6 to 12 h in beef (Ordoñez et al., 1989). The typical course of the toughening of the breast meat of chicken during the time after development of rigor mortis is shown in Figure 3. Maximum toughness is reached approximately 6 h postmortem, after which it gradually decreases.

Other Postmortem Changes With the decrease in pH, the surface electric charges of proteins changes in the direction of equal numbers of positive and negative charges (the isoelectric point). As positive and negative charges attract each other, the water-filled myofibrillar structures shrink in volume. Immobilized water or movement-restricted water is squeezed out into the sarcoplasm, where it is much less immobilized. The water-holding capacity of meat is reduced by internal forces exerted by pH or shrinkage and disintegration of membranes and by external force (Honikel, 2006). Then some water is released from the muscle as a drip loss. The amount of water released depends on the extent and rate of pH drop. Soluble compounds such as sarcoplasmic proteins, peptides, free amino acids, nucleotides, nucleosides, B vitamins, and minerals may be partly lost in the dripping, affecting nutritional quality (Toldrá and Reig, 2006):

With the drop of pH to 5.5, a number of spoilage organisms can no longer grow and the meat is protected. Additionally, lactic acid has a pleasant flavor. Furthermore, ATP, which is converted to ADP, is degraded to adenosine monophosphate (IMP). IMP also has a favorable flavor. A longer period of storage produces hypoxanthine from IMP via inosine. Hypoxanthine has a bitter flavor. During long storage, more and more free amino acids such as glutamic acid are formed from degraded proteins and influence flavor in a positive manner (Honikel, 2006).

Postmortem glycolysis has other effects, several of which influence quality and meat properties. The lack of energy prevents protein molecules from resynthesizing. Those molecules present begin to denaturalize and are susceptible to the attack from endogenous proteinase, including calpains and cathepsins. There is also a tendency to oxidation of the meat pigments, leading to the undesirable metmyoglobin (Pérez-Alvarez, 2006; Pérez-Alvarez and Fernández-López, 2006) and the consequent oxidation of precursors of the flavor of cooked meat (Varnam and Sutherland, 1998).

FACTORS INFLUENCING THE COURSE OF RIGOR MORTIS

Around the time of the slaughter of an animal and during subsequent processing of the carcass, many factors can be identified as influencing its muscular metabolism (Schreurs, 2000). Premortem factors such as catching, cooping, transportation, and suspension from the slaughter line have a large impact on the metabolic status of animals at the time of slaughter. Factors such as bleeding, scalding, plucking, eviscerating, cooling, deboning, and packing, as well as storage time and temperature, influence the course of the postmortem metabolism.

The characteristics of poultry meat can be greatly affected, depending on the handling of the animal in the period immediately before its processing and slaughter. Deficiencies in the well-being of poultry during this period are linked to a decrease in meat quality. After the death of the animal, anaerobic metabolism reduces the pH from about 7.2 in muscle to 5.8 in meat and stiffness develops (rigor mortis). The rate of rigor mortis development can be affected at all stages of production, both pre- and postslaughter, and variations in its rate, in turn, affect the sensory and functional properties of raw meat and of further processed products (Dransfield and Sosnicki, 1999).

Premortem Factors

Poultry meat reaches the rigor state extremely quickly. In the breast muscles of commercially processed chicken, for example, rigor can appear an hour after death, although there may be wide variations in the same lot. The speed of glycolysis can vary and lead to PSE and DFD conditions (Varnam and Sutherland, 1998). The situation of avians differs from mammals where postmortem changes, such as catabolism of ATP and accumulation of lactic acid, do not seem to be

related to the development of rigor mortis. The type of muscle is of considerable importance for determining the speed of postmortem glycolysis. This is due to the differences in evolution, which are a result of the different roles of "red" and "white" muscles (Varnam and Sutherland, 1998). Stress before slaughter (overcrowding, exhaustion, and heat) is one of the principal factors in the decrease of glycogen reserves and therefore in the final high-pH level. To ensure an optimum postmortem process, it is necessary to try to slaughter only rested and calm animals. Similarly, before slaughter, animals should be less stressed and slaughter should be carried out in such a way that it does not cause violent movements or convulsions (Prändl, 1994).

Postmortem Factors

Due to external factors after slaughter, postmortem processes may follow a normal or an abnormal course. The temperature during glycolysis is related intimately to the quality of meat and postmortem processing. Electrical stimulation (ES) increase the rate of rigor development as shown by a more rapid decrease in pH and increase in the inosine/adenosine ratio (Thompson et al., 1987; Alvarado and Sams, 2000). The ES seemed to elicit an earlier metabolic acceleration effect in the duck muscle than in the broiler muscle (Alvarado and Sams, 2000). Considering that the duck muscle was a model for red fibers and the broiler muscle was a model for white fibers, Alvarado and Sams (2000) suggested a greater metabolic sensitivity of the red fibers to ES relative to the white fibers and that red and white fibers do not differ substantially in the effect of ES on their postmortem myofibrillar fragmentation and calpain-mediated protelysis. Other studies reported that there was little difference in birds (rigor development, meat color or meat quality) between conventional killing and decapitation following high-frequency stunning (McNeal et al., 2002; McNeal and Fletcher, 2003).

POSTMORTEM ABNORMALITIES

Because of physiological changes or certain external factors, the postmortem processes can follow abnormal processes. A serious problem for final meat quality can be created by a very fast or incomplete pH drop postmortem. In this way, acceleration of the process of degradation of glycogen from endogenous or exogenous causes is normally associated with low-quality meat (e.g., PSE and DFD meat). Rapid acidification when corporal temperature is still high causes the denaturalization of proteins. Reduction of solubility and a decrease in water retention means that meat will have a pale, soft, and exudative (PSE) appearance. The opposite phenomenon, when pH does not decrease due to low reserves of glycogen, generates a dark, firm, and dry (DFD) meat with a high water-retention capacity (Figure 4).

DFD Meat

For the animals, capture, loading, and transport operations represent a situation of overexcitement and greater muscle activity. All this leads to premortem

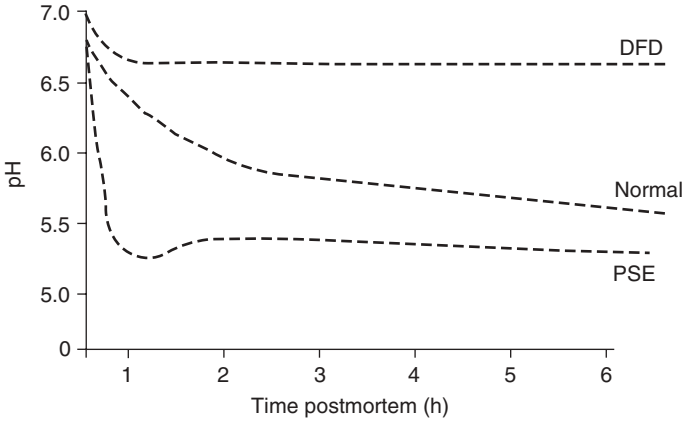

FIGURE 4 Typical postmortem pH drop of normal, PSE, and DFD meats.

acceleration in the consumption of ATP and glycogen, the substances free from degradation of glycogen (CO_2, lactic acid) are forced out of the muscle by the circulatory torrent. When the slaughter of animals is carried out, the muscle has only small quantities of glycogen and there is minimal or no lactic acid production. Therefore, acidification of meat is low and the drop in pH is incomplete (e.g., not lower than 6.2). These meats have a dry appearance, a closed structure, and are dark red in color (Pérez-Alvarez and Fernández-López, 2000; Pérez-Alvarez, 2006). The pH remains high in these meats, which constitutes a risk from the microbiological point of view. These meats constitute a risk because they are prone to contamination by foodborne pathogens and must be processed carefully, with extreme attention to good hygienic practices (Toldrá and Reig, 2006). The meat in general has less pH-induced shrinkage (higher water-holding capacity and firmer structure), which leads to a darker color (no denaturalization, higher oxygen binding). DFD-like muscle was observed in the breast and thigh of ducks that had been stressed (Chen et al., 1991).

PSE Meat

Very fast pH decrease at the prevailing body temperature, more or less above 40 to 42°C, leads to PSE meat. These characteristics occur as a result of early membrane leakage and protein denaturalization, causing shrinkage of fiber. Poultry has been subjected to intense genetic selection for rapid lean muscle growth. This selection carries with it quality anomalies, such as in the case of PSE muscle. In PSE bird muscle, an increase in fiber size and structural regularities are found, such as capillary density, hypercontracted (giant) fibers, and myoplasmic calcium loading (Solomon et al., 1998). Sosnicki and Graser (1996) confirm that in turkeys, PSE is associated with a rapid rate of glycolysis; the rate of glycolysis in pale turkey muscle was twice as fast as in normal-colored turkey muscle. There are numerous similarities between PSE poultry and PSE pork

(Solomon et al., 1998), but the poultry industry has not yet identified such a genetic market and currently has to deal with management, transportation, processing, and other issues to try and alleviate the consequence of the problem (Barbut and Mittal, 1993; Barbut, 1998; Woelfel et al., 2002; Zhang and Barbut, 2005). This industry is currently working on the means to reduce preslaughter stress, and various researchers have managed to develop a nondestructive method of monitoring the rate of rigor mortis development (Barbut, 1998; Cavitt and Sams, 2003).

CHANGES IN MEAT DURING AGING

Aging is the name given to the process of meat tenderization that occurs though the actions of endogenous muscle enzymes, present in living-mortem (Devine, 2003). The stage after rigor mortis is *resolution*, in which muscular tissue gradually recuperates a certain amount of elasticity due to the loss of the integrity of tissue, improving texture and forming precursor compounds of the aroma of the meat (Ponce Alquicira, 2006). These changes take place even before the appearance of stiffness. Myofibrillar and sacoplasmic proteins experience transformations during aging. Aging is affected by the live animal's history prior to slaughter, including preslaughter stress effects. The rate of aging is different for different muscles of the same animal and for different animal species (Devine, 2004).

Another process related to muscular protein metabolism is responsible for tenderization. Proteolysis of key myofibrillar and associated proteins by endogenous proteolytic enzymes is the cause of meat tenderization (Ouali, 1990; Schreurs, 2000). The enzymes responsible for the postmortem degradation of structural muscle are the neutral Ca^{2+} activated proteinases (calpains and calpastatin) and the acid proteinases of lysozomal origin (cathepsins). One of the effects of proteolytic breakdown of structural proteins is myofibrillar fragmentation. As a result of the degradation of the protein responsible for lateral and longitudinal integrity, the myofibrills tend to break more easily under force with the passage of time after death. Microstrutural changes observed during the course of aging after death include (Schreurs, 2000):

- Disappearance of Z lines
- Reduction in density of M lines
- Loss of lateral integrity between adjacent Z lines, M lines, and other structural elements
- Loss of longitudinal integrity at Z–I junctions and at N lines

The majority of studies about degradation of postmortem structure have been carried out with beef, and very few have studied the effects of the action of proteins in poultry meat. The oldest studies about proteolitic activity of myofibrillar proteins in chickens of different ages during storage concluded that the

solubility of the myofibrillar proteins increased after the time of slaughter (Khan and Van den Berg, 1963). Other authors observed the disappearance of the Z line (Fukazawa et al., 1969, 1970) and breakage of myofibrillar primarily in the union between the I band and the Z line after rigor (Fukazawa et al., 1969, 1970; Sayre, 1970). In contrast to beef, the increase of myofibrillar fragmentation is only slightly related to tenderness (Olson et al., 1976). Hay et al. (1973) demonstrated that 48 h postmortem the Z lines of chicken breast disappear, whereas in the thigh they are not damaged. After 168 h postmortem the Z lines in the breast have disappeared completely, whereas in the thigh, the Z lines are damaged but they are still visible. With respect to titin and nebulin, changes have not been found during aging 3 days at 2°C (Suzuki et al., 1985).

The aging of meat, apart from leading to the decrease of hardness, carries with it a high pH and an increase in water-retention capacity, due to degradation of proteins that give peptides and amino acids and the release of sodium calcium ions in the sarcoplasmic reticulum. The pH level and osmotic pressure of muscular cells is increased (Prändl, 1994). Potassium ions released in the sarcoplasm are absorbed by the muscle proteins and displace the Ca^{2+} ions, which increase the meat clear of proteins and its water-retention capacity. This means that the meat is juicier.

Another important fact regarding this stage is the development of aroma. The postmortem processes lead to degradation of the ATP through ADP and AMP until the formation of inosine monophosphate, inorganic phosphorus, and ammoniac. When the IMP degrades, it leads to ribose, phosphate, and hypoxantine. The latter compound contributes positively to the aroma of meat, along with other compounds that occur through the degradation of proteins and fats (Prändl, 1994).

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13

PHYSICOCHEMICAL CHANGES DURING FREEZING AND THAWING OF POULTRY MEAT

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Handbook of Poultry Science and Technology, *Volume 1: Primary Processing*, Edited by Isabel Guerrero-Legarreta and Y.H. Hui

INTRODUCTION

Freezing is considered a very good method for preserving poultry meat for an extended period of time. However, it should be realized that frozen poultry undergoes some chemical changes that limit the storage life of the product (Barbut, 2002). Freezing is a process of bringing down the temperature of food below its freezing point, and frozen storage generally refers to storage at temperatures below -10°C. Common frozen storage temperature is -18°C (Ramaswami and Marcotte, 2006).

The primary objective of freezing is the preservation of the functionality of the materials frozen so that they can be utilized at a later time. *Functionality* means primarily the retention of organoleptic and safety characteristics. Freezing is one of the most effective preservation methods in this respect, but it is not invariably effective in eliminating all undesirable changes in functionality (Karel and Lund, 2003). Lowering the freezing temperature reduces the rate of chemical deterioration, mainly oxidative rancidity, which results in off-flavor development. Other changes might result from protein denaturation, which can cause textural changes of the meat (Barbut, 2002). Most of the changes attributed to the freezing process were unrelated to that process, and except for cases where texture is affected adversely by freezing, the frozen product is indistinguishable from the fresh product when thawed immediately. The evident changes are due to changes during freezer storage rather than to the freezing process (Jul, 1984). Freezing implies two linked processes: a lowering of temperature and a change of phase of water from liquid to solid. Both processes tend to reduce the rates of physical and chemical changes and might be expected to enhance the product shelf life. (Blond and Le Meste, 2004).

FREEZING AND FROZEN STORAGE

Producers of poultry products are increasingly using frozen chicken in the form of carcasses, portions, or boned-out blocks of meat as a raw material (James, 2005). Freezing concentrates solutes, including salts and small organic molecules. Changes in ionic strength and possibly pH (Van den Berg and Rose, 1959) in the remaining unfrozen aqueous phase ensue, leading to the denaturation of proteins; in addition, aggregation and precipitation may occur (Blond and Le Meste, 2004). Growing ice crystals may disrupt structures such as cell membranes and various polymer aggregates (micelles). Separation of water as pure ice freeze-concentrates the nonfrozen solution. These changes affect such important parameters of importance to food properties as pH, ionic strength, and redox potential (Karel and Lund, 2003).

Changes in muscle proteins during freezing depended on the freezing rate. Compared with fast freezing, slow freezing caused a larger loss of drip on thawing, a larger loss of nitrogenous constituents and nucleic acid derivatives to the drip, and a larger loss of water-holding capacity of meat. In addition, compared

to fast freezing, slow freezing increased proteolysis and caused a greater decrease in the adenosine-triphosphatase activity of myofibrillar proteins (Khan and Van den Berg, 1967).

Fellows (2000) explained in detail what happens to meat structure during freezing. Meats have a flexible fibrous structure, which separates during freezing, and as a result, the texture of meat is damaged by freezing. The extent of damage depends on the size of the crystals. During slow freezing, ice crystals grow in intercellular spaces and deform and rupture adjacent cell walls. Cells become dehydrated and permanently damaged, and on thawing, they do not regain their original shape and turgidity. The food is softened and cellular material leaks out from ruptured cells. In fast freezing, smaller ice crystals form within both cells and intercellular spaces. There is little physical damage and minimal dehydration of the cells. The texture of the food is thus retained to a greater extent. However, very high freezing rates may cause stresses within some foods that result in splitting or cracking of the tissues.

Freezing is the most common and efficient way to maintain the quality of poultry products for long periods of time. However, tougher texture, discoloration, and drying have been reported as a result of long-term frozen storage. Storage in the frozen state is generally maintained under conditions minimizing changes. Well-controlled commercial storage results in substantial high-quality life (HQL). Fennema (1966) has listed HQL values for meats frozen 4 to 14 months at $-18^{\circ}C$ (Karel and Lund, 2003).

THAWING

Thawing is the process of bringing a product back to a nonfrozen state. In the freezing process heat is removed from water, and during the thawing process, heat is added to ice. Frozen poultry carcasses can be thawed by immersing in water, by spraying with water, or by thawing in air with adequate protection against contamination. When meat and poultry are frozen, the water that is a natural component of all meats turns to solid ice crystals. The water expands when it freezes, with sharp-edged crystals pushing into the surrounding tissue, rupturing the cells. Water outside the cell wall freezes first. As it does, it leeches water from inside the cell walls. When it thaws, the original balance does not return to normal; the thawed product will have lost some of its natural springiness. The water released during freezing seeps out of the thawing meat and poultry into the package.

During thawing, the temperature rises rapidly to near the melting point and remains there throughout the relatively long course of the thawing process. This results in a longer thawing period than the freezing period and allows more time for chemical and microbial changes (Barbut, 2002). The thermal conductivity and thermal diffusivity of ice are much higher than those of water. So under comparable conditions, thawing takes longer to accomplish (Ramaswami and Marcotte, 2006). The effects of thawing are often more damaging than those of freezing.

This is due to the fact that residence time in the most damaging temperature zone just below the freezing point is very much longer than in freezing. The reason for this phenomenon is due to the heat transfer occurring through unfrozen portions, and the heat transfer through these is much slower than heat transfer through the frozen layer occurring in freezing (Karel and Lund, 2003). Different types of chemical changes are particularly troublesome: oxidative processes and protein degradation, denaturation/aggregation; texture, flavor, and color degradation; and vitamins loss (i.e., decreases in sensory and nutritional qualities).

Ice formation in poultry muscles during freezing will always cause some cell disruption. Therefore, the thawing of meat results in the release of cell constituents to form drip losses. Fast freezing causes less cell disruption than slower freezing and consequently, less drip on thawing (James, 2004). This causes the loss of water-soluble nutrients. In addition, drip losses form substrates for enzyme activity and microbial growth. When food is thawed by microwave or dielectric heaters, heat is generated within the food and the changes do not take place. The main considerations in thawing are to avoid overheating, to minimize thawing times, and to avoid excessive dehydration of the food (Fellows, 2000).

Warm-water thawing of chicken results in lower shear values than does cold-water thawing. Yu et al. (2005) evaluated the effects of thawing temperature on the biochemical and physicochemical properties of prerigor frozen chicken breast and leg muscles. They observed that the ultimate pH of 18°C-thawed muscle was lower than that of 0°C-thawed and 2°C-chilled muscles. The shortening of sarcomere length and muscle length of thaw-rigor muscles was more than those of chilled muscle, but there were no significant differences between chilled muscle and 0°C-thawed muscle. They also found that samples thawed at 0°C had a higher myofibrillar fragmentation index (MFI) and a lower shear value than those of samples thawed at 18°C. Shear force value and MFI were not significantly different between chilled muscle and 0°C-thawed muscle. By thawing at 0°C, thaw shortening was prevented and tender meat comparable to the chilled meat was obtained.

LIPID OXIDATION

Lipid oxidation corresponds to the most important chemical reactions associated with quality change during frozen storage. Products of autoxidation of unsaturated fatty acids affect wholesomeness and nutritional value. Postslaughter biochemical changes involved in the conversion of muscle to meat are accompanied by a loss of cellular antioxidant defenses and an increased propensity of meat lipids to undergo oxidation (Theron, 2008). It is generally agreed that storage at temperatures maintaining maximal freeze concentration may be optimal (T_g'). However, these are difficult to achieve in practice because maximal concentration is not consistent with the rapid freezing required to achieve good quality during freezing. Furthermore, temperatures corresponding to the range below T_g' are difficult to maintain in the distribution chain from factory to consumer storage. Fennema (1966) has reported values for T_g' for meat at -18°C.

Even with proper packaging materials, rancidity will occur over time. Off-flavors are the result of this chemical change. Rancidity is controlled by trimming excess fat from meat before freezing, using a wrapping material that prevents air from reaching the product, and storing foods for the length of time recommended.

In foods, lipids can be oxidized by both enzymatic and nonenzymatic mechanisms. It is generally agreed that autoxidation (i.e., reaction with molecular oxygen) is the main reaction involved in oxidative deterioration of lipids (Blond and Le Meste, 2004). Oxidative rancidity develops more rapidly in certain types of poultry products, such as ground turkey, turkey patties, and fried chicken (Nonaka and Pippen, 1966; Olson and Stadelman, 1980) Rancidity becomes more prominent when the poultry has been cooked (Jacobson and Koehler, 1970). Studies show that using antioxidants such as butylated hydroxyanisole (BHA) in poultry products retards oxidation significantly (Dawson et al., 1975). However, when studying the palatability and other characteristics of chicken broilers refrozen repeatedly, Baker et al. (1976) found that 2-thiobarbituric acid (TBA) values did not increase over those for the control until after four refreezes.

Igene et al. (1979) reported that cooking accounted for a significant increase in rate of lipid oxidation and that cooked meat held at 4°C for 48 h was more susceptible to development of off-flavor than similar samples held at −18°C for 48 h. The stability of different types of meat, either raw, frozen, or cooked, was in the order beef > chicken white meat > chicken dark meat. Pikul et al. (1984) examined fresh chicken breast and leg meat samples which were frozen for 3 or 6 months at −18°C and cooked in microwave and convection ovens and tested for levels of lipid oxidation. After 6 months in storage, malonaldehyde in fat from meat samples increased 2.5-fold. Fat from meat cooked in a convection oven averaged 83% higher malonaldehyde concentration and 21% higher fluorescence compared to levels before cooking. Levels of lipid oxidation products in fat from chicken breast and leg meat were not significantly different in microwave than in convection oven cooking.

Some reports have indicated that sensitive meats such as mechanically deboned meat intended for frozen storage of more than 6 months can exhibit problems if carbon dioxide is used as a result of carbonic acid formation and pH reduction, which can contribute to some lipid oxidation. In many cases where the meat is intended for prolonged frozen storage, vacuum packaging and an oxygen barrier film are used. The removal of oxygen helps to decrease the rate of oxidation and the development of rancid off-flavor formation. For cooked poultry products, recommended frozen storage is at −18°C, where the overall storage life depends on ingredients added and the inclusion of antioxidants (Barbut, 2002).

Rancidity has been investigated with a commercial solid-state-based gas-sensor array system in freeze-stored turkey stored up to 9 months at two different temperatures, −10 and −20°C, and different atmospheric conditions, in the presence of air and under vacuum, respectively. The gas-sensor readings showed high correlation with reference measurement data as this barbituric acid reactive substances, secondary volatile oxidation products, and rancidity-related sensory attributes ($r > 0.9$, $p < 0.001$). It could be demonstrated that the gas-sensor-based method

was similar to a trained sensory panel in its ability to detect lipid oxidation in freeze-stored turkey meat. For samples stored in vacuum or at −10°C, better discrimination was obtained with a gas-sensor array system (Haugen et al., 2006).

The importance of lipid oxidation varies with the quantity and nature of the lipids; highly unsaturated lipids are less stable than saturated ones. Polyunsaturated fatty acids are autoxidized in the presence of oxygen to hydroperoxides that decompose into volatile compounds, forming flavor and aroma compounds characteristic of rancid foods (Blond and Le Meste, 2004). The production of meat, particularly chicken, with a more unsaturated profile has been the focus of some attention, as such meats are perceived as having a "healthier" image (Theron, 2008).

Antioxidants are used regularly to stabilize the flavor of composed foods; they delay the development of rancidity by interfering with the initial step of the free-radical reactions or by interrupting propagation of the free-radical chain (Nawar, 1985). Research showed that vitamin E supplementation of broiler feed increases the oxidative stability of broiler carcasses under frozen and refrigerated storage. Carcasses of broilers from birds fed nonsupplemented diets could only be refrigerated for 3 days and frozen for less than a month. Supplementation of as little as 20 mg of vitamin E/per kilogram of feed doubled the frozen storage time, whereas supplementation of 40 mg of vitamin E/per kilogram of feed extended storage time by 1 day in refrigerated broiler carcasses. If this concentration is increased to 160 mg of vitamin E/per kilogram of feed, storage at 4°C can be extended to 8 days. This investigation further showed that vitamin E supplementation under these conditions had no significant effect on broiler performance, microbial spoilage, color deterioration, fatty acid composition, or postmortem pH changes (Theron, 2008).

Feed composition has an appreciable effect on the storage stability of frozen products. Sheldon et al. (1997) investigated the effect of dietary vitamin E on the oxidative stability, flavor, color, and volatile profiles of refrigerated and frozen turkey breast meat. They reported that the TBA values were inversely related to the dietary vitamin E levels. No differences in TBA values were detected for samples frozen for 5 months. Mean color scores increased, indicative of less pale meat, as the level and duration of feeding dietary vitamin E increased. Their findings showed that varying dietary vitamin E levels significantly influenced the oxidative stability and functionality of turkey breast meat.

The effects of diets containing fish meal (0 or 4%), fish silage (0 or 4%), and vitamin E (60 or 200 mg/kg) and the processing effect of marinating with sodium citrate (0.24 or 0.48%) or ascorbate (0.31 or 0.62%) have been studied by Mielnik et al. (2002). They used a trained sensory panel to assess the samples after storage at −25°C for 1 week, 3 months, and 6 months. Feed with 4% fish meal resulted in increased fish flavor and odor of the thighs, while 4% fish silage had a smaller effect on these attributes. Four percent each of fish meal and fish silage added together into the feed caused a strong fish flavor and odor in the product and accelerated the rancidity process. A high concentration of vitamin E (200 mg/kg) in the feed reduced rancidity when 4% fish products were added to

the feed, but no effect was noted when 4% fish meal plus 4% fish silage were added together. A high concentration of ascorbate in the brine (0.62%) decreased the sensory score for rancidity attributes (hay, grass, soap, and paint), while a high concentration of citrate (0.48%) increased these parameters in frozen stored chicken thighs.

Grau et al. (2001a) reported the cholesterol oxidation in frozen dark chicken meat as influenced by a dietary fat source (beef tallow, fresh and oxidized sunflower oils, and linseed oil), and α-tocopherol (α-TA) and ascorbic acid (AA) (225 and 110 mg/kg feed, respectively) supplementation on the cholesterol oxidation product (COP) content and 2-thiobarbituric acid (TBA) values in raw and cooked dark chicken meat vacuum packaged and stored at -20°C for 7 months. Dietary α-TA was highly effective in protecting raw or cooked meat from cholesterol and fatty acid oxidation, regardless of its degree of unsaturation. In contrast, AA supplementation was ineffective and even promoted oxidation in raw meat from broilers fed unsaturated-fat diets that had not been supplemented with α-TA. Oxidation values (raw or cooked meat) from α-TA or α-TA + AA-supplemented diets were not statistically different ($P > 0.05$). TBA and COP values were correlated significantly in raw samples ($r = 0.6466$, $p = 0.0001$).

In a similar study, Grau et al. (2001b) used factorial design to ascertain the influence of a dietary fat source (e.g., linseed, sunflower and oxidized sunflower oils, beef tallow) and the dietary supplementation with α-tocopheryl acetate (α-TA) (225 mg/kg of feed) and ascorbic acid (AA) (110 mg/kg) on dark chicken meat oxidation (lipid hydroperoxide and TBA values and cholesterol oxidation product content). They observed that α-TA greatly protected ground and vacuum-packaged raw or cooked meat from fatty acid and cholesterol oxidation after 0, 3.5, or 7 months of storage at -20°C. In contrast, AA provided no protection, and no synergism between α-TA and AA was observed. Polyunsaturated fatty acid–enriched diets (those containing linseed, sunflower, or oxidized sunflower oils) increased meat susceptibility to oxidation. Cooking always involved more oxidation, especially in samples from linseed oil diets. The values of all the oxidative parameters showed a highly significant negative correlation with the α-tocopherol content of meat.

A recent work has again demonstrated that dietary fat and vitamin E influence the concentrations of total cholesterol oxidation products (COPs) in broiler muscle. Eder et al. (2005) investigated the effect of dietary fat (palm oil, soybean oil, or linseed oil) and vitamin E (20, 40, or 200 mg/kg) on concentrations of COPs in broiler muscle. They reported that COP concentrations were influenced by dietary vitamin E concentration, dietary fat, treatment, and type of muscle ($p = 0.001$). Increasing the dietary vitamin E concentration generally reduced the concentration of COP. This effect was strongest in broilers fed linseed oil and weakest in broilers fed palm oil; the effect of vitamin E was also stronger in heated muscles than in raw or frozen-stored muscles. Moreover, the concentration of COPs in thigh muscle was more strongly influenced by dietary vitamin E than that in breast muscle. COP concentrations in muscles were on average highest in broilers fed linseed oil and lowest in broilers fed palm oil, but the effect of

the dietary fat also depended on the vitamin E concentration, the treatment, and the type of muscle. In conclusion, our study shows that dietary fat and vitamin E influence the concentrations of total COP in broiler muscle.

Fat source also influenced fatty acid composition of duck meat. Russell et al. (2003) observed that ducks fed tallow had a higher percentage of saturated fats, whereas ducks fed olive oil had a higher percentage of monounsaturated fats than did other dietary groups. In the absence of supplemental α-TA, duck muscle stability to lipid oxidation was greatest for those receiving diets containing sunflower oil and lowest for those receiving tallow. α-Tocopherol content and oxidative stability of duck muscle were increased ($p < 0.05$) by α-TA supplementation irrespective of fat source. Interestingly, oxidative changes were much more extensive in duck breast meat than corresponding thigh meat for all treatment groups. This finding is in contrast to those from similar dietary trials for chicken and turkey. Therefore, oxidative stability of duck meat differs from that of other poultry meats.

Recently, Racanicci et al. (2008) conducted research with broiler chicks raised from 10 to 40 days of age and fed a corn–soy diet with 4% of fresh or oxidized poultry offal fat to evaluate the effects of dietary fat quality on broiler performance and on oxidative stability of frozen thigh meat during storage. At 41 days of age, birds were slaughtered and carcass characteristics were evaluated. Skinless and deboned raw thigh meat was packed and stored for 9 months at -20°C. Thiobarbituric acid reactive substances (TBARSs) were assessed monthly in the frozen samples to evaluate the oxidative status of stored meat. Birds performance and carcass characteristics were not affected by the presence of oxidized poultry fat in the diet. After 6 months of storage, the oxidative stability of frozen thigh meat from broilers fed oxidized poultry fat was reduced, as indicated by higher TBARS values.

Herbs and other natural ingredients have also been investigated as potential antioxidants of meat. Botsoglou et al. (2003) conducted a research on the antioxidative effect of dietary oregano essential oil and α-tocopheryl acetate supplementation on susceptibility of chicken breast and thigh muscle meat to lipid oxidation during frozen storage at -20°C for 9 months. Their results clearly demonstrated that all dietary treatments had a major impact on the oxidative stability of broiler meat. Dietary oregano essential oil supplementation at the level of 100 mg/kg feed was significantly ($p \leq 0.05$) more effective in reducing lipid oxidation than the level of 50 mg of oregano essential oil per kilogram of feed and control, but less effective ($p \leq 0.05$) than α-tocopheryl acetate supplementation. Thigh muscle was found to be more susceptible to oxidation than breast muscle, although the former contained α-tocopherol at markedly higher levels. Mean α-tocopherol levels in muscle samples decreased during frozen storage, the decrease being sharper between 1 and 3 months and 3 and 6 months of frozen storage for breast and thigh muscle samples, respectively. O'Sullivan and others (2004a) added antioxidants (concentration range 0 to 4%) to fresh minced chicken meat and observed that in fresh meat, butylated hydroxyanisol/butylated hydroxytoluene (BHA/BHT) was the most effective antioxidant, while rosemary was the

most effective among the food ingredients tested. In previously frozen meat, vitamin E, tea catechins, sage, BHA/BHT, and rosemary were effective antioxidants. In cooked chicken patties, BHA/BHT was the most effective antioxidant, and tea catechins were the most effective among the food ingredients tested. Antioxidants (BHA/BHT, rosemary, vitamin E, tea catechins, and sage) were more active in patties formed from previously frozen meat than in patties formed from fresh meat and were most active in cooked patties. Thus, increasing the oxidative stress on the meat product increased the effectiveness of added antioxidants. Overall, tea catechins, rosemary, and sage had the best antioxidant potential in fresh, previously frozen, and cooked chicken patties. These authors also reported that the use of α-tocopheryl acetate, rosemary (0.10%), sage (0.10%), and tea catechins (0.01%) reduced lipid oxidation in chicken nuggets in both the presence and absence of salt. However, when sodium tripolyphosphate was incorporated into the same product system, the effect of antioxidants was reduced to a significant degree (O'Sullivan et al., 2004b).

Packaging affects lipid oxidation of mechanically deboned turkey meat in frozen meat. Mechanically deboned turkey meat stored in packages where a natural antioxidant (α-tocopherol) was used in production of one of the polyethylene layers had, in almost every instance, the lowest TBARS values and hexanal content when stored in a vacuum or modified atmosphere. However, this difference was not statistically significant. Neither TBARS values nor hexanal content showed dependency on the temperature profile (frozen or frozen/thawed/refrozen) during storage (Pettersen et al., 2004).

Hashim et al. (1995) studied the effects of irradiation of refrigerated and frozen chicken on sensory properties investigated on skinless boneless breasts and leg quarters. Irradiation did not affect the appearance of moistness and glossiness of raw chicken (white or dark). Leg quarters irradiated while refrigerated were darker ($p \leq 0.05$) than controls (nonirradiated chicken). Raw irradiated chicken had higher "fresh chickeny," bloody, and sweet aromatic aroma intensities than those of nonirradiated samples. Cooked irradiated frozen dark meat had more chicken flavor, and cooked irradiated refrigerated dark meat was more tender than controls. No other sensory attributes of cooked chicken were affected. The state at which chicken had been irradiated (refrigerated or frozen) did not affect its sensory properties.

PROTEIN DENATURATION

The conformation of protein derives from its secondary and tertiary structure. As a result, every treatment of proteins with concentrated saline solutions, organic solvent, heat, and cold may modify this conformation. The effects of protein denaturation are numerous: decreased solubility, altered water-binding capacity, loss of biological activity, particularly enzymatic, and increased susceptibility to attack by proteases due to the unmasking of peptide bonds in unfolded structures (Blond and Le Meste, 2004). Zhang and Barbut (2005) showed that meat proteins

were damaged during freezing and that PSE (pale, soft, and exudative) meat was more severely affected than DFD (dark, furin, and dry) meat, or that more protein denaturation occurred in the PSE meat.

The solubility of skeletal muscle myofibrillar proteins in water was examined by Ito et al. (2004). In this study the solubility of the proteins was found to be sensitive to the ionic strength and pH of the solution. At an ionic strength of less than 12 mM and neutral pH, more than 80% of myofibrillar proteins were solubilized. Heating at a temperature above 70°C was required for the proteins to retain their solubility. The solubility of freeze-dried protein powder prepared from water-soluble myofibrillar proteins was also examined, and it was found that the addition of trehalose and heating were essential for resolubilization in water. Amino acid composition of water-soluble myofibrillar proteins was found to be almost the same as that of myofibrillar proteins.

The myofibrillar proteins, which aggregate during frozen storage, are probably linked by secondary interactions and disulfide bonds. As these aggregates tend to grow in number and size, the proteins lose more or less of their water-binding capacity (Blond and Le Meste, 2004). Even at the low temperatures used for storage, most enzyme systems are still active (Blond and Le Meste, 2004). Uijttenboogaart et al. (1993) carried out research to determine whether stabilization of myofibrillar protein isolates (MPIs) during frozen storage could be achieved by addition of certain cryoprotectants. For 2 to 4 weeks at −21°C MPIs were exposed to different freezing and thawing treatments to determine to what extent cryoprotectants may prevent denaturation of MPIs. They found that an overall evaluation of color, weight losses of gels during cooking, and texture proved that 2.8% sorbitol in combination with 4% starch was the best cryoprotectant. A positive effect was also noted for a mixture of 2.8% sorbitol and 4% sucrose. In contrast, the addition of a dextrose polymer mixture to MPI was not effective in maintaining product integrity.

TEXTURE

Freezing involves the change of water contained in the food from a liquid to a solid. When water freezes it expands, and the ice crystals formed cause cell walls of food to rupture. As a result, the texture of the product will be much softer when it thaws. The location, number, and size of the ice crystals formed determine the resulting texture of the frozen–thawed product. The freezing rate has a strong effect on the texture because slow freezing results in large ice crystal formation, while fast freezing results in small crystals. Formation of large crystals is more damaging to the cellular and membranous structures of the muscle because they are formed in extracellular locations, which actually tend to squeeze the cell structures as they grow. Fast or quick freezing is a process in which the temperature is lowered to about −20°C within 30 min. Slow freezing is a process in which the desired temperature is achieved within 3 to 72 h. Fast freezing is advantageous in maintaining a product's quality but is substantially

more expensive. Fast freezing results in small ice crystal formation that causes less damage to the muscle cell structure. The damage is only seen later, during thawing, where less drip loss is exudating the product compared to poultry frozen at a slow rate (Barbut, 2002). Hence, upon thawing, they leave a product with severe textural breakdown. Temperature fluctuations cause the tiny nuclei to merge, resulting in larger crystals, with the result being that the advantage of quick freezing disappears. Therefore, proper temperature maintenance during storage is as important as the freezing process itself. However, in general, rapid freezing provides a better texture than slow freezing (Ramaswami and Marcotte, 2006).

Freezing increases tenderness in carcasses aged for less than 6 h. Where carcasses had been aged for 24 h, there was little difference in tenderness between frozen and unfrozen birds (James, 2004). Thielke et al. (2005) showed that aging prior to freezing of poultry fillets decreased shear values significantly after between 8 and 9 h of aging, instrumental tenderness was confirmed by sensory evaluations. Longer frozen periods have not shown good results. Lee et al. (2008) studied changes in broiler breast fillet tenderness during long-term frozen storage and observed a decrease in tenderness during frozen storage up to 8 months at -18°C. They suggested that for optimal tenderness, frozen broiler breast fillets are best consumed within 2 months of freezing.

Baker et al. (1976) found that shear values for dark meat in the cooked muscle showed no change, while shear values for light meat decreased. In another study the textural and rheological differences among broiler breast meat ranging from pale, soft, and exudative (PSE) to dark, firm, and dry (DFD) in their fresh and frozen (and thawed) forms were investigated by Zhang and Barbut (2005). The PSE meat showed significantly higher lightness values and lower pH and water-holding capacity values than those of normal and DFD meats; DFD meat was also significantly different from normal meat. During cooking, PSE meat lost significantly more liquid and produced a softer gel than did normal or DFD meats; texture profile analysis parameters were lower for the PSE meat. The storage modulus values (G', rigidity of elastic response of the gelling material) showed that DFD meat produced a more rigid gel during cooking (especially above 54°C) and later during cooling (back to 30°C) compared with the PSE meat. Freezing resulted in a trend toward lower G' values before, during, and after cooking. The results indicated that meat proteins were damaged during freezing and PSE meat was more severely affected, or that more protein denaturation occurred in the PSE meat. It is also important to note that fatty acids formed during autoxidation may produce indirect effects on textural degradation by promoting protein denaturation (Blond and Le Meste, 2004).

FLAVOR

Probably the most important reaction leading to both quality and nutrient losses in frozen foods is oxidation. The consequences of oxidative instability are the key

factors that limit the storage life of frozen foods. Just as in foods kept at more normal ambient temperatures, unless they are stored in a vacuum or in an inert gas, atmospheric oxygen will diffuse through frozen food and may react with many of the soluble and insoluble components. One consequence of oxidation on sensory quality is the development of off-flavors and rancidity, usually caused by oxidative breakdown of membrane and storage lipids (Erickson, 1997).

The polyunsaturated fatty acids in meat and fish are particularly susceptible to oxidation. As with vegetables and fruits, it is the products of fatty acid oxidation that give rise to characteristic off- and rancid flavors and aromas (Fletcher, 2002a). The storage times recommended for frozen meat and fish products are chosen to be within the period before off- and rancid flavors and aroma are detectable. In general, those meat and fish products that contain a larger amount of polyunsaturated fatty acids are least stable and have shorter storage lives. For example, oily fish have a typical frozen shelf life of about 6 to 9 months at $-18^{\circ}C$, whereas white fish have a frozen shelf life of 12 to 24 months. Equivalent cuts of pork and beef have frozen shelf lives of 10 to 12 and 18 to 24 months, respectively (International Institute of Refrigeration, 1986).

Taste panel comparisons of fresh and frozen chicken meat showed that freezing caused a significant change in the odor of uncooked breast and leg meat and a decrease in tenderness of cooked breast meat. The results suggest that rapid freezing preserves the integrity of muscle proteins to a greater extent than does slow freezing (Khan and Van den Berg, 1967). The juiciness and flavor of frozen poultry are important, but they are more a function of product preparation and infrequent, but acute, production or processing errors, which are usually easily corrected or avoided (Fletcher, 2002a).

Turkey roasts that had been cooked before freezing and reheated after thawing had a less intense turkey flavor and were drier than roasts that were not cooked before freezing (Cash and Carlin, 1968). Brunton et al. (2002) stated that cooked turkey breast is particularly susceptible to lipid oxidation-mediated off-flavor development during refrigerated storage. Compared to liquid nitrogen–cooled turkey breast, the levels of a number of unsaturated carbonyl compounds were much higher in freshly cooked air-cooled samples and showed large increases in chilled meat during storage (James, 2004).

COLOR AND APPEARANCE

Color changes can occur in frozen foods. Since appearance is so critical for consumer selection, poultry producers go to great lengths to produce products with the appropriate color for a particular market and to avoid appearance defects that will affect product selection or price negatively (Fletcher, 2002b). Some adverse consequences of oxidation may include color loss and/or change (Fletcher, 2002b). The bright red color of meat as purchased usually turns dark or pale brown. This may be due to lack of oxygen, freezer burn, or abnormally long storage. Freezing does not usually cause color changes in poultry. However,

the bones and the meat near them can become dark. Bone darkening results when pigment seeps through the porous bones of young poultry into the surrounding tissues when the poultry meat is frozen and thawed.

Brant and Stewart (1950) reported that the occurrence and amount of bone darkening in frozen poultry could not be related to the extent of bleeding, chilling method, freezing rate, temperature and length of storage, or temperature fluctuations during storage. The age of a bird had a significant effect, with 16- to 17-week-old birds showing less discoloration than is shown by younger birds. No discoloration was found in 1-year-old birds. A combination of storage at -30°C, rapid thawing and immediate cooking, or cooking the carcasses before freezing reduced the discoloration.

Bone darkening is a condition seen in young chickens after freezing. This shows as a dark/bloody appearance of the tips of the bones and muscle areas close to the bone. Myoglobin squeezed out from the bone marrow through the relatively porous bone structure of young chickens during the freezing process causes this. When myoglobin is present at the bone surface, it will turn to a dark color during cooking, and the product becomes unacceptable to consumers. Most often, this is seen around the leg, thigh, and wing bones and sometimes in the breast and backbone areas. Although it appears unappealing, the problem does not affect the safety, flavor, texture, or odor of the meat (Barbut, 2002). Lee et al. (2008) observed that the color of frozen breast fillets tended to be darker, redder, and less yellow than that of the control, with increased storage duration: up of 8 months of storage.

Perlo et al. (2006) evaluated the effects of different proportions (0%, 10%, 20%, 30%, 40%) of washed mechanically deboned chicken meat (WM), as a substitute for hand-deboned chicken meat, on the physicochemical and sensory characteristics of chicken nuggets. The addition of WM increased the fat content but was significant ($p < 0.05$) only when 40% of WM was added, whereas the protein content was reduced significantly ($p < 0.05$) with 20% of WM. Significant differences ($p < 0.05$) were found in L^*, a^*, and b^* values with different proportions of WM; however, these differences were evidently not discerned, as shown by the lack of significant differences ($p > 0.05$) in ΔE^* color scores. The addition of WM did not affect ($p > 0.05$) the sensory attributes of chicken nuggets. From a technical viewpoint, instead of hand-deboned chicken meat, up to 40% WM could be incorporated into nugget formulation without affecting the sensory attributes of the product. Minor changes in composition were observed, but they were probably not detrimental to the product.

Evaporative chilling has an influence on meat appearance. Evans et al. (1988) found that evaporative chilling at an airspeed of 3.0 m/s and a temperature of 0°C with spraying for 60 s at 20-min intervals during the first half of the chilling period produced the best appearance. Chilling in air at 3.0 or 0.2 m/s and 0°C without sprays produced birds of slightly inferior appearance. Lyon and Lyon (2002) state that discoloration of raw or cooked tissue can occur from cell disruption and blood migration caused by slow or variable chilling rates (James, 2004).

Cold stores have low humidity because moisture is removed from the air by the refrigeration coils. Meat surfaces that are exposed to cold air during storage will eventually dehydrate and result in freezer burn. Such areas have a lighter color, due to microscopic cavities, previously occupied by ice crystals, which alter the wavelength of reflected light. Freezer burn is a particular problem in foods that have a large surface area/volume ratio but is minimized by packaging in moisture-proof materials (Fellows, 2000; Barbut, 2002). Freezer burn does not make food unsafe, merely dry in spots. Heavily freezer-burned foods may have to be discarded for quality reasons. Color degradation is also related to oxidation during storage. The discoloration of meat is due to the oxidation of myoglobin to metamyoglobin. Color stability is improved by the presence of ascorbic acid or the addition of citric acid, which maintain the phenolic substances in a reduced colorless state (Blond and Le Meste, 2004).

In an early work, Baker et al. (1976) studied the effect of refreezing on packed broiler carcasses frozen at -18° or -30°C. At 2- to 4-day intervals they were thawed at room temperature for 7 to 8 h (to 4°C internal). Random carcasses were removed for testing and the remainder were refrozen up to five times. Visual observations showed no appreciable increase in sliminess or bone discoloration due to repeated refreezings. Lee et al. (2008) investigated the changes in broiler breast of color attributes during long-term frozen storage. They reported that the color of the frozen fillets tended to be darker, redder, and less yellow than the control, with increased storage duration.

PSE meat is a growing problem in the poultry industry and is characterized by a rapid postmortem pH decline (Woelfel and Sams, 2001). The low-pH condition while the body temperature remains high leads to protein denaturation, causing a pale color and reduced water-holding properties. Rapid freezing of poultry results in the production of very small reflective ice crystals at the surface, but poor temperature control during storage will cause the small crystals to grow, merge, and lose their lightness (James, 2004).

Galobart and Moran (2004) studied the changes in light reflectance and the extent of thawing loss after extended freezing with breast fillets from late-marketed broiler males using population representatives having L^* values above and below the median. They used skinless boneless fillets exhibited a median 48-h postmortem of $L^* = 63.0$ when held at -20°C for 5 months. Muscles were thawed 3 days at 4°C. The total drip was 10.7%, and similar losses occurred for samples above and below the 48-h postmortem L^* median. L^* values measured on thawed fillets decreased significantly from their respective 48-h postmortem values with samples that had been located above the median but were similar with those below. Redness (a^*) was similar among fresh samples, whereas a greater yellowness (b^*) occurred with muscles having L^* above the median than below it. Freezing led to increased a^* and b^* to the same extent after thawing. They concluded that light reflectance of fillets from late-marketed broilers indicates that PSE-like muscle would prevail with the population at large and exhibit associated problems uniformly.

DRIP LOSS

Freezing and frozen storage does not significantly affect the nutritional value of meat and fish, proteins. However, on thawing frozen meat and fish substantial amounts of intra- and extracellular fluids and their associated water-soluble proteins and other nutrients may be lost (*drip loss*). The volume of drip loss on thawing of meat and fish is highly variable, usually on the order of 2 to 10% of wet weight, but in exceptional circumstances up to 15% of the weight of the product may be lost (Fletcher, 2002b). From the moment an animal is slaughtered, the meat produced begins to lose weight by evaporation. Freezing does not stop weight loss. After meat is frozen, sublimation of ice from the surface occurs. Tight shrink wrapping will decrease the problem, whereas loose wrapping and temperature fluctuations will accelerate sublimation. Carcasses will lose weight during air chilling but gain in either a continuous water spray or an immersion process (James, 2004). Simeonovov et al. (1999) found average weight gains of $0.7 \pm 1.7\%$ in the spray chilling of dressed broilers and up to 3.3% in immersion chilling.

When studying the palatability and other characteristics of repeatedly refrozen chicken broilers, Baker et al. (1976) found that total drip increased but total loss (which included cooking losses) changed little after the first refreezing. Total moisture in the cooked product for dark meat showed no change until after four refreezings. From the results of this study, it appears, that poultry can be safely refrozen several times, provided that the meat is handled properly.

Crigler and Dawson (1968) carried out a study of the effect of freezing rate on drip and cell disruption. Their data indicate that there are critical freezing times to aim for and others that should be avoided. The rate of freezing at the center of the muscle may not be the critical factor. In industrial practice, the range of freezing rates between and within individual poultry carcasses will be far larger. It is therefore impossible to recommend a practical freezing process that will minimize drip production on thawing (James, 2004).

Lee et al. (2008) studied the changes in broiler breast fillet water-holding capacity during long-term frozen storage. They observed that the moisture content of cooked meat decreased gradually, showing a significant drop between 2 and 6 months of storage, while thaw and cooking loss increased consistently over the entire storage period. The color of the frozen fillets tended to be darker, redder, and less yellow than that of the control with increased storage duration.

NUTRITIONAL VALUE

The freezing process itself does not destroy nutrients. In meat and poultry products, there is little change in nutrient value during freezer storage. The main effect of freezing on food quality is damage caused to cells by ice crystal growth. Freezing causes negligible changes to pigments, flavors, or nutritionally important components, although these may be lost in preparation procedures or deteriorate later during frozen storage (Fellows, 2000).

Van Heerden et al. (2002) found that frozen skin had a higher mineral and vitamin A content but a lower level of vitamin E than fresh chicken skin. Medium-chain fatty acids were higher and long-chain unsaturated fatty acids were lower in frozen than in fresh chicken tissues. Cholesterol was higher in fresh than in frozen fat. Compared with air-blast freezing, carbon dioxide freezing of mechanically deboned poultry meat will reduce its frozen storage life because of increased lipid oxidation (Barbut et al., 1990). When combined with aerobic storage, this method achieved a life of 2 months at -18°C, and vacuum packing extended it to 4 months. A storage life of up to 5 months was achieved with air-blast freezing (James, 2004).

During prolonged storage, oxidation may lead to significant chemical changes and loss of labile vitamins (Fletcher, 2002b). Similarly, products of autoxidation of unsaturated fatty acids affect wholesomeness and nutritional value (Theron, 2008). The main change in frozen foods during storage is loss of vitamins. Water-soluble vitamins (e.g., vitamin C, pantothenic acid) are lost at subfreezing temperatures. Losses of other vitamins are due mainly to drip losses, particularly in meat and fish. Residual enzyme activity such as proteolytic and lipolytic activity in meats may alter the texture and flavor over long storage periods and lead to oxidation of lipids. This reaction takes place slowly at -18°C (Fellows, 2000). Although macromolecular components such as carbohydrates and protein may undergo limited oxidation, any influence on nutritional value is likely to be small. However, several vitamins, notably ascorbate and folates, are particularly susceptible to oxidative damage (Fletcher, 2002).

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14

LOW-TEMPERATURE STORAGE OF POULTRY

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Handbook of Poultry Science and Technology, *Volume 1: Primary Processing*, Edited by Isabel Guerrero-Legarreta and Y.H. Hui

INTRODUCTION

The term *raw meat* is used in some contexts, including for muscles that underwent chemical and physical changes after slaughtering but had little or no processing (e.g., marinated, ground, refrigerated, frozen) (Aberle et al., 2001). Several characteristics affect the quality of raw poultry attributes, from breeding to processing. Every person involved in the food chain, from the animal producer to the consumer, has specific expectations about attributes related to poultry quality, such as odor, color, texture, and flavor (Northcutt et al., 1994; Aberle et al., 2001). A wide variety of processes have been used for poultry preservation, but low-temperature storage (chilling and freezing) is the most common and efficient way of extending poultry shelf life. However, low-temperature storage may result in quality changes (Reid, 1998; Winger, 2000). A phase change from water to ice, which occurs on freezing foods, can result in unpredictable results in relation to reaction rates. In addition, some foods have accelerated reaction rates at subfreezing temperatures. This may be due to the concentration of reactants, as freezing results in the crystallization of water as pure ice. It may also be due to the disruption of cellular structures, thus allowing previously separated chemicals to come in contact and react (Winger, 2000). Freezing preservation is based on the concept that most chemical reactions are slower at lower temperatures. In general terms, the Arrhenius equation indicates the dependence of reaction rates on temperature. For this reason, refrigeration is useful in preserving the freshness of foods by reducing the rate of chemical reactions and the microbial growth rate. Since this relationship appears to have general validity, rates would be expected to be even slower in frozen storage (Reid, 1998) (Table 1). According to Yoon (2002), the most important factor related to the oxidation of frozen chicken is its capacity to retain water, which results in a higher or lower degree of toughness and juiciness in the meat. Ice crystal formation during freezing is related directly to quality due to crystal formation: If poultry meat is treated prior to freezing with 10% trisodium phosphate or tripolysodium phosphate, crystal formation is avoided within myofibrills.

As mentioned earlier, lowering the temperature to the freezing point of a food tissue tends to extend food shelf life. Exceptions are associated primarily with potential chill damage, where cell metabolic processes are disrupted by low temperature and abnormal metabolism pathways take place. The mechanisms proposed for chilling damage often include phase change in the cell membrane lipids as well as conformational changes in cell biopolymers. These physical

TABLE 1 Poultry Storage Life (Days) at Several Temperatures

Product	−12°C (10°F)	−18°C (0°F)	−24°C (−12°F)
Chicken, whole	9 (260)	18 (540)	>24 (750)
Chicken, parts/cuts	9 (260)	18 (540)	>24 (750)

Source: Reid (1998); Symons (2000).

changes within the cell are believed to lead to changes in cell chemistry and biochemistry (Reid, 1998).

As adverse effects appear to result from physical changes in some components (e.g., lipids) similar effects are expected under below-freezing conditions. There are signs of damage (similar to chill damage) at such temperatures, perhaps as a consequence of phase change in some membrane lipids. The phase change of water from liquid to ice, as expected, has consequences both in supercooled (i.e., with no ice formation) tissues and in frozen (i.e., with ice formation) tissues. In the supercooled state, a food system may undergo physical damage, but in the frozen state, damage is more extensive (Reid, 1998).

CHILLING AND FREEZING METHODS

Common freezing and chilling methods used by the poultry industry include the following (Barbut, 2002):

- *Still air* is the method commonly employed in domestic refrigerators and in some large refrigerated rooms in meat-processing plants. The temperature of the freezer usually ranges between −10 and −40°C, and heat is slowly removed from the product (Faw and Chang-Mei, 1987).
- *Blast freezing* uses high-velocity cold air circulated by fans to provide rapid air movement. The rate of heat transfer is greatly improved over that of still air, and the freezing rate is higher. Air velocities commonly used in a commercial air-blast freezer can range from 30 to 1100 m/min, and the temperature can range from −10 to −40°C (Barbut, 2002).
- *Plate freezing* is used for wrapped meat placed in trays in direct contact with metal freezer plates or shelves. The temperature of the plates can range from −10 to −30°C. Plate freezing is generally used for thinly packed fillets or ground meat patties (Barbut, 2002).
- *Liquid immersion/spray* is used for poultry pieces and sometimes for whole carcasses. The products to be frozen are packaged in plastic bags and immersed in a freezing liquid such as a sodium chloride brine, glycol, or propylene glycol (Barbut, 2002).
- *Cryogenic freezing* uses liquid or condensed gases such as nitrogen (N_2) and carbon dioxide (CO_2); both can be used in liquid or vapor form. The freezing rate is very fast, because the boiling points of liquid nitrogen and carbon dioxide are −196 and −78.5°C, respectively (Barbut, 2002).

Poultry carcasses are commonly chilled by water immersion or cold air immediately after evisceration. This process allows a reduction in body heat from around 39°C to about 5°C within a few hours. Regulations require the temperature of frozen poultry to be down to −18° C within 72 h of being chilled and packaged. The resulting product is relatively stable (Reid, 1998). The cooling rate is the most important condition in food freezing and chilling. The rate at which

temperature declines during the process depends on factors such as bird size, chilling method, amount of insulating fat, refrigeration equipment, and product load (Barbut, 2002).

When related to the ability of tissue to dissipate heat, slow freezing occurs when the rate of cooling does not exceed the capability of the cells to export water; only extracellular ice is formed. In this process, the temperature desired is achieved within 3 to 72 h. Fast freezing occurs when the ability of the cell to export water has been exceeded. As a consequence, critical internal supercooling is exceeded and water is nucleated within the cells. In this process the temperature is lowered to about -20°C within 30 min. This can be achieved by direct immersion in a very cold medium, or indirect contact of the meat with a cold refrigerant or air blast of cool air across relatively small portions of the meat. Slow freezing leads only to extracellular ice crystals, whereas fast freezing leads to both intracellular and extracellular ice. During slow freezing the time allowed for ice crystal formation is very long, resulting in large crystal formation, and is indicative of potential cell dehydratation. Since the permeability of cell walls and membranes and the potential magnitude of critical supercooling are properties of individual cell types, the actual conditions that correspond to either slow or fast freezing will differ from cell to cell. It should be noted that the ability of animals cells to resist internal ice formation is much less than that of many plants. Thus, the rates of change of temperature that produce only extracellular ice in many plant systems may still result in the formation of intracellular ice in animal tissue system (Reid, 1998; Barbut, 2002). Fast freezing is advantageous in maintaining product quality, but is substantially more expensive. Fast freezing results in the formation of small ice crystals, which cause less damage to the muscle cell structure. The damage is not seen until later, during thawing, when less drip loss is exudating the product compared to poultry frozen at a slow rate (Barbut, 2002) (Table 1).

COLOR IN POULTRY

Color is the major appearance attribute of most foods, and as such is an important characteristic of food quality. There are many reasons for its importance, among them standarization of the product (the consumer is suspicious of different product batches showing color variability), the measurement of quality, and as an indicator of biological and/or physicochemical breakdown. Color is also critically important in the many dimensions of food choice, and it influences the perception of other sensory characteristics by consumers, who like to see a consistent amount of color in meat and skin (Sunde, 1992; Clydesdale, 1998; Fletcher, 1999b). The demand by consumers for color in poultry carcasses shows pronounced regional differences around the world. In some countries, intense pigmentation of birds is highly desirable; in others, pale skin is preferred (Fletcher, 1999b).

The major cause of color in most foods is the presence of natural pigments. In poultry skin, the most abundant pigments are carotenoids, whereas

in muscles, color is due to hemopigments (myoglobin and, to a lesser extent, hemoglobin) (Clydesdale, 1998). Carotenoids are a group of yellow to red lipid-soluble pigments very widespread in nature. They include carotenes and xantophylls. Structurally, they consist of eight isoprenoid units arranged symmetrically, with cyclized ends. The main cause of carotenoid degradation is oxidation, the severity of which depends on whether the pigment is in vivo or in vitro. For instance, lycopene is very stable in tomatoes but highly unstable when extracted and purified. In processed foods the oxidative mechanism is more complex and depends on factors such as light, heat, and the presence of pro- and antioxidants, since the reactions are caused by free-radical formation (Clydesdale, 1998).

The pigmentation in poultry skin depends on the genetic capability of the bird, the presence of pigments in the diet, the health of the bird, and meat processing. Meat color is due to hemopigments and their derivatives. In a live animal, hemoglobin is the predominant pigment, but in a slaughtered and bled animal, myoglobin accounts for some 95% of the remaining heme pigments. Hemoglobin and myoglobin are both complexes that include a protein moiety, globin, and a nonpeptide component, heme, composed of an iron atom and tetrapyrrole, or porphyrin, a large planar ring similar to that found in the chlorophylls but with iron at the center rather than magnesium. In myoglobin, the heme is attached to globin, whereas hemoglobin is a tetramer made of four units linked together (Clydesdale, 1998). Myoglobin reactions involve the heme and globin moieties and ligands in which iron is in a dynamic state (Fe^{3+}) or a reduced state (Fe^{2+}). In raw meat, there is a reversible cycle among the major pigments: oxymyoglobin, myoglobin, and metmyoglobin. Myoglobin (Mb) is purple and in the presence of oxygen becomes oxygenated (i.e., producing a covalent complex between myoglobin with Fe^{2+} and molecular oxygen) to form the bright-red oxymyoglobin (O_2Mb), which is the familiar bloom of raw meats when exposed to air, or is oxidized to metmyoglobin (MMb), containing Fe^{3+}, resulting in an undesirable brown color (Clydesdale, 1998). Red O_2 Mb is stabilized by the formation of a highly resonant structure, and as long as the heme moiety remains oxygenated, no further color changes will take place. However, the oxygen is continually associating and dissociating from the heme nucleus, a process influenced by a number of conditions, including low oxygen pressures. When this happens, the reduced form is oxidized to brown MMb (Clydesdale, 1998).

Effect of Refrigeration on Color

The increasing trend for further poultry processing generally demands epidermis removal. However, skin color is important for some markets; since carotenoid pigments are deposited in the epidermis, care must be exercised during refrigeration because freeze burn can cause a spotted appearance of the skin (Fletcher, 1999b). The effect of chilling on poultry heme pigments is not clear. Fleming et al. (1991) reported no effect of immersion versus air chilling on heme pigments of broiler breast or thighs. However, Boulianne and King (1995) reported that pale boneless broiler breast fillets are due to loss of heme pigments during storage

in ice-slush tanks. Yang and Chen (1993) found that lightness (L) and redness (a) values in ground breast and thigh meat decrease with storage. Muscle pH and meat color are highly correlated; high muscle pH is associated with darker meat, whereas low muscle pH is associated with lighter meat. At the extremes, high-pH meat is often characterized as being dark, firm, and dry (DFD) and low pH results in pale, soft, and exudative (PSE) meat. Muscle pH affects both light reflectance properties of the meat and myoglobin chemical reactions (Fletcher, 1999a,b).

At 3°C, the pH of ground poultry meat increased significantly with increased storage time over a 28-day period. As storage time progressed, Hunter L (lightness) and a (redness) values of ground chicken meat both decreased; this indicated a reduction in reddish color with time. An inversed relationship was observed between pH values and L or a values. Results of this study support the observations of Troutt et al. (1992), who indicated that L and a values decreased as the storage time of ground beef patties stored at 3°C increased (Yang and Chen, 1993). Hunter color values from refrigerated ground chicken meat samples seem to be linearly related to pH. Regression equations for the effect of refrigerated storage on L values indicated that ground chicken meat lightness decreased as pH increased during storage. It also became less red and yellow (b) during storage, as show by regression analyses. The correlation between Hunter color readings and the pH of refrigerated ground chicken meat was highly significant (Yang and Chen, 1993). Muscle pH also affects the enzymatic activity of the mitochondrial system, thereby altering the oxygen availability for heme reactivity (Fletcher, 1999b).

The most important visual defects are those associated with bruising and hemorrhage. Discoloration of muscle tissue due to bruising or to blood accumulation has negative effects on product appearance. If severe enough, bruises and hemorrhages result in product rejection by consumers. Bruises are due to aging of capillary hemorrhaging in the tissue due to physical trauma, whereas hemorrhages refer simply to any blood accumulation (Fletcher, 1999b). Dark brown to black bones can also be caused by freezing (Fletcher, 1999b).

Methods of Measuring Color and Pigmentation

The terms *pigmentation* and *color* are often used interchangably, although they refer to different attributes. Pigmentation refers to coloration with a pigment or to the deposition of pigment, whereas color refers to a property of the object in terms of how light is reflected from that object (Fletcher, 1992). Therefore, methods used to analyze the deposition of a given pigment are based primarily on spectrophotometry or reflectance colorimetry. Measuring color implies analyzing the actual color or the subjective appearance of the product by a color fan color, such as the DMS color fan for poultry skin (Fletcher, 1992).

TEXTURE IN POULTRY

Texture is important in food quality, as it results in acceptance or rejection by consumers. Its role as a quality attribute is defined as the result of physical

properties perceived by touching, appearance, and sound. Peluffo and Monteiro (2002) define texture as "difficulty or facility for chewing meat." Kramer (1951) and Meullenet et al. (2004) defined firmness/tenderness as "the main textural characteristics of all meat products, raw or processed," and meat quality as "the sum of this food acceptability or preference characteristics by the consumer." Meat texture is affected by such animal premortem factors as breed, sex, age, handling practices (premortem, slaughtering, and postmortem), temperature and storage time, cooling rate, and meat processing. Changes produced during muscle conversion into meat also affect texture (Peluffo and Monteiro, 2002).

Proteins have a marked influence on foods' physical characteristics, as postmortem storage mainly involves ripening. Ripening of poultry meat has recently been related to quality loss; recently, it has been reported that ripening may improve textural properties, although it can also cause reactions between proteins and fats that result in reducing protein solubility and increasing denaturation and, as a consequence, reducing meat texture.

Effect of Storage Temperature on Texture

Temperature and time are the most important factors regarding chilled or frozen storage, since enzymatic activity is reduced considerably at low temperature. When broiler carcasses are held at high temperature (30°C), the meat softens 86% of its initial value, whereas under refrigeration conditions, only 8% softening occurs (Dransfield et al., 1992). At an experimental level, high temperatures and low pH postmortem tenderness occur due to calpains (Fletcher, 1999b). Murphy and Marks (2000) observed a peak in proteolysis of high-pH breast and leg meats at 3 to 4 h postmortem when stored at 0°C due to calcium-induced calpain activity.

At very low freezing temperatures, other changes result from protein denaturation, causing textural deterioration (i.e., toughening). The freezing rate has a marked effect on the texture because slow freezing results in large ice crystal formation, whereas fast freezing results in small crystals. The formation of large crystals is more damaging to the cellular and membranous structures of the muscle (Barbut, 2002). Moreno (2005) observed that a high cooling rate during the onset of rigor mortis strongly influenced final muscle tenderness. In general, chilling of prerigor meat to 15 to 20°C reduces hardness, due to further reduction in fiber contraction when the temperature is reduced to 4 to 6°C, although the extent of this reduction depends on the fiber type.

Freezing inhibits calpain activity but does not inactivate these enzymes completely, and reactivation can occur after thawing. Freezing also influence toughness, as described by Goll et al. (1970), who studied freezing–thawing cycle effects on rigor onset at various levels of muscle maturity. Meat freezing before the onset of rigor mortis also affects the texture, producing an extremely tough meat when thawed (thawed rigor), caused by disrupts of the calcium pump and release of calcium to the sarcoplasmic reticulum, producing rigor conditions; when thawed, extensive contraction occurs (Dransfield et al., 1992).

Methods of Measuring Meat Texture

A number of methods have been developed to measure meat texture. Instrumental and descriptive sensory analysis, as well as consumer sensory evaluations, or combinations of all of them, have been used to measure tenderness. The assessments are divided into subjects: sensory, objective, structural, and chemical (Chrystall, 1994) (Table 2). Subjective assessment is based mainly in tasting and smelling the product; the main disadvantage of the method comprises existing differences in taste due to factors such as age, gender, and cultural differences. The most common meat texture assessment is carried out by consumers or by a trained and experienced panel. Two types of tests can be employed: discriminatory, when a group of judges decide from several different samples, and descriptive, with evaluation taking place by means of characterization or scoring (Chrystall, 1994).

Objective assessment is carried out by instruments, some of them imitating the mechanical principle of human chewing, divided basically into cutting and compression. Instrumental methods such as the Allo–Kramer multiple-blade shear compression system, Warner–Bratzler shear blade, and texture profile analysis are commonly used in the poultry industry to evaluate tenderness in broiler breast meat (Sams et al., 1990) (Table 2).

CUTTING METHODS

Cutting methods are based on measuring the force necessary to cut a food sample. The most widely used cutting equipment for meat analysis is the Warner–Bratzler shearing device, developed in 1928 by K.F. Warner, a U.S. Department of Agriculture research scientist, and modified in 1932 by L. J. Bratzler, a graduate student at Kansas State University. It consists of a triangular knife that cuts a meat sample. Warner–Bratzler shear values are the force to shear a $\frac{1}{2}$-in. core of a meat sample, commonly reported in grams, kilograms, or newtons. To standardize Warner–Bratzler values, research conducted at Texas A&M University established tenderness threshold values for the Warner–Bratzler shear force. For example, for a beef loin sample with shear values of 3.2 kg or less, there is 95% confidence that consumers will find the steaks at least slightly tender. If beef loin steaks had shear values of 3.9 kg, there is 68% confidence that consumers will find those steaks at least slightly tender (Zhang and Mittal, 1993).

The multiblade Kramer shear press has been adapted to a variety of instruments to measure poultry meat tenderness. The effects on shear press performance of friction (Bourne, 1972; Voisey and Reid, 1974), tolerance (Voisey, 1977), cell size (Voisey and Kloek, 1981), number and thickness of blades (Timbers and Voisey, 1985), and sample weight (Szczesniak et al., 1970) have been studied. The system includes elements of cutting, compression, and extrusion. The sample analyzed can be of a wide range of geometries; once in the press the food is aligned and subject to a variety of grinding and cutting forces. The result is the average strength required to cut and grind the sample (Hart and Fisher, 1991; Chrystall, 1994).

TABLE 2 Some Texture Measurement Instrumentation

Texture Parameter	Type of Texture Measuring Device	Instrument
Firmness	Penetrometer	Magness–Taylor fruit pressure tester
		Christel texturometer
		Maturometer
		Instron
		Texture analyzer
Resistance to compression	Compressiometer	Baker Compressimeter
Tenderness	Shearing devices	Christel Texturometer
		Allo–Kramer shear press
		Lee–Kramer shear press
		Warner–Bratzler shear press
		Pabst texture tester
		Dassow's shear-jaw device
		Texture analyzer
Cutting firmness	Cutting device	Asparagus fiberometer
		Cherry Burrell curd
		Tension meter
Texture close to mastication (firmness, hardness, cohesiveness, crispness, springiness)	Masticometer	Volodkevich bits tenderometer
		Denture tenderometer
		MIT denture tenderometer
		General Foods texturometer
		Allo–Kramer shear press
Hardness, crispness		Shortometer
Extrusion	Extrusion	FIRA/NIRD extruder
Resistance to flow	Capillary viscosity	Ostwald viscometer
		Cannon–Fenske viscometer
		Lamb capillary viscometer
	Rotational viscosity	MacMichael viscometer
		Brookfield viscometer
		Zahn viscometer
	Other viscosity	Haake Rotovisko viscometer
		Hoeppler viscometer
		Parten–Megberd falling number
Semisolid consistency	Consistometer	Adams consistometer
		Kramer shear press
		Rotovisco rheometer

(*continued overleaf*)

TABLE 2 (*Continued*)

Texture Parameter	Type of Texture Measuring Device	Instrument
Elasticity	Extension elasticity	Brabender extensograph
		Simon research extensometer
		Moxograph
		Resistograph
Gel strength	Empirical methods	Bloom gelometer
		Boucher electronic jelly tester
		Exchange ridgelimeter
	Fundamental tests	Weissenberg rheogoniometer
		Air turbine viscometer
		Parallel-plate viscoclastometer
		Chainomatic balance relaxometer
		Oscillating concentric cylinder
	Multipurpose units	Instron universal testing machine
		Food technology's texture test system (Kramer shear press)
		General Foods texturometer

Source: http://food.oregonstate.edu/texture/table.html.

Other texture analysis systems combine subjective and instrument analysis, as described by Cavitt et al. (2004). The authors compared the Allo–Kramer (AK) and razor blade (RB) shear and laser sarcome length determination to analysis by a trained panel performing a descriptive sensory evaluation to analyze the hardness of deboned breast fillets after various postmortem times (0.25 to 24 h). The RB shear method has a higher correlation to sensory attributes than that of the AK method (Table 3).

COMPRESSION METHODS

Examples of compression equipment include the MIRINZ (Meat Industry Research Institute of New Zealand) instrument, developed by Farlane and Marer in 1966, and the Volodkevich system, developed in 1938. Both systems are based on the use of probes that compress a sample placed on a platform (Sherman, 1979; Hart and Fisher, 1991; Chrystall, 1994). The Volodkevich system was developed to simulate cuts with incisor teeth. Originally designed to analyze the firmness and softness of meat samples, it can also be used to analyze raw and cooked vegetables (Sherman, 1979; Hart and Fisher, 1991; Chrystall, 1994). Consideration of factors affecting instrument measurement of chicken meat tenderness is important in experiments. To determine the factors affecting tenderness measurement, such as shear rate, sample shape, sample temperature,

TABLE 3 Texture Lexicon Used for Profiling the Texture of Pectoralis Major Muscles

Term	Definition	Technique
First bite/chew		
Initial hardness	The force required to compress the sample	Compress or bite through the sample one time with molars or incisors
Cohesiveness	The amount the sample deforms rather than splits apart, cracks, or breaks	Place the sample between the molar teeth and compress fully; may also be done with incisors
Moisture release	The amount of wetness or moistness felt in the mouth after one bite or chew	Compress the sample with molars one time only (chew references five times)
Chewdown characteristics after 10 to 12 chews		
Chewdown hardness	The force required to bite through the chewed sample	Chew the sample up to 12 times; form a bolus with the chewed sample and evaluate the force required to bite through the chewed sample (do not chew references)
Cohesiveness of mass	The amount that the chewed sample holds together	Chew the sample with molar teeth 10 to 12 times and evaluate (chew references 10 times)
Number of chews to swallow	The amount of chewing required to prepare the sample for swallowing	Chew the sample and count the number of chews to the bolus stage

Source: Cavitt et al. (2004).

and suitable load cell, the multiblade Kramer shear cell is also used. Heath and Owens (1997) concluded that shear rate affects shear values directly, but these two parameters are not linearly correlated; as sample size increases, shear value is reduced, but sample shape and temperature prior to analysis have no effect on shear values. Changing load cell size created no statistically significant difference in shear values, as shear values calculated with a peak force and a yield force showed the same trends in tenderness; shear values calculated with a peak force had less variation, indicating that they will be more precise than those calculated using a yield force.

Texture profile analysis (TPA) is another tool used to describe mechanical food properties. Lyon and Lyon (1990b) reported on the relationship between TPA and a trained panel response to intact broiler breast meat using four postmortem deboning times (<5 min; 2, 6, and 24 h) and two cooking methods (bags in a water bath; in a microwave oven). The trained panel developed 17 attributes and rating scales to evaluate texture (Table 4) for a four-stage profile ranging from the first compression with molar teeth to swallowing and the aftertaste in the mouth. Instrumental TPA attributes of hardness, springiness, cohesiveness, and chewiness were also calculated. Meat from muscles deboned 5 min and 2 h postmortem was significantly different from that deboned 6 or 24 h postmortem for 16 of the 17 sensory attributes. No sensory differences were noted for meat from muscles deboned 6 or 24 h postmortem. Muscles removed 5 min postmortem had significantly higher hardness and chewiness values than did those deboned 2, 6, or 24 h postmortem. The panel scored meat cooked via microwave as being more succulent and having less aftertaste compared to samples cooked in a water bath. The microwaved meat was more cohesive and chewy than was water bath–cooked meat.

FLAVOR IN POULTRY

From the sensory evaluation point of view, flavor is a series of sensations perceived by two senses, taste and smell. Taste is perceived by the buds on the tongue and other parts of the mouth; four basic tastes can be perceived: salt, sweet, bitter, and sour/acid. However, there are some sensations, such as pain, metal, and "umami" (see below), which can also be detected. The sense of smell also takes part in this event. Some chemicals can stimulate the olfactory receptors at the top of the nasal cavity. For this reaction, chemical structure of an odoriferous compound is important. The odor substances can be detected in the air above the food before it is actually eaten; the consumer then decides whether or not to eat. During eating, odor compounds are detected as they pass in the breath from the mouth through the back of the nose (retronasal effect) into the nasal cavity.

Substances contributing to flavor can be divided into aroma compounds and taste compounds. Salty meat flavor is normally due to sodium chloride, monosodium glutamate, inosine monophosphate, and guanosine monophosphate. The Japanese call these compounds, used to improve flavor, *umami*. Sweetness is caused by sugars formed by postrigor glycolysis and certain amino acids; bitterness is due to the presence of amino acids and peptides, and sour and acid tastes are caused by acids such as lactic acid, amino acids, organic acids, and acidic phosphates. The aroma compounds are formed largely during the cooking process.

Effect of Refrigeration on Flavor

The main compounds involved in flavor formation are the Maillard reaction precursors, lipid oxidation reagents, and products of thiamine degradation. The

TABLE 4 Descriptive Texture Attributes and Definitions Used to Evaluate Intact Broiler Muscle

Term	Definition
Stage I. Place the sample between the molars. Compress slowly (three cycles) without biting through the sample.	
Springiness	Degree to which the sample returns to its original shape after partial compression (*Scale:* low to high)
Stage II. Place the sample between the molars. Bite through the sample (no more than six cycles) using the rate of one chew per second.	
Initial cohesiveness	Amount of deformation before rupture (*Scale:* low = very little deformation before rupture to high = high degree of deformation before rupture)
Hardness	Force required to bite through the sample to rupture it (*Scale:* low to high)
Initial juiciness	Amount of moisture in the meat (*Scale:* low, dry to high, juicy)
Stage III. Place the sample between the molars. Chew at the rate of one chew per second. At 15 to 25 chews, begin evaluation of the following attributes.	
Hardness	Force necessary to continue biting through the sample (*Scale:* low to high)
Cohesiveness of mass	How the sample holds together during chewing (*Scale:* Low = fibers break easily, wad dissipates; grows high = wad in size, resists breakdown)
Saliva produced	Amount of saliva produced in the mouth during sample manipulation to mix with the sample to ready it for swallowing (*Scale:* none to much)
Particle size and shape	Description of size and shape of the particles as sample breakdown continues on chewing (*Scale:* fine, small particles to coarse, large particles)
Fibrousness	Degree of fibrousness or stringness (*Scale:* small to large)
Chewiness	(*Scale:* tender, chewy, tough)
Chew count	Number of chews to get the sample ready to swallow
Bolus size	Size of the wad at the point of swallowing (*Scale:* small to large)
Bolus wetness	Amount of moisture in or moisture feel of the wad at the point ready to swallow

(*continued overleaf*)

TABLE 4 (*Continued*)

Term	Definition
Stage IV. Evaluate the following at the point the sample is swallowed.	
Ease of swallowing	(*Scale:* easy to hard)
Residual particles	Amount of loose particles left in the mouth after swallowing
Toothpack	Amount of material packed in and around the teeth (*Scale:* none to much)
Mouth coating	Amount of moisture and fat coating the oral cavity after swallowing (*Scale:* low to high)

Source: Lyon and Lyon (1990a).

Maillard reaction precursors present in raw poultry meat are derived from the degradation reactions occurring in postmortem muscles: reducing sugars and some sugar phosphates formed by glycolysis and adenosine triphosphate breakdown. During refrigeration and freezing, these reactions proceed at a much slower rate. The concentration of precursor and volatile odoriferous compounds derived from reactions occurring between the components of raw meat and reaction rates are influenced by the cooling method. Low temperatures reduced the production of some of the precursors, as the temperature affects the reaction rate (Mottram, 1991, 1994).

Lipid oxidation is considered a major problem in the poultry industry, due to the production of highly unpleasant flavors caused by rancidity development. This oxidation reaction is a complex process in which unsaturated fatty acids react with molecular oxygen to form free radicals and peroxides, which later oxidize to aldehydes, cetones, and esters, compounds responsible for rancid flavor during frozen storage. Rancidity in chilled or frozen storage can be reduced by the addition of antioxidant or by packing the meat in oxygen-impermeable films (Pettersen et al., 2004).

Bird diets rich in antioxidants such as α-tocopherol and selenium (100 IU and 8 ppm, respectively), or inclusion of ingredients containing these compounds, such as sorghum (with high levels of tannins and other phenol compounds), have a beneficial result on meat sensory characteristics (Du et al., 2002). These compounds provide meat stability against oxidation when stored at 4°C for 7 days; flavor and color were not affected (Ryu et al., 2005).

Oxidation changes such as rancidity or color fading are the most important aspects considered in cooked poultry, a food very sensitive to oxidation changes, due to its high content of unsaturated fatty acids. Cooking techniques start free-radical reactions, damage the cell structure, and expose membrane lipids to environmental extracellular conditions. Storage time also influences the oxidation of precooked turkey breast when stored at −40°C, especially under aerobic conditions. However, when turkey breasts are stored under vacuum, oxidation changes are prevented (Nam et al., 2002).

Adequate thawing is necessary to prevent deterioration in frozen poultry, allowing a slow thawing rate. Freezing small pieces rather than large loads also allows homogeneous thawing. It is convenient to avoid unfreezing with cold or hot water, as ions present can alter such quality characteristics as tenderness, juiceness, color, and flavor.

CONCLUSIONS

- Refrigerated chicken meat must be cooked immediately, whereas frozen meat must first be thawed.
- Oxidative changes are the major cause of meat deterioration, as autoxidation of unsaturated fatty acids affects wholesomeness; this process is faster in refrigerated than in frozen products.
- To avoid surface drying (sublimation), it is necessary to wrap meat before freezing.
- The consumer preference is, first, chilled meat, then frozen meat.
- Domestic freezing, being a slow process, can reduce meat quality. As industrial freezing proceeds at a faster rate, meat quality is preserved if frozen storage is appropriate, not affecting texture, pH, or fatty acid oxidation.
- When fluid loss during thawing is minimized, the meat keeps its tenderness, juiciness, and color. In this respect, the thawing method strongly affects water release and the presence of the Maillard reaction. Other quality-related compounds, such as water-soluble heme pigments and vitamins, are also eliminated with water. In addition, microbial contamination is more likely to occur in low-water-holding meat.
- Flavor is the characteristic most affected during refrigeration, due to the possibility of rancidity development; during freezing the characteristics most affected are skin color and flavor.
- The use of antioxidants in the packing material or their addition to the feed is an alternative to prevent oxidation in frozen or chilled meat.

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15

ENGINEERING PRINCIPLES OF FREEZING

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ENERGY AND HEAT

Energy is defined as the capacity to do work. A system's total energy (E) and the changes in stored energy can be expressed as

$$E = U + E_{\text{pot}} + E_{\text{kin}} \tag{1}$$

$$\Delta E = \Delta U + \Delta E_{\text{pot}} + \Delta E_{\text{kin}} \tag{2}$$

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where U is the internal energy, E_{pot} the potential energy, and E_{kin} the kinetic energy. In a closed system, the energy content may be modified by convection, radiation, mechanical compression or expansion, electromagnetic fields, and so on. Energy loss or gain between the system and its surroundings may be as heat (Q) or work (W).

Heat is a form of energy, thermodynamically defined as energy transferred from one body to another as a result of their difference in temperature. The heat added to one system involves energy absorption (positive sign), while the work done by the system involves energy consumption (positive sign). Heat added to a system in state 1 or 2 may be expressed as

$$Q_{12} = E_2 - E_1 + W_{12} \tag{3}$$

The heat leaving the system represents negative heat absorption, and the work done on the system represents negative work expenditure.

Heat Exchange Heat exchange from one body to another takes place when there is a difference in temperature between them, passing from a high-energy body to a low-energy body. When there is a heat balance with the surroundings, no heat transfer will occur. Energy transfer as heat takes place in three ways: conduction, convection, and radiation.

Temperature Temperature is a measure of a body's thermal pressure. High thermal pressure levels indicate a high temperature; the opposite indicates a low temperature, and the body is said to be cold. Temperature is a function of the internal kinetic energy and, as such, is an index of the average molecular velocity. Cold is a sensation demonstrating the absence, loss, or reduction in heat.

REFRIGERATION AND FREEZING

Refrigeration Refrigeration is defined as any process intended for heat removal and is the branch of engineering dealing with the processes of temperature reduction and maintenance of a given space or material at a lower temperature relative to its surroundings. To achieve this, heat from the body to be refrigerated must be removed and transferred to another body (primary or secondary refrigerant), the temperature of which is lower than that of the refrigerated body.

Freezing Freezing is one of the processes most commonly used for food preservation, because a broad range of microorganisms fail to grow at low temperatures, and when food is frozen, part of the water contained in it becomes ice, so that the food's water activity drops, thus affecting microbial growth. In the case of food, refrigeration involves cooling of materials from environmental temperature to -2°C, since the presence of solids reduces the freezing point of food. Cooling treatment operations, either by refrigeration or freezing, followed by storage at

low temperatures, can kill some microorganisms present in food. Under proper freezing operations, storage at a temperature below -10°C inhibits microbial growth almost totally. Although it fails to kill all microorganisms, it is considered an effective method to protect food from microbial spoilage.

Freezing Temperature

In industry and commerce, the term *freezing* is frequently adopted for products such as meat and poultry kept at a temperature from -2 to -18°C during storage and distribution. Occasionally, the term *ultrafreezing* is used for conservation at a temperature of -18°C or lower, with the smallest fluctuations possible; this term also implies that the freezing velocity has been adequate for the product, generally taking place faster than the conventional freezing process. The difference between refrigeration and freezing processes lies in the fact that the temperature, humidity, time, and equipment used for both processes are essentially different. These differences are useful to establishing the two types of processes commonly used to preserve meat products.

Freezing Methods

Ground ice, mechanical refrigeration, or a combination can be used to achieve refrigeration temperatures. This makes it possible to preserve poultry for short periods of time. In the case of freezing, the use of freezing fluids combined with mechanical refrigeration is recommended, thereby ensuring that the required temperatures will be reached. Preservation under these conditions makes it possible to retain optimum quality for several weeks. Poultry may be frozen using air, liquid, or frozen plates and by deep-immersion cooling at -15 to -28.8°C with no air circulation for 3 to 72 h. Rapid freezing, also called *quick frozen*, takes place by retaining a mean freezing velocity of 0.3 cm/min, passing through the crystal-formation zone in 30 min at most; under these conditions, the product will be totally frozen in less than 90 min. The main difference between products frozen using this method is the smaller ice crystal size formed relative to the size when using deep freeze. Crystal size has a direct effect on frozen food, making small crystals desirable, as is the case with quick freezing. The use of air-blast tunnels with air temperatures ranging from -30 to -40°C and air velocities of at least 2.5 m/s also result in rapid freezing. The temperature range -3.8 to -0.5°C, known as the *zone of maximum crystal formation*, results in the formation of large ice crystals under slow freezing conditions. The faster this zone is passed through, the smaller the ice crystals, hence minimizing meat exudates or drops.

Rapid freezing leads to lighter-colored carcasses than result from slow freezing. During slow freezing the skin dries up, shrinks, and becomes clearer; consequently, the carcass appears darker than with rapid freezing. During slow freezing, large ice crystals form, due to the clear surface layer, and frozen carcasses become darker at the surface. Darkening occurs mostly at the skin and in the remaining

meat surface layers. The freezing velocity of meat below the skin has no effect on color. Although carcasses with a proper appearance are preferable, fat acts as an isolator, slowing down freezing velocity. Poultry meat softness may be improved using maturation plus freezing.

Three stages are observed during freezing. First, temperature drops gradually to the freezing point; second, the product freezes; and third, the product is overcooled. After poultry freezing, it is recommended that the product be stored in chambers at temperatures of -17.73°C or lower. Most freezing warehouses keep poultry chambers at -23.3°C or lower.

Cooling by Mechanical Compression (Refrigeration Cycle)

Cooling operations, which use the cooling cycles, require proper isolation of rooms, with vapor (refrigerant) compression being the simplest and most important method. Figure 1 describes a typical refrigeration cycle:

1. The compressor sucks in the fluid (refrigerant) under saturated vapor; this takes energy from the compressor and goes from point 1 to point 2 through polytropic compression (variable enthalpy) in which fluid pressure and temperature, and hence its enthalpy, increase, in an isoentropic way (constant entropy); as a result of this external work, vapor goes through an overheating stage.

2. In the condenser, the fluid reduces its energy content through an isobaric process (constant pressure), going from a gaseous state (point 2) to a liquid state in point 3, transferring only its latent heat of vaporization to the environment; that is, it undergoes an isothermal (constant temperature) change of state.

3. Next, the fluid passes through an expansion valve in an isoenthalpic process (no enthalpy change), resulting in a reduction in pressure and temperature at

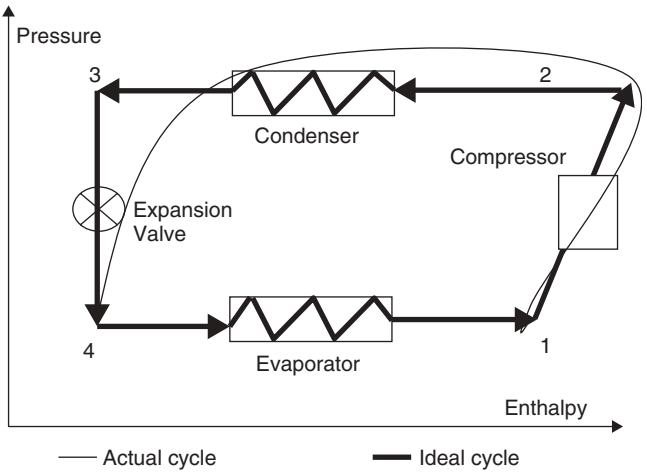

FIGURE 1 Typical theoretical refrigeration cycle.

point 4. For this reason, part of the fluid is transformed into a vapor mixture in an adiabatic-expansion process; point 4 is characterized by a cooling fluid, consisting of a fluid–gas mixture.

4. The fluid–gas mixture becomes a saturated vapor (pure vapor with no fluid) in the evaporator, in which the fluid takes heat from food in an isobaric and isothermal process, shifting from a liquid to a vapor state, absorbing heat from products inside the refrigerating or freezing room. The cycle then returns to the starting point.

Although an actual refrigeration cycle deviates to some extent from a theoretical cycle, its analysis is useful for understanding an actual cycle and deriving the relative efficiency of an actual refrigeration cycle. The theoretical compressor potency (Pot) is essential in estimating the actual compressor size and the energy supplied to the system. The work supplied to the system, the compression work (W_c), is multiplied by the mass flow (w) of the refrigerant fluid circulating through the system:

$$\text{Pot} = wW_c = w\,(H_2 - H_1) \tag{4}$$

where H_1 and H_2 are the respective enthalpies, or energy per refrigerant mass unit at the compressor's entrance and exit; enthalpy values can be obtained from tables of refrigerant fluid thermodynamic properties.

At the condenser, the amount of energy leaving the fluid is determined from enthalpies at points 2 and 3 (Figure 1), so that the heat flow from the fluid is

$$Q_s = w\,(H_3 - H_2) \tag{5}$$

Similar to point 2, where the fluid leaving the compressor possesses a higher enthalpy value than that at point 3, a negative heat value is obtained, indicating that heat was transferred from the fluid to the environment. This heat is used to dimension the condenser (external coil) as well as to calculate the amount of cooling fluid to use.

The expansion stage (3 to 4) is isoenthalpic, that is, there is a nil change in enthalpy. In the evaporation stage (4 to 1), the system's cooling effect, in which the heat is transferred from the environment to the fluid, is

$$Q_e = w\,(H_1 - H_4) \tag{6}$$

This heat is absorbed by the fluid and represents the refrigerant's capacity, which is the objective of the process (refrigeration load).

There is an important parameter in all refrigeration processes, the yield rate (Φ), defined as the cooling effect divided by the work supplied externally. Given that this work is only compression, the cooling system's yield rate is

$$\Phi = \frac{H_1 - H_4}{H_2 - H_1} \tag{7}$$

The refrigerant's potency per kilowatt is the inverse of the yield rate, and an efficient refrigeration system must have a low potency value but a high yield rate:

$$\text{refrigeration potency} = \frac{H_2 - H_1}{H_1 - H_4} = \frac{1}{\Phi} \tag{8}$$

Refrigerants

A *refrigerant* is any body or substance acting as a coolant, absorbing heat from another body or substance. With regard to the compression–vapor cycle, the refrigerant is a cycle's working fluid, which alternates vaporizing and condensing, absorbing and releasing heat, respectively. A refrigerant can be used in a compression–vapor cycle provided that it possesses chemical, physical, and thermodynamic characteristics that make it a safe and economical option. Refrigerant fluids used in vapor–compression systems are called *primary refrigerants*; those used in low-temperature transportation are called *secondary refrigerants*. Solutions with freezing temperatures below $0^{\circ}C$ are used as secondary refrigerants. Of them, the most commonly used are aqueous solutions of ethylene glycol, propylene glycol, and calcium chloride. All share similar properties, although propylene glycol has the advantage of being innocuous for contact with food. Primary refrigerants include halocarbons, hydrocarbons, inorganic substances, and fluorocarbons (fluorinated hydrocarbons, or CFCs). The choice of refrigerant type depends on the process to be used. Refrigeration systems may have leaks and may contaminate food if the refrigerant comes in contact with it.

Refrigeration Load

The velocity at which heat must be removed from a refrigerated space or material in order to achieve and maintain the desired temperature is called the *refrigeration load*, *cooling load*, or *thermal load*. In virtually any refrigeration application, the refrigeration equipment cooling load is the sum of all heat inputs from various sources:

1. Heat transmitted by conduction through isolated walls
2. Heat that must be removed through doors that are opened and closed
3. Heat that must be removed from the refrigerated product to take its temperature to the storage temperature
4. Heat from the staff working in the refrigerated space as well as from motors, light sources, and other heat-producing equipment operating in such a space

The capability of refrigeration equipment is expressed in energy/time units (e.g., refrigeration tons/hour). For refrigeration equipment, the total cooling load is generally calculated for 24-h periods, that is, is expressed as energy units/24 h. This type of estimate has been investigated extensively, so that empirical rates

are available, making it possible to estimate the total load of refrigeration or freezing systems easily. These rates can be obtained from specialized references.

Kinetic Behavior of Freezing Processes

In food freezing, knowledge of how food temperature varies as the freezing process progresses is critical. The freezing temperature of pure water is 0°C, so if the process begins with water above this temperature, first a temperature drop occurs below 0°C (subcooling); when ice starts to form, fusion heat is released, so that the temperature rises to 0°C again. At this point, the temperature remains constant until all the water has become ice; then the temperature drops again with a steeper slope, since the thermal conductivity of ice is higher than that of liquid water. The final temperature will be the temperature at the exit of the equipment used for freezing and should preferably be similar to the storage temperature. In food, including chicken, the freezing process differs from that of pure water. First, the temperature drops below the T_c temperature. Once the first ice crystals are formed, the temperature rises to T_c. However, the temperature does not remain constant: There is a steady slight decrease as water becomes ice and unfrozen water concentrates in the product's soluble solids. Finally, a temperature will be reached at which no further water will freeze, given that the soluble solid content is so high that very low temperatures will be required. This is the final freezing point, and from it the product temperature drops steadily until it reaches the temperature of the freezing environment or storage temperature. For food, it is evident that the concentration of soluble solids in unfrozen water rises steadily as freezing proceeds, so that the freezing temperature varies with both time and the initial product water content. For this reason, the initial freezing temperature corresponding to the appearance of the first ice crystals is normally used to simplify the calculations involved in freezing equipment design.

Freezing Time Determination

The *freezing time* is the period of time required for the temperature at the food geometric center to change to a predetermined final temperature below the initial freezing temperature. The *effective* or *nominal freezing time* is the time that passes after the food surface reaches 0°C until the center reaches a temperature 10°C below the baseline freezing temperature. Calculating the freezing time is a complex task, since the freezing temperature of food changes during the process and hence also the physical properties involved in the freezing process. At the beginning of freezing, there is a diluted aqueous solution, so that in a first approximation the initial freezing temperature may be calculated through *Raoult's law*:

$$T_c = K_c \frac{m_s}{M_s} \tag{9}$$

where T_c is the freezing temperature (°C), K_c the water cryogenic temperature (18.6, expressed as g water/°C), m_s the mass of solutes expressed as g

solute/100 g water, and M_s the solute molecular mass (in the case of food, M_s is a molecular equivalent of solutes in the product).

T_c may also be determined from empirical correlations that make it possible to estimate this parameter only as a function of product moisture content:

$$T_c = \frac{T_{0A}\lambda}{1 - RT_{0A}\ln X} \tag{10}$$

where T_{0A} is the freezing temperature of pure water (273 K), λ the water latent heat of freezing (6003 kJ/kmol), R the gas constant (8.314 kJ/kmol · K), and X the unfrozen water molar fraction. T_c values for several food products, including chicken, may be found in the literature. Other parameters that are important for determining the freezing time and which vary along the freezing process include food-specific enthalpy, proportion of ice formed, thermal conductivity, thermal diffusivity, density, specific heat, and latent heat of fusion. All these physical properties and parameters can be estimated from empirical or theoretical equations, or obtained from the literature (Ciobanu et al., 1976; Heber et al., 2000; Alvarado and Aguilera, 2001). In general terms, these physical properties and parameters vary with moisture content, process temperature, solute nature, and solute microstructure.

Heat is transferred through the frozen layer by conduction, and through the surface to the environment by convection, so that the heat flow or heat output, Q_s, can be expressed as

$$Q_s = \frac{Ak(T_c - T_s)}{x} = Ah(T_s - T_e) = \frac{A(T_c - T_e)}{x/k + 1/h} \tag{11}$$

where A is a transfer area [i.e., surface exposed to the cooling environment (m)], k the thermal conductivity (J/s · m · K), ρ the frozen layer density (kg/m^3), and h the heat transmission coefficient by convection to the environment (J/s · m^2 · K).

Energy dissipation through freezing (Q_d) can be derived from

$$Q_d = A\rho\lambda_H \frac{dx}{dt} \tag{12}$$

Making equation (11) equal to (12) and canceling A yields

$$\rho\lambda_H \frac{dx}{dt} = \frac{A(T_c - T_e)}{x/k + 1/h} \tag{13}$$

integrating the equation for the limit conditions $t = 0$ and $x = 0$ and $t = t_c$ and $x = e/2$ (when cooling takes place at both sides). The solution of equation (13) integration can be used to isolate the plate freezing time t_c (*Planck's equation*):

$$t_c = \frac{\rho\lambda_H}{T_c - T_e}\left(\frac{e^2}{8k} + \frac{e}{2h}\right) \tag{14}$$

For infinite plates, the coefficients are 8 and 2, replaced by 16 and 4 for infinite cylinders and by 24 and 6 for spheres, where the radius becomes the thickness e. The latent heat λ_H (in J/kg) corresponds to the frozen fraction and is calculated by multiplying the latent heat for pure water x_H (J/kg) by the frozen water mass fraction λ:

$$\lambda_H = x_H \lambda \tag{15}$$

The freezing time can be obtained from a dimensional number relationship such as Fourier's, Biot's, or Stefan's number, leading to

$$t_c = F_0 \frac{\rho C p e^2}{k} \tag{16}$$

It is important to bear in mind that the main factors affecting freezing velocity include package size, shape, and vehicle; amount of packaging material, packaging nature; and thickness. These packaging features may act as barriers and slow down the freezing velocity.

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16

QUALITY OF FROZEN POULTRY

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INTRODUCTION

Freezing of food is a natural progression from refrigeration. When excess meat is available or when meat is to be distributed to distant locations, preservation becomes essential to allow products to be consumed some time later. Nowadays, an important amount of meat may have been frozen for storage or distribution.

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Consumers usually prefer the appearance and oxygenated color of chilled rather than frozen meat; however, freezing is still the most feasible alternative to assuring long storage shelf life. The mechanisms of food preservation acting in frozen foods are the subzero temperatures and the reduction in water available through conversion to ice. Heat transfer properties (thermodynamics), mass transfer properties (kinetics), and product composition and size strongly influence the freezing process as well as the water mobility of unfrozen water, ice distribution, and recrystallization during frozen storage. According to Jeremiah (2003), most broiler chickens are merchandized chilled, whereas most turkeys are merchandized frozen. A deep chilling process, to about -2°C, and holding temperatures between -2 and -4°C are preferred to freezing for broiler chicken, due to the possibility of development of discoloration around the bone in frozen chicken. The storage life of deep chilled chicken is 3 to 5 weeks. Poultry accommodates freezing very well, as it has a relative rapid freezing rate. Frozen storage must be strictly controlled at -18°C or below, and products may be packaged using high-barrier packaging materials. Temperature fluctuations during frozen storage must be avoided, and thawing methods may be selected to minimize microbial growth and maintain safe temperatures. The preferred poultry products to be frozen are boneless cuts and slices as well as a great variety of cooked, microwave-ready, and ready-to-eat products. In recent years, freezing has been used combined with other technologies, such as irradiation, to extend poultry shelf life while enhancing its microbial quality, with little or no effect on sensory scores (Javanmard et al., 2006).

QUALITY INDICATORS OF FROZEN POULTRY

The principal quality parameters of meat products are those related to sensory perception (color, texture, taste, and flavor) and safety (microbial populations and chemicals). Moreover, the food industry is interested in product yield, reduced production costs, and convenience (distribution and packaging or presentation). Sensory characteristics of fresh and frozen–thawed poultry are quite similar. Baker and Darfler (1981) roasted fresh and frozen chicken broilers, chicken roasters, turkeys, and ducks and brought them to a test panel for a triangle test. The taste panel could not distinguish significantly between fresh and frozen–thawed paired halves of roast poultry. However, of the few judges who could distinguish between fresh and frozen–thawed samples, most preferred the fresh samples. They also evaluated moisture losses and texture by objective testing, but they were not significantly different either. Color, lipid oxidation, and texture [closely related to water-holding capacity (WHC)] are the quality parameters of poultry reported in the literature to be affected by freezing.

Color

The color of meat is an important determinant of meat acceptability (Pérez-Alvarez et al., 2000). The low concentration of heme pigments results in considering poultry to be white meat. Poultry skin color generally ranges from

cream-colored to yellow. The color is dependent on the type of feed used and is the result of dietary carotenoids, which are laid down in the fat (Pérez-Alvarez and Fernández-López, 2006). Raw muscle typically has a pink to reddish color due to hemoglobin and myoglobin. Color in poultry is a result of several parameters (McKee, 2007a; Totosaus et al., 2007), such as heme pigment concentration and chemical state, altering the light reflectance, preslaughter factors (e.g., diet, heat stress, handling, stunning), slaughtering conditions, and postmortem treatment during refrigerated and frozen storage. Final pH, additivation, and processing temperatures also determine color. Freezing and thawing increase bone darkening. This is one of the main color defects detected in poultry meat, although surface color under the skin of cooked meat is not greatly affected by storage temperature.

Studies on color changes due to freezing date from the 1940s. Koonz and Ramsbottom (1947) explained that darkening around bones is more intense in young animals, as bones are immature and pigments easily escape to adjacent tissues through porous, spongy, incompletely calcified bones; darkening is also promoted by splitting the bones before freezing; and cooking may minimize color differences between defrosted and unfrozen poultry.

Lyon and Lyon (2002) evaluated color problems of frozen poultry meat containing bone and dark muscle as influenced by chilling (from 4 to -18°C) and cooking processes (75 and 85°C) and concluded that discoloration of raw or cooked tissue can occur from cell disruptions and blood migration caused by slow chilling rates (0 and -3°C); the surface color of leg quarter tissue under the skin was not influenced by chilling; the color of cooked meat adjacent to the femur was affected by a combination of chill history and cooking treatment; and cooking to 85°C internal temperature negated color differences attributed to the chill temperature. Other authors also proved that cooking to a high-temperature endpoint reduces red/bloody discoloration (Smith and Northcutt, 2004).

Frozen storage causes chicken to darken and become more red and yellow over time (Heath and Owens, 1992). Darker breast meat has been reported to have a lower shelf life based on more rapid odor development (Allen et al., 1997), although no relation has been found with counts of psychrophilic bacteria. Color can be assessed easily online by instrumental equipments (Pérez-Alvarez et al., 2004). Several research workers have suggested the possibility of using color measurements to predict the functional properties of poultry meat. Poultry line inspectors separate carcasses into normal or dark. The choice of cutoff points is important, as it is applied in deciding whether a carcass is normal in color and thus kept for human consumption, or dark-colored and condemned. Redness (a^*; color coordinate 100/−100 red/green) value is more likely to classify dark-colored versus normal-colored broiler chicken breast fillets correctly than are L^* (lightness) and yellowness (b^*; color coordinate 100/−100 yellow/blue) values (Totosaus et al., 2007). Several researchers have suggested classifying poultry carcasses according to L^* values in order to optimize meat functionality (discussed in the next section).

Texture

Tenderness is the most valued attribute of meat. Meat texture is affected primarily by protein structure and integrity. Although it seems contradictory, both tenderization and increased toughness have been related to the freezing of poultry, depending on the freezing and thawing temperature, the aging conditions before freezing, and the quality of the raw meat. Tenderization due to freezing and frozen storage appears to be due to myofribilar fragmentation (Yamamoto et al., 1977). Protein denaturation during frozen storage may be caused by one or more of the following factors: (1) ice crystal damage to cells and membranes, (2) dehydration of protein molecules, (3) increase in solute concentration in the unfrozen water phase, (4) enzymatic activity, (5) reaction of proteins with free fatty acids and other intact lipids, and (6) reaction of proteins with oxidizing lipids. Huber and Stadelman (1970) reported that the lower the freezing rate, the higher the extractability of sarcoplasmic proteins in chicken and turkey. According to Smith (1987), frozen storage of poultry causes protein insolubilization and changes in biochemical and functional properties of proteins. Toughening by freezing also has its mechanisms. Thaw rigor results from thawing muscle that was frozen prerigor, in which case a severe form of rigor mortis sets in upon thawing the muscle. If thawing is done rapidly at high temperature, the muscle can then suffer from the defects associated with high-temperature rigor. The muscle is free to shrink as soon as the ice within the flesh melts; as the muscles shrink, they lose a large amount of drip. The muscle contraction is more severe in red meats that contain a high percentage of red fibers. At temperatures just above freezing, although rigor mortis proceeds rapidly, the presence of ice prevents contraction. Yu et al. (2005) studied the effects of thawing temperature on the texture of prerigor frozen chicken. The authors reported that muscle shortening was higher in poultry thawed at 18°C, showing a detrimental effect of high thawing temperatures on muscle shortening. Thawing temperature affected the texture quality of prerigor frozen chicken muscle; the contraction of muscle induced by thaw shortening appeared to be the main contributing factor to the textural toughening of chicken meat (thawing at 18°C yielded the tougher fillets). When evaluating drip losses due to thawing and cooking, we assume that the loss of water from the muscle originates from volume changes in the myofibrils during thawing. The higher muscle contraction of thaw-shortened muscle results in a higher thaw drip loss. But when evaluating total losses (thawing plus cooking), no significant differences were detected among thawing treatments except for muscle type: Breast muscles had less cooking loss than did leg muscles. However, other authors report no texture modification from freezing. Yoon (2002) reported that no significant texture toughening was observed in frozen chicken breasts after 10 months of storage at −20°C, suggesting that toughening is not a determinant factor in quality loss of frozen chicken breast.

Lipid Oxidation

Lipid oxidation is a major problem in the meat industry, due to the resulting flavor deterioration and loss of nutritional value. Lipid oxidation is a common

concern in poultry products, due to the high degree of fat unsaturation compared to other meats. Prolonged storage and processing may accelerate lipid oxidative processes. Mechanically deboned poultry meat is easily oxidized, and the major strategies for preventing its lipid oxidation are the use of free-radical terminators and restricting the access of oxygen during storage. Pettersen et al. (2004) reported that in mechanically deboned poultry meat (MDPM) stored under freezing, avoidance of lipid oxidation could be achieved by using vacuum or oxygen-free packaging and the use of a natural antioxidant (α-tocopherol), whereas the freezing process (frozen or frozen–thawed–refrozen) did not affect lipid oxidation.

In a study of dietary fat, α-tocopherol, and ascorbic acid on the oxidative stability of frozen ground poultry, Grau et al. (2001) concluded that the supplementation of broiler diets with α-tocopherol (225 mg/kg feed) resulted in effective protection of meat from fatty acid and cholesterol oxidation, regardless of the dietary fat source, and when combined with vacuum packaging, greatly reduced oxidation during frozen storage. The protective effect of endogenous vitamin E on oxidative changes in meat and meat systems is very pronounced in labile meat systems. Regarding dietary fat, Eder et al. (2005) reported that the effects of vitamin E (20, 40, and 200 mg/kg feed) on cholesterol oxidation product concentration depend largely on the dietary fat, treatment of the muscle, and type of muscle: The higher the polyunsaturated fatty acid contents in the diet, the higher the oxidation products, particularly during heating and in thigh muscle. Only high vitamin E levels inhibited cholesterol oxidation. The authors suggest selecting a favorable combination of dietary fat and vitamin E supplementation to achieve proper protection against cholesterol oxidation.

This protective effect has also been reported in other species. Russell et al. (2003) reported that supplementation of antioxidants in the diet of ducks showed a protective effect on meat lipid oxidation during frozen storage. In a study on frozen turkey meat, Sheldon et al. (1997) reported that a longer duration of feeding elevated vitamin E levels in turkeys, thus providing protection against lipid oxidation, better scores for flavor and color, and a lower incidence of very pale meat, which is an important achievement, as a PSE-like (pale, soft, and exudative) condition affects as much as 40% of a market tom flock.

Other dietary supplements, such as ascorbic acid (Grau et al., 2001) and vitamin A (Bartov et al., 1997), have been tested and proved no protection against lipid oxidation during the frozen storage of meat. Dietary oregano essential oil combined with α-tocopheryl acetate was tested by Botsoglou et al. (2003) to inhibit lipid oxidation during chicken frozen storage. They observed that oregano essential oil inhibited lipid oxidation but was less effective than α-tocopheryl acetate. α-Tocopherol levels in muscle decreased with increased frozen storage time. Thigh muscle was found to be more susceptible than breast muscle to lipid oxidation.

FACTORS AFFECTING FROZEN POULTRY MEAT QUALITY AND CHARACTERISTICS

Raw Material Characteristics

Many factors may alter the quality of frozen poultry, such as the intrinsic meat quality, including slaughter conditions; the onset, development, and resolution of rigor mortis; and the aging conditions before freezing. In the present section the effects of meat quality (bird age, PSE condition, composition), aging prior to freezing, and deboning technique on the quality of frozen poultry are reviewed. The focus of packing and freezing hot-cut poultry is to improve microbial quality and reduce drip losses, although it is associated with a little reduction in tenderness. It is well documented in most species that rapid cooling can interfere with the tenderization process and that early deboning causes toughening compared to muscles attached to the carcass. Goddard and Heath (1978) reported that hot-cut broilers frozen immediately after cutting are an acceptable product. Behnke et al. (1973) evaluated the effect of prerigor poultry storage at -3°C previous to freezing and concluded that cold shortening and reduced tenderness due to freezing in the prerigor state can be avoided simply by holding frozen poultry at an air temperature of 0°C or somewhat higher for 2 h at some convenient point during frozen storage or marketing. They reported that cold shortening between 20 and 40% leads to reduced tenderness, whereas over 50%, tenderness is increased, but drip losses are increased as well.

Thielke et al. (2005) investigate the effect of aging prior to deboning with the tenderness of cooked poultry meat. They found a correlation between the firmness of raw meat and the tenderness of cooked poultry meat as measured by objective methods and by a sensory panel. They found that fillets of carcasses aged between 0 and 5 h were described predominantly as tough. After aging for at least 6 or 8 h, most of the samples were judged by the panelists to be tender. The moment of completion of rigor mortis seems to be crucial for the prediction of tenderness in breast fillets. If rigor mortis has not been completed, deboning and freezing may lead to severely increased product toughness.

Park et al. (2003) tested laying hens at different stages (72, 80, and 92 weeks old) for bone-breaking strength after being refrigerated or frozen. The bone-breaking strength of refrigerated tibias of 72-week-old hens was higher than that of frozen hens, although frozen storage could be used for the sample storage of bones from older hens.

Abdullah and Al-Najdawi (2005) compared the functional properties of poultry meat according to the deboning method. They reported increased emulsifying properties of manual deboned hen meat in the early months of frozen storage, and a decrease afterward due to the partial denaturation of proteins. The WHC of deboned skinned meat was decreased due to frozen storage but not that of whole skin carcasses. Sensory scores of deboned meat in the early stages of frozen storage (<6 weeks) were not modified; only after frozen storage for up to 12 weeks did sensory scores decrease.

Several researchers have suggested classifying poultry carcasses according to L^* values, to optimize meat functionality. Galobart and Moran (2004a) reported that when poultry meat with high L^* values (over 68) is frozen and thawed, fillet size is reduced and exudates are increased, indicating poor meat quality, related to their soft character and extensive water loss, which is similar to the PSE condition in swine white muscle. The L^* value of fillets is negatively related to ultimate pH and moisture losses. The same authors (2004b), evaluating the effect of freeze–thaw and cooking on breast fillets according to the initial L^* values, concluded that thawing reduced the L^* value in pale fillets and increased it in dark fillets. Parameters a^* and b^* increased after thawing; the increase in a^* was lower for the pale than for the dark fillets. Cooking increased L^* values further and reduced color differences between groups. Thawing and cooking losses were not affected by initial L^*, but when combined, total losses increased with initial L^* together with decreased fillet thickness after cooking. The authors suggest online implementation of L^* measures to best fit meat characteristics to the temperature of preservation and further processing. The same argument is supported by Zhang and Barbut (2005), who investigated the rheological characteristics of fresh and frozen PSE (pale, soft, and exudative), normal, and DFD (dark, firm, and dry) chicken breast meat. Chicken was classified in these categories according to L^* values. Meat with the highest L^* values presented the lowest pH, cooking yield, and fracture force; moreover, when cooked they did not form a coherent gel and the cooked meat pieces did not bind as well as did normal and DFD meats. Frozen meats were less rigid and more ductile than fresh meat, indicating that freezing resulted in some protein damage or denaturation. When cooked, PSE meat (high L^* values) showed the lowest rigidity and elasticity. The authors reported differences in physical characteristics and functionalities (WHC, cooking loss, texture) among PSE, normal, and DFD poultry meats. The differences were also seen during the gelation process. The introduction of a freezing treatment further reduced the functionality of PSE meat, so meat classification (by L^*) is strongly recommended prior to processing to avoid the freezing of PSE meat and to best fit meat characteristics to further processing.

Additives

The effects of dietary supplements on frozen meat quality were discussed previously; now the discussion is centered on meat additives. Phosphates have been used in poultry products to improve water binding, texture, color, and flavor as well as to control microbial contamination and growth and to minimize freezing damage and protein denaturation. Yoon (2002) investigated the effects of 10% NaCl, trisodium phosphate (TP), sodium tripolyphosphate, and tetrapotassium prytophosphate treatments on textural and microstructural properties of chicken breasts during 10 months of frozen storage at -20°C. All treatments reduced drip losses and enhanced water-binding abilities as both NaCl and phosphates induced swelling caused by electrostatic repulsion, which allows more water to be immobilized in the myofibril lattices. They concluded that treating chicken breasts with

trisodium phosphate and sodium tripolyphosphate significantly reduced drip and cooking losses as well as minimizing ice crystal formation and freeze-induced shrinkage of myofibrils observed by transmission electron microscopy. The water-binding ability of chicken meat was the most important factor in maintaining the quality of chicken breast during extended frozen storage and could be accomplished by treating chicken breasts with 10% trisodium phosphate and sodium tripolyphosphate solutions before frozen storage. Phosphate effects on breast texture are not clear, and it seems that their effect on poultry texture is affected by their interaction with processing parameters (electrical stimulation, stunning time, and time postmortem). Addition during the postrigor state did not affect breast texture (Yoon, 2002).

An interesting particular case of frozen poultry is that of breast dices. Frozen-cooked broiler breast dice is utilized in food services, but many cracked pieces often appear after the freezing step. Cracked pieces are often discarded or sold as low-quality products. To improve meat juiciness and yield, poultry dices are usually tumbled to increase the water-holding capacity. Sungtong et al. (2006) studied the effects of moisture content on cracking as well as the effects of 1% sodium triphosphate (STPP) and transglutaminase (TGase) on the prevention of freeze cracking of diced broiler breast. They reported that moisture incorporated during tumbling makes the dices more prone to cracking when freezing. When tumbling with 1% STPP, cracking was reduced to 24%, and tumbling with 0.5% TGase reduced cracking to 25% and caused narrower and shorter cracks, improving the quality of the dices.

Handling and Freezing Process

The freezing procedure itself is a main factor affecting frozen poultry quality. Khan and van de Berg (1967) reported that the freezing rate determines the quality of frozen poultry, as slow rates lead to large drip losses when thawing as well as reduced water-holding capacity and protein losses. These authors suggested that proteolysis is increased due to the great cell damage derived from a slow freezing (-18°C compared to -80°C temperature) rate, which leads to enzymes released by lysosomes. Slow freezing has been related to increased color defects in frozen poultry (Lyon and Lyon, 2002).

A freeze crack is a defect usually related to cryogenic freezing and due to volume changes associated with water–ice phase transition. Freeze cracks may affect only the surface or be originated from the inside. As discussed previously, Sungtong et al. (2006) tested air-blast, still-air, and cryogenic freezing, providing a wide range of freezing rate. Air-blast and still-air freezing had quite slow freezing rates that avoid cracking, but freezing and cooking losses were increased dramatically. Cryogenic freezing provided the best meat yield but favored cracking. A faster freezing rate provided a wider gap and a longer cracking line. Cryogenic freezing at a freezing rate of 37.5 cm/h produced 38.34% cracked pieces, and increasing the freezing rate produced more cracked pieces.

Storage and Packaging

The effect of frozen storage and thawing conditions on poultry quality has also been investigated. Baker et al. (1976) reported that poultry can be refrozen safely (from the sensory, microbial, and chemical points of view) several times (up to five refreezing steps), provided that the meat is handled properly. Regarding specific pathogens, it has been reported that thawing temperatures close to 0°C favor the survival of *Campylobacter* spp. (Georgsson et al., 2006) and that higher thawing temperatures (22 to 30°C) are not particularly hazardous regarding *Salmonella, Escherichia coli* and *Staphylococcus aureus* survival (Ingham et al., 2005). The main functions of packaging are the protection of the product against bruising, physical and chemical changes, and microbial contamination, to provide information to retailers and consumers, and to provide an attractive and convenient presentation of the product. Regarding frozen poultry, for the selection of packaging material its gas permeability is important, as the presence of oxygen affects myoglobin oxidation and lipid rancidity in the meat. Poultry meat has fewer demanding color requirements than those of red meats. Red meats require an oxygen supply to maintain surface color, whereas only minced poultry requires it for short periods. A good package design that provides easy and convenient handling also contributes to preserving food quality until final destination.

Rey and Kraft (1971) tested packaging materials of different oxygen and vapor permeability for the packaging of poultry to be frozen-thawed and held at 5°C for several days. They concluded that freezing of poultry meat prior to refrigerated storage enhanced the development of spoilage when highly permeable films were used; when vacuum or impermeable films to oxygen were used, the lipolytic and proteolytic activities of psychrophilic bacteria were reduced. Uncooked poultry may be frozen and thawed several times (storage period tested, 35 days) without noticeable increase in microbial loads compared to continuous frozen storage.

Polyethylene bags are generally used to wrap poultry before immersion chilling (Totosaus and Kuri, 2007). The preservative packaging used in meat freezing is based mainly on modification in the gas atmosphere surrounding the meat. Skin packaging is one of the preferred packages for frozen poultry; its barrier properties influence product redness significantly, and its thickness influences the rate of heat transfer during the heating and cooling process. Another advantage is the water vapor barrier, which avoids ice sublimation and, consequently, dehydration, preventing freezing burns and weigh losses.

Considerations to be taken into account when selecting packaging for poultry meat to be frozen (Totosaus and Kuri, 2007) are the following:

1. *Enzyme activity*. Enzyme activity is slowed down by low temperatures but not inactivated. The primary active enzymes are lipolytic (lipases and phospholipases) and proteolytic, leading to quality losses.

2. *Lipid oxidation*. Poultry meat, especially mechanically deboned poultry meat, is prone to lipid oxidation, and major strategies used to prevent it are the

use of free-radical terminators (antioxidants) and the use of packaging systems that restrict the entrance of oxygen.

3. *Moisture migration*. This may be due to sublimation, moisture absorption and redistribution in foods, ice recrystallization, and drip loss during thawing. Moisture losses affect poultry appearance, juiciness, and texture, and cause weight loss, but some surface drying is needed to retard microbial growth and avoid a glassy appearance of the meat surface.

4. *Freezing and thawing*. The formation of protein aggregates due to the freezing process may lead to incomplete rehydration when the meat is thawed.

5. *Freezer burn*. This defect is due to the exposition of the food surface to the external environment of the storage facility.

Most of these factors may be controlled by proper packaging (e.g., tight-fitting film impermeable to water and vapor, high relative humidity in the storage facility) and handling to avoid damaged packaging.

MICROBIAL QUALITY OF FROZEN POULTRY: SAFETY ISSUES

The shelf life of frozen products depends on product characteristics, prefreezing treatment, the freezing process, the packaging film and process, and storage conditions (Pérez-Chabela, 2007). Poultry meat spoilage is due largely to gram-negative psychrotrophic bacteria such as *Pseudomonas* spp., *Achromobacter* spp., and *Micrococcus* spp. (Dawson and Spinelli, 2007). Rey and Kraft (1971) reported that frozen storage shifted poultry meat microbiota and increased populations of psychrophiles. Bailey et al. (2000) determined the effect of different refrigeration and freezer temperatures on the microbial profile of chicken. Mesophilic bacteria increased in refrigerated poultry, psychrotrophic bacteria increased in poultry held at refrigerated but not subfreezing temperatures, coliforms and *E. coli* decreased under all refrigerated and frozen conditions tested and *Salmonella* spp. did not change appreciably at any storage temperature. No counts for any organism changed significantly after frozen storage at -18°C.

Abu-Ruwaida et al. (1996) studied the microbial shelf life and quality of frozen broiler chickens and reported that prolonged frozen storage did not cause substantial changes in the bacterial counts of carcasses stored at -12°C, whereas it decreased slightly when stored at -18°C. Relatively high sensory scores were obtained by frozen carcasses, although freezer burn was observed in some pieces, and this defect increased with storage time. Drip losses were not increased significantly, whereas free fatty acids and peroxide values increased with storage time.

The most common pathogens in poultry are, in order or prevalence, *Campylobacter* spp., *Listeria* spp., *E. coli*, and *Salmonella* spp.; the most common spoilage microorganisms are *Pseudomonas* spp. associated with the spoilage of refrigerated poultry stored under aerobic conditions, *Lactobacillus* spp. associated

with the spoilage of refrigerated poultry stored under microaerophilic or anaerobic conditions, and such proteolytic or lipolytic yeasts as *Candida zeylanoides* and *Yarrowia lipolytica* (McKee, 2007b). High microbial loads are associated with off-odors, related primarily to sulfur-containing compounds, and sliminess on poultry. Both defects become noticeable when microbial levels reach 10^6 to 10^8 CFU/cm^2. Washing treatments with organic acids, modified-atmosphere packaging, irradiation, and other processed have been investigated to reduce poultry microbial loads, but they often cause undesirable changes in sensory properties, so none of them seem to be the final solution.

Several authors have investigated the effects of freezing on pathogens in poultry meat. *Campylobacter* is one of the most studied pathogens in poultry. Sandberg et al. (2005) found that although freezing appears to be an efficient way to reduce the level of *Campylobacter* on broiler carcasses, in 80% of the carcasses *Campylobacter* could still be detected using quantitative culturing following 120 days of freezing. Georgsson et al. (2006) evaluated the influence of freezing and frozen storage on the survival of *Campylobacter* and fecal coliforms in broiler carcasses. They observed that freezing followed by storage at -20°C for more than 31 days caused a significant decrease in the populations of *Campylobacter* but did not reduce fecal coliform counts. Thawing conditions affected microbial survival; thawing at 7°C improved *Campylobacter* survival after frozen storage for 31 days but had no effect for longer storage times, whereas fecal coliform survival was best when defrosting at 22°C. Ingham and others (2005) evaluated the effect of whole-chicken thawing (at 22 and 30°C) conditions on the growth of *Salmonella* serovars, *E. coli* O157:H7, and *S. aureus*. They suggest that thawing whole chickens of more than 1670 g at a temperature below 30°C for less than 9 h is not a particularly hazardous practice, but thawing smaller portions at higher temperatures or for longer times cannot be recommended.

CONCLUSIONS

Main quality concerns when freezing poultry are meat darkening, lipid oxidation, texture modifications, and decreased water-holding capacity. Many factors affect frozen meat quality, and if optimized, they may effectively assure minimized meat quality modifications due to freezing and frozen storage. These factors include (1) bird diet: a proper combination of dietary fat and vitamin E supplementation may efficiently reduce lipid oxidation during frozen storage; (2) aging prior to freezing: it seems that 6 to 8 h of aging assure frozen poultry tenderness; (3) proper meat classification: to avoid PSE in poultry meat to be frozen, poultry meat with L^* values over 68 should not be frozen; (4) proper packaging to avoid oxygen presence, ice sublimation, and freezing burns; (5) freezing at appropriate conditions to reduce freeze cracking and minimize protein denaturation and, consequently, texture changes and reduction in water-holding capacity; and (6) good hygienic practices and temperature control in storage and thawing to assure efficient control of microbial populations.

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17

QUALITY OF REFRIGERATED POULTRY

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INTRODUCTION

Meat has long been a central component of the human diet, both as a food in its own right and as an essential ingredient in many other food products. Throughout the world in recent years, an increase in consumption of poultry meat has

Handbook of Poultry Science and Technology, *Volume 1: Primary Processing*, Edited by Isabel Guerrero-Legarreta and Y.H. Hui

been recorded in both developed and developing countries (Oliveira et al., 2005). In 1999, global production of broiler chicken reached 40 billion, and based on predictions, poultry is expected to become the overall meat of choice by 2020 (Bilgili, 2002). The higher consumption of poultry and tremendous growth of the industry are the result of various factors, such as its low cost and its status as healthy food that presents few cultural restrictions and has no adaptability problems (Van Horne, 2002). Therefore, more emphasis is being placed on the quality aspects of poultry meat. The final quality of any food depends on its origin and life history: from when the food source leaves the sea, slaughterhouse, or farm to when it arrives on the customer's plate. Broad consideration of meat quality encompasses appearance and eating quality, but considering quality concisely takes account of many factors: sensory aspects, nutritional content, microbiological evaluation, and toxicological factors (Hill, 1987).

Quality factors can be influenced by pre- and postmortem processing operations. Commercial broiler processing consists of several operations, including scalding, defeathering (picking), evisceration, and refrigeration/chilling (Lillard, 1989). Soon after evisceration poultry carcasses are chilled to remove the animal heat and to produce a safe product by reducing the temperature to a point where the rate of growth of spoilage microorganisms is reduced and growth of most pathogenic microorganisms is prevented. Low temperature not only protects the product from microbiological spoilage but also slows the rate of other degradative biochemical reactions. Despite many advantages, low temperature causes unfavorable changes in meat quality. However, the quality of refrigerated poultry represents the quality of poultry before refrigeration as well as the treatment the poultry receives after refrigeration. To ensure high quality, the poultry should be of high quality to begin with (Kramlich et al., 1975). Refrigeration does not improve food quality; it is only expected to maintain the initial quality. Hence, the quality and safety of refrigerated poultry depend on how the product is handled before, during, and after refrigeration. With this train of thought in mind, the chapter has been divided into two principal parts. In the first part we deal with the effects of prerefrigeration conditions on poultry quality, considering conditions that prevailed prior to slaughter as well as those that occurred during and following slaughter. In the second part we consider the effect of refrigeration and refrigerated storage on various facets of poultry quality.

FACTORS THAT AFFECT THE QUALITY OF POULTRY MEAT

The quality of meat is influenced by a number of independent but interacting variables. Research has shown that meat quality attributes may be affected by several factors associated with the animal and its environment (Ngoka et al., 1982). These factors could be pre- and postmortem production factors, which invariably affect the chemical composition of muscle or its structure and metabolism, and therefore the mechanism involved in turning muscle into meat. In the following subsections we review briefly factors that can influence the final quality of refrigerated poultry.

Premortem Production Factors

Age The poultry produced specifically for meat is slaughtered at a younger age. Age affects body composition, particularly the amount of fat (Edwards and Denman, 1975; Twining et al., 1978; Tzeng Becker, 1981) and also the proportion of muscle to bone, which influences palatability primarily through its well-known effect on sensory attributes (Carlin et al., 1949; Fry et al., 1958) as well as physicochemical characteristics of muscle. The protein content of breast and thigh meat increases with increase in slaughter age, as reported in many studies (Singh and Essary, 1974; Touraille et al., 1981b; Grey et al., 1983; Zanusso, 2002). Studies have revealed contradictory results with respect to the lipid fraction of muscle. A few point to an increase (Zanusso, 2002), whereas others showed a decrease (Touraille et al., 1981b) and a few showed no drastic effect of age on the lipid content of poultry meat (Singh and Essary, 1974). Experimental studies by several groups have shown, in general, that age has a marked influence on the tenderness and juiciness of poultry meat, which generally decreases as birds age (Brant and Hanson, 1962; Nakamura et al., 1975; Yamashita et al., 1976; Touraille et al., 1981; Sonayia and Okeowo, 1983). Meat from aged poultry tends to be tougher than meat from younger poultry. This toughness is due to changes in the structure of muscle fiber and its size and distribution in poultry meat (Grey et al., 1986). However, contradictory results have also been reported (Sonayia et al., 1990), such as no difference in tenderness and juiciness between younger and older poultry groups and increased tenderness and juiciness for aged poultry (Tawfik et al., 1990; Farmer et al., 1997). Flavor and odor also improved with increased age in live poultry (Chambers et al., 1989; Sonayia et al., 1990; Tawfik et al., 1990; Farmer et al., 1997; Baeza et al., 1998). Meat tends to be darker in older animals (Delpech et al., 1983), due to the deposition of brown pigments in muscle and the greater amounts of myoglobin (Miller, 1994).

Genetic Strain Animal genetics can play a significant role in meat quality. Genetic strains may influence the lipid content, protein content, and muscle fiber and connective tissue content (Goodwin et al., 1969) in meat on the basis of feed conversion or rate of growth. Meat quality trails are generally regulated by the unique genetic code of the particular animal, which also determines the production of protein, an important meat quality attribute.

Sex Body composition varies according to the sex of the poultry, and one of the most noticeable differences is in fat content (Edwards and Denman, 1975; Twining et al., 1978; Tzeng and Becker, 1981). The carcass from a male broiler has a lower proportion of fat and a higher proportion of lean meat and yields slightly less breast meat than does a female broiler (Moss, 1968; Ricard and Touraille, 1988).

Rearing Conditions Rearing conditions are expected to be another important factor influencing poultry meat quality. In commercial broiler production, if animals are overcrowded there may be more interaction between birds, resulting

in an array of carcass defects (Ricard and Touraille, 1988; Elfadil et al., 1996; Gregory, 1998). Under conditions of high stocking density, there may be limited access to diet and water, and animals may exhibit undesirable social behavior, such as fighting, chewing, and the inability to rest properly. In these situations growth will be affected due to prevailing stress, and subsequent meat may be lower in overall quality. High density can also increase the likelihood of the spread of infections because of bad litter management, which also leads to carcass downgrading.

Husbandry Husbandry conditions during commercial broiler production have a substantial effect on meat produced and its quality. Environmental conditions under which production is carried out, such as flooring, temperature, humidity, light, and stocking density are external factors that can affect meat quality. Broilers reared under a low-temperature regime (e.g., 12°C) during the rearing period are significantly more tender and have a higher flavor score than do those reared at higher temperatures.

Diet Feed and diet are other important aspects that determine the nutritional status of poultry. Extensive work has been carried out on nutritional factors that affect the chemical composition of poultry meat. Feeding a high-energy carbohydrate diet leads to faster growth and earlier fat deposition in all livestock. Changes in protein/energy ratios in diet were found to greatly affect fat content in broilers (Summers et al., 1965; Goodwin et al., 1969, Tzeng and Becker, 1981).

Veterinary Practices Poor veterinary practices may lead to infected carcasses at slaughter. Accidental infections from vaccines injected into muscle can lead to abscess formation in muscle, and certain chemical compounds can result in discoloration. Surgical operations may result in downgrading of a carcass due to bruising, adhesion, or local abscesses, so proper care must be exercised to provide an adequate period of recuperation after medication prior to slaughter.

Transport Catching and loading chickens for transport to a slaughterhouse present great problems and are very unpleasant jobs. Performed badly these operations can cause considerable loss due to such injuries as broken legs and wings and various degrees of bruising. Hence, the quality of final products produced by a processing plant is determined largely by the quality of the live poultry supplied. In poor conditions of high temperature and high humidity during transportation, large numbers die from hyperthermia and asphyxia. It is therefore best to proceed with extreme care along the route from shed to shackle. Movement from farm to processing plant also has stressful effects on poultry, resulting in considerable loss of weight during transport, referred to as *road shrinkage*. Thus, a first-class animal can be reduced to a product of inferior quality as a result of poor loading and transport conditions.

Lairage Holding in lairage prior to slaughter provides opportunity to recover from transport stress and fatigue. The shrinkage loss tends to be reduced by 1.5% after keeping birds overnite in lairage.

Processing Conditions

The main effect that a variation in slaughter conditions has on poultry quality is the completeness of bleeding and the resulting appearance of the carcass. During processing, scalding and chilling are the unit operations that most influence the eating quality of poultry meat. Harsh scalding treatments have a toughening effect on broiler (Koonz et al., 1954; Pool et al., 1959; Wise and Stadelman,1959; Shrimpton, 1960) and turkey (Klose et al., 1959; Wise and Stadelman, 1961) meat. Another detrimental effect of harsh scalding is an increased tendency in chicken (Margolf et al., 1956) and turkeys (Klose and Pool, 1954; Pool et al., 1954)] to lose body moisture. A low scalding temperature produces tender meat. Chilling methods are also associated with subsequent drip and cooking loss and reduced nutritive value (Pippen and Klose, 1955; Fris Jensen and Bøgh-Sørensen, 1973; Zenoble et al., 1977). Processing conditions also determine the microbial quality of poultry meat. The shelf life of poultry meat is limited by the number of microorganisms in and on a poultry carcass before refrigeration. For this reason, processing conditions should be maintained under scrupulously hygienic conditions (Willenberg and Hughes, 1997).

REFRIGERATION AND REFRIGERATED STORAGE

Efficient refrigeration can preserve poultry in conditions approaching its natural state for periods adequate for commercial requirements (Sun, 1998). However, deterioration of poultry quality during refrigerated storage often occurs as a result of improper control of storage temperature. The initial physicochemical (most important, pH) and microbial quality of poultry as well as technical factors such as refrigeration time, load, overload, variation in size and shape of product, poor packaging, and poor refrigeration environment also result in failure to provide wholesome poultry.

EFFECT OF REFRIGERATION ON POULTRY QUALITY

Color

The appearance of poultry meat determines the attractiveness of fresh meat, which in turn influences the consumer acceptance of meat products (Pearson, 1994). The color of poultry meat is due primarily to the quantity and chemical state of muscle pigment myoglobin and can also be influenced by the way in which light is reflected off the meat. As already mentioned, preslaughter factors such as species, breed, age, sex, and muscle have a substantial effect on pigment concentration and subsequently on the color of meat. Color is more stable at lower temperatures because the solubility of O_2 is greater and oxygen-consuming reactions are slowed down (e.g., the rate of pigment oxidation decreases). Different chilling methods can also influence the color of poultry (Evans et al., 1988; Lyon and

Lyon, 2002). Bacterial activity during refrigerated conditions can also result in meat discoloration by reducing the oxygen tension in the surface tissues (Walker, 1980; Faustman et al., 1990). The length of refrigeration also has a substantial effect on the rate of color change during refrigerated storage. Control of both storage temperature and oxygen content can improve the color retention of refrigerated poultry. Low-humidity air at high velocities may result in desiccation of the surface tissue and can result in a dry, spongy, unattractive layer on unwrapped or poorly wrapped poultry. Storage temperature, illumination level on the display area, and method of packaging can also affect the color of poultry under refrigerated displays. Among the factors mentioned, light is the most serious factor, which results in enhanced metmyoglobin formation by exposure of fluoroscent illumination. The rate of discoloration is roughly doubled for a 5°C rise in temperature under either refrigerated storage or in display cabinets. Several researchers have demonstrated a significant relationship between raw breast meat color and raw meat pH (Barbut, 1993; Boulianne and King, 1995, 1998; Allen et al., 1997; Fletcher, 1999; Qiao et al., 2001). Yang and Chen (1993) observe that ground chicken meat with a high pH was darker red and yellow than was meat with a low pH. Cornforth (1994) also stated that meat with a high pH had a higher water-holding capacity, thereby making it darker. Another important concern in refrigerated poultry meat color is pale, soft, exudative meat, characterized by rapid postmortem pH decline (Woelfel and Sams, 2001). Low pH and high body temperature can result in protein denaturation, causing pale color and reduced water-holding capacity; however, rapid chilling can alleviate this problem. Bone darkening, also known as *bone taint*, is common and affects the appearance of the poultry. It is caused by bloody marrow leaching through the bone. Bone darkening is confined to young chickens before the bones are calcified and is not noticeable in mature chickens (Zhu and Brewer, 1998).

Flavor

Flavor is another important quality attribute that can influence acceptability by consumers even before the food is eaten. While poultry in the fresh raw state has little flavor of its own, upon heat processing a specific poultry flavor develops (Northcuttt et al., 2001). Cooked poultry or poultry product flavor may be influenced by the chilling processes employed; (Hale et al., 1973) however, major changes occur during refrigerated storage (Mielnik et al., 1999). Several studies have reported conflicting results regarding the effect of chilling on flavor. According to Grey and Mead (1986), leaching of flavor components occurs by immersion chilling, but how far this assumption is true is still questionable (Jul, 1986). Hale and Stadelman (1969) found that boilers chilled by a dry-chilling method had a subtle but detectable flavor advantage over conventional immersion-chilled broilers. However, in studies by Zenoble et al. (1977) and Pedersen (1972), no effect of chilling on meat flavor was reported, and Ristic (1982) showed that both leg and breast meat had more favorable flavor using an immersion-chilling method compared to air-chilling method. Cryogenic chilling using CO_2 and N_2 has also

been said to result in improved flavor (Lillard, 1982); however, a study conducted by Brodine and Carlin (1968), who investigated three chilling methods, showed that no method had any effect on either the flavor or juiciness of poultry meat. The relatively large proportion of polyunsaturated fatty acids in the composition of poultry meat makes it highly susceptible to lipid oxidation (Watts, 1954; Labuza, 1971; Lawrie, 1998). It is well documented (Igene and Pearson, 1979, 1980; Maraschiello et al., 1989; Buckley et al., 1995; Ruiz et al., 1999) that a phospholipid fraction plays an important role in chicken meat lipid oxidation and development of a warmed-over flavor. Igene et al. (1979), and Brunton et al. (2002) stated that cooked turkey breast was particularly susceptible to lipid-oxidation-mediated off-flavor during refrigerated storage. So especially for cooked poultry products, it is highly recommended that for both short- and long-term frozen storage, vacuum packaging be employed to get a more meaty and less warmed-over flavor.

Texture

There is considerable evidence to indicate that tenderness ranks high among the eating-quality attributes of poultry meat. Some of the factors that influence poultry texture are inherent in the live animal, while refrigeration and storage also have a substantial effect on poultry texture. Among all the factors, conditioning and cold shortening are the two major concerns that influence poultry texture. However, texture-related problems are present in poultry to a lesser degree than in red meats (Wood and Richards, 1974; Bilgili et al., 1989; Sams, 1999). Pale, soft, exudative (PSE) meat is a growing concern, particularly for turkey, and is caused by rapid postmortem pH decline (Woelfel and Sams, 2001) when the body temperature is still high. This condition may result in a pale color and reduced water-holding capacity (Alvarado and Sams, 2004). Rapid chilling may alleviate this problem but increases the danger of cold shortening (Alvarado and Sams, 2002; James and James, 2002). Chilling has a serious effect on the texture of meat if it is carried out rapidly when meat is still in the prerigor condition: that is, before the meat pH has fallen below 6.2 (Bendal, 1972). Hot boning is sometimes used soon after evisceration as an alternative to chilling to minimize cold shortening.

Some reduction in tenderness has also been reported by Mielnik (1986). In a study by Contreras and Beraquet (2001), hot deboned birds had higher shear values and lower tenderness scores than those of conventionally aged and boned birds. Hence, an alternative avenue has found favor: the widespread use of electrical stimulation of poultry carcasses immediately after slaughter, to reduce the effect of cold shortening (Cross, 1979; Li et al., 1993; Craig et al., 1999; Dickens et al., 2002; Sams, 2002). Electrical stimulation accelerates postmortem glycolysis, thereby accelerating rigor and reducing aging time.

Tenderness is related directly to aging. The rate of cooling, the length of time, and the temperature are the most important refrigeration factors controlling the texture of meat. Poultry meat requires less aging time than is required by red

meat. Chicken has a very much higher tenderizing rate (5.2 per day), which means that 50% of the tenderizing occurs in about 3 h and 80% in 10 h (Dransfield, 1986). During chilling and aging, poultry tenderization occurs rapidly, with a high tenderness score being recorded for a carcass aged for 24 h.

Drip Loss

The problem of exudates or drip which accumulates in the container during refrigerated storage or display is not confined to red meats but is also present in poultry meat, although to a lesser extent. The amount of drip exuded from poultry meat depends on its intrinsic characteristics, postmortem treatment, and the pH of the meat. The mechanism of drip formation has been well described by Taylor (1972), Bendal (1974), and Penny (1974). In commercial practice the amount of drip that appears depends greatly on the cut-surface area/volume ratio. A higher ratio will result in a considerable volume of drip and can reduce its sales appeal substantially (Malton and James, 1983). This not only looks unattractive but also accounts for significant weight loss and decreased palatability attributes. Excessive drip loss can also result in dryness, with loss of flavor and increased toughness. Drip losses can be minimized by preventing cold shortening (Honikel, 1990), reducing storage time and temperature.

Weight Loss Through Evaporation

Weight loss by evaporation gets started from the moment poultry is slaughtered. This accounts for loss in salable meat, and if corrective measures are not taken, excessive evaporation may produce a dark, unattractive surface on a carcass or portion. Hence, the quality is degraded and the sales appeal is reduced. A considerable amount of weight is reduced during the chilling and refrigeration process, because soon after slaughter the carcass is hot and wet, so the rate of evaporation is high. The chilled air temperature velocity can also influence weight loss. To attain minimal weight loss, air should be kept at its lowest temperature, minimum velocity, and highest humidity that are practically feasible. After chilling operations, during refrigeration since there is no further requirement to extract heat from poultry, the air velocity should be kept minimum, and fluctuations in relative humidity should also be minimized to prevent evaporative losses. During chilling operations carcasses lose weight when air chilling is employed, but continuous spray or immersion chilling results in a gain in weight. Usually, a weight loss of 1 to 1.5% occurs, but poor conditions may result in weight losses up to 3%. A weight increase of 4 to 8% is seen in the case of immersion chilling (Veerkamp, 1990). During evaporative and air chilling at 3.0 m/s, at 0°C weight losses were about 1.1% (Evans et al., 1988). Use of intermittent sprays at 5- to 15-min intervals during air chilling weight loss can be reduced to up to 0.8%, and the use of fine spray during chilling can eliminate any loss (Veerkamp, 1986). Simeonovov et al. (1999) reported a weight gain of 0.7 to 1.7% and 3.3% in spray and immersion chilling, respectively, well within the permissible limit of 4.5% set by the European Union.

Microbiology

Fresh meat undergoes various changes during refrigerated storage (Show, 1972; Gill, 1983). Microbial changes predominate during refrigeration, and psychrotrophic microorganisms that survive processing may multiply during refrigerated storage and cause spoilage of fresh poultry (Gallo et al., 1988; Russell et al., 1996; Jackson et al., 1997; Hinton et al., 2002). The principal low-temperature spoilage organisms of poultry are species and strains of the genera *Pseudomonas, Acinetobacter, Moraxella, Brochothrix thermosphacta, Aeromonas, Psychrobacter*, and Enterobacteriaceae. In addition to playing a major role in spoilage of refrigerated fresh poultry, some of these bacteria have been identified as potential pathogens (Gallo et al., 1988; Barnhart et al., 1989; Russell et al., 1996; Georgnaras et al., 1998; Sundheim et al., 1998; Sarimehmetoglu and Kuplulu, 2001). The most important are *Salmonella* spp., *Campylobacter* spp., *Clostridium perfringens, Listeria monocytogenes*, enterohemorrhagic *Escherichia coli*, and *Yersinia enterocolitica* (Mead and Hinton, 1996; Mead, 2004). Major bacteria involved in the spoilage of refrigerated poultry is summarized in Table 1.

Refrigerated storage of poultry is for only a short period, usually less than a month. In a test on cut-up chicken, Ayres (1959) reported that compared wih room-temperature storage, life was extended to 2 days at 10°C, 6 days at 4.4°C, and 14 days at 0°C and attainable chilled storage lives for poultry products (IIR, 2000) were 32 days at −4.1 to 1.1°C, 17 days at −1 to 2°C, 12 days at 2.1 to 5.5°C, and 7 days at 5.2 to 8.2°C, respectively. Hinton et al. (2002) enumerated and identified yeasts associated with commercial poultry processing and spoilage of refrigerated broiler carcasses (Table 2). Similar results for the presence and changes in population of yeast on raw and processed poultry products stored at refrigeration temperature have been reported by Ismalia et al. (2000). In another study, in storage trials carried out on half poultry carcasses at

TABLE 1 Major Bacteria Involved in the Spoilage of Refrigerated Poultry

Product	Bacteria	Reference
Raw eviscerated carcasses	*Pseudomonas fluorescens, P. putida, Acinetobacter, Moraxella*	
Dark meat, pH 6.4–6.7	*Acinetobacter, Alteromonas, Pseudomonas*	Barnes and Impey (1968)
White meat, pH 5.7–5.9	*Pseudomonas* and others	Barnes and Impey (1968)
Chicken wrapped in oxygen-permeable films	Microaerophillic bacteria, lactic acid bacteria, and others	
Vacuum-packed chicken	Enterobacterin and others	Arafa and Chen (1975)

Source: Frazier (1995).

TABLE 2 Population of Aerobic Microorganisms, Yeasts, and Molds and Yeasts on Chicken and Turkey Parts and Products

Product	Time (days) at 5°C After Purchase	Population (log CFU/g)					
		Aerobic Count (PCA)		Yeast and Molds (DRBC)		Yeasts (TGYC)	
		Initial	Expiration	Initial	Expiration	Initial	Expiration
Chicken							
Ground	8–10	5.35	7.59	2.24	5.12	2.05	3.51
Breast							
Fresh	7–12	5.77	6.88	2.96	3.72	2.89	3.35
Marinated	3–19	5.49	7.69	2.45	2.56	2.04	3.02
Roasted	7–24	3.32	6.94	9.71	1.65	1.13	1.81
Leg	7–10	5.30	6.57	1.83	3.24	1.64	3.19
Wing	9–12	4.74	9.72	2.58	3.68	2.67	3.14
Gizzard and heart	6–7	4.44	8.31	2.05	4.89	2.22	5.06
Liver	6–8	4.54	9.68	1.98	3.88	1.94	4.47
Whole	9–9	4.65	8.90	2.06	5.05	2.03	4.63
Turkey							
Ground	8–10	4.48	8.04	1.99	4.16	1.47	3.52
Leg	5–7	6.48	8.62	2.90	3.98	2.37	4.68
Neck	7–9	5.58	7.70	4.06	4.75	2.34	4.06
Sausage	2–9	4.65	7.18	1.95	4.30	1.78	4.54
Roasted	30–64	0.00	4.19	0.00	0.00	0.00	0.37
Smoked	14–30	3.64	5.82	0.59	3.36	1.84	2.98

Source: Adapted from Hinton et al. (2002).

temperatures between 4 and −18°C, Bailey et al. (2000) reported a 2 log increase in mesophillic bacterial count. The psychrotrophic count also showed about a 4 log increase; however, *E. coli* and coliform counts were reduced to about 1.7 and 2 log cycles at 4°C, respectively.

CONCLUSIONS

In summary, no detrimental effect is caused by the preservation of poultry by refrigeration if the processing, packaging, and refrigeration operations are conducted properly. The refrigeration process itself does not destroy nutrients. In meat and poultry products there is little change in nutritive value during refrigerated storage; however, drip loss and other poor processing conditions may result in reduced nutritive value. To assure having wholesome poultry, preslaughter factors should also be kept in mind. The scalding and feather-picking operations must be conducted as gently as possible to prevent unnecessary toughening of the meat. Chilling should be done carefully to prevent cross-contamination of poultry carcasses. Aging should be conducted properly, and efficient packaging material having a good moisture and oxygen barrier should be used for packing. Vacuum packaging and modified- and controlled-atmosphere packaging can

maintain the quality of poultry for more than 5 weeks at refrigerated temperatures (Barbut et al., 1990; Mane and Sharma, 2006). Dipping in acid solution and acid treatment can also improve the quality of refrigerated poultry (Robach and Ivey, 1978; Toe and Robach, 1980). The storage temperature should be maintained at or below requirements with a minimum of fluctuation. According to Barbut (2002), the storage temperature should be 10, −0.4, −11, and −22°F for storage periods up to 2, 4, 8, and 10 months, respectively.

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18

REFRIGERATION EQUIPMENT AND OPERATIONS

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INTRODUCTION

In ancient times natural means for heat dissipation were adopted: Animals were slaughtered in seasons of low temperatures and the products were stored in caves to prolong the keeping quality. Over the centuries much sophisticated means have been developed to remove heat from freshly slaughtered animals. Today, however, technology advancement has led to the adoption of mechanical and more sophisticated refrigeration systems that can accomplish the task of chilling carcasses (Savell et al., 2005).

In different regions of the world, poultry is sold in a variety of ways. In developing and third-world countries, sale of live birds, on-the-spot slaughter, and same-day slaughter are common practices. However, in developed countries, refrigeration is used extensively for poultry preservation. Compared to such other means of preservation as salting, drying, smoking, and cooking, refrigeration is a far better technique, as it causes minimal changes in nutritive value, structure, and composition of foods. Therefore, the quality of food preserved by refrigeration is high. Refrigeration is considered an expensive technology, but the market price of refrigerated products compensates for the high cost. Being a high-value product, poultry can be produced in developing countries, refrigerated, and shipped to developed countries, where consumers can afford to pay the highest market prices. Refrigeration also provides liberty to the manufacturer to sell produce when the prices are high. In the context of meat, refrigeration is an economical preservation method if utilized properly. Further, refrigeration becomes particularly important in foods of animal origin, as they need to be produced in a way that ensures their safety for human consumption. With increasing health concerns, focus has shifted toward white meat. Poultry has become a substantial portion of present-day diets, and thus concerns for marketing a safe high-quality product are increasing. With consumers getting more critical of preservatives and additives, refrigeration has the advantage of eliminating the need for preservatives and additives.

During the postevisceration cooling process, it is generally considered desirable to reduce the temperature of a carcass to 10°C or below (Barnes et al., 1978) to delay the multiplication of psychrophilic organisms associated with the deterioration and subsequent spoilage of poultry meat and to prevent the multiplication of any microorganisms of public health significance during the subsequent stages of grading, weighing, packing, and final chilling (Thomas, 1977). *Chilling* and *refrigeration* are used synonymously in this chapter.

Chilling inhibits the growth of microorganisms and restricts the activity of enzymes. Chilling involves reducing the temperature of the poultry carcass to the optimum temperature in the shortest possible time. However, the optimum cooling temperature and time vary with products and must be standardized. The optimum storage temperature and life are influenced by the age of bird, species of poultry, and other factors. The International Institute of Refrigeration (IIR, 2000) defines *chilled storage life* as "the greatest length of time for which the bulk

of produce may be stored either with maximum commercially acceptable loss in quality and nutritive value or with maximum acceptable waste by spoilage." Regulations require that poultry carcasses be chilled to 7°C (45°F) within 2 h of processing (USDA, 1972). In the United States, poultry carcasses weighing less than 4, 4 to 8, or over 4 lb must be chilled to 4.4°C or lower in 4, 6, or 8 h, respectively (*Code of Federal Regulations*, 1992).

Refrigeration ensures food safety, maximizes shelf life, reduces shrinkage, and helps maintain color and tenderness. Today, a variety of processes are available for refrigerating poultry. The choice of process is related to the type of product and its marketing requirements. Next we discuss processes that can be used for refrigerating poultry.

REFRIGERATION PROCESSES

Vacuum Cooling

Vacuum cooling can be applied to solid products that have a large surface area/volume ratio and an ability to release internal water. The products are placed in a vacuum chamber and the resulting evaporative cooling removes heat from the food. Every 1% of water evaporation results in a 5°C reduction in product temperature. Prewetting is commonly employed to facilitate cooling without loss of weight. The capital costs of vacuum cooling are high, although operational costs are low.

Immersion Chilling

In immersion chilling carcasses are passed through a tank or series of tanks containing chilled water or a mixture of ice and water. Immersion chilling also helps to reduce the microbial load of carcasses as they get washed by the cooling medium. Generally, counterflow water chilling systems are considered better. Nowadays, countercurrent immersion chilling systems are used with a maximum water inlet temperature of 4°C (James et al., 2006). Jul (1986) enumerated the following advantages of counterflow chilling systems:

- The quality of the water is maintained, as birds leave the water at the point where the latter just enters the chiller.
- It is a more efficient method, as the birds that have the lowest temperature meet the water that has the lowest temperature.
- Ice need not be used in counterflow chilling systems, thereby making the system more economical.

The chilling rate in the immersion chiller depends on the cooling medium used, the temperature of the cooling medium, the size of the carcasses, and whether the carcass is wrapped or unwrapped. Chilling times of poultry carcasses in immersion chilling systems are reported in Table 1, where it can be observed

TABLE 1 Chilling Times of Poultry Carcasses in Immersion Chilling Systems

Carcass Type	Weight (kg)	Chilling Method	Temperature (°C)		Time (min)	Reference
			Start	Finish		
Uneviscerated broiler	2.5–3.5	Immersion in ice/water at 0°C	40	10	126	Hannan and Shepherd (1956)
Broiler	—	Immersion 28 L/min	32	4	25	Mickelberry et al. (1962)
	—	Immersion free convection	—	—	About 40	Sivacheva et al. (1970)
	—	Water circulation rate about 0.1 m/s	—	—	About 35	Sivacheva et al. (1970)
	—	Water circulation rate about 0.5 m/s	—	—	About 32	Sivacheva et al. (1970)
	1.33	50 : 50 ice water	—	2–4	30	Young and Smith (2004)
	—	Immersion chiller	—	<4.0	30–50	Stadelman (1961)
	—	Immersion chiller 50% methanol at −29°C	38	4.0	35	Lentz and Van den Berg (1957)
	1.36–1.47	Immersion in ice water mix at 0°C	—	4	80	Fromm et al. (1966)
	—	Immersion chiller, convection counterflow	39.6	7	< 90	Allen et al. (2000)

	—	Paddle chiller	—	2.2	< 60	Dickens and Whittemore (1995)
	—	Static ice slush	—	4.2	60	Dickens and Whittemore (1995)
	—	Static ice slush with air agitation	—	1.9	60	Dickens and Whittemore (1995)
Roaster	2.3–3.2	Immersion in 33% ice immersion system	—	—	100	Mickelberry et al. (1962)
	2.3–3.2	Immersion in 50% ice immersion system	—	—	95	Mickelberry et al., (1962)
	2.3–3.2	Immersion in 66% ice immersion system	—	—	70	Mickelberry et al. (1962)
	2.3–3.2	Immersion in 100% ice	—	—	165	Mickelberry et al. (1962)
Broiler	0.9–1.4	Immersion in 33% ice immersion system		—	60	Mickelberry et al. (1962)
	0.9–1.4	Immersion in 50% ice immersion system		—	55	Mickelberry et al. (1962)
	0.9–1.4	Immersion in 66% ice immersion system		—	56	Mickelberry et al. (1962)
	0.9–1.4	Immersion in 100% ice immersion system		—	140	Mickelberry et al. (1962)
	—	Two-stage immersion chiller		4	25	Thomson et al. (1975)

(*continued overleaf*)

TABLE 1 (*Continued*)

Carcass Type	Weight (kg)	Chilling Method	Temperature (°C)		Time (min)	Reference
			Start	Finish		
	—	Two-stage immersion chiller plus air −7°C, 3.5 ms^{-1}	4	−2	45	Thomson et al. (1975)
	0.9	0°C slush ice, wrapped		4.5	95	Esselen et al. (1954)
	0.9	0°C slush ice, unwrapped		4.5	50	Esselen et al. (1954)
	1.1	0°C water, wrapped		4.5	105	Esselen et al. (1954)
	1.1	0°C water, wrapped		4.5	60	Esselen et al. (1954)
	1.0	−5°C brine, wrapped		4.5	70	Esselen et al. (1954)
	1.0	−5°C brine, unwrapped		4.5	27	Esselen et al. (1954)
	0.9	−18°C brine, wrapped		4.5	42	Esselen et al. (1954)
	0.9	−18°C brine, unwrapped		4.5	24	Esselen et al. (1954)
	1.3	−29°C brine, wrapped		4.5	35	Esselen et al. (1954)
	1.3	−29°C brine, unwrapped		4.5	16	Esselen et al. (1954)
Fowl	2.0	0°C slush ice, wrapped		4.5	190	Esselen et al. (1954)
	2.0	0°C slush ice, unwrapped		4.5	90	Esselen et al. (1954)
	1.9	0°C water, wrapped		4.5	195	Esselen et al. (1954)
	1.9	0°C water, unwrapped		4.5	100	Esselen et al. (1954)
	1.6	−5°C brine, wrapped		4.5	105	Esselen et al. (1954)
	1.6	−5°C brine, unwrapped		4.5	38	Esselen et al. (1954)
Turkey	6.8	In drained ice at 0°C	35	4.4	420	Matson et al. (1956)
	6.5	In ice water at 0°C	35	4.4	180	Matson et al. (1956)

Turkey (16-week stag)		Immersion 40 min at 16°C, 30 min at 0°C, air at 3°C	5.0	300	Raj (1994)
		Immersion 70 min at 0°C, air at 3°C	4.8	300	Raj (1994)
Turkey (22-week stag)		Immersion 40 min at 16°C, 30 min at 0°C, air at 3°C	9.8	300	Raj (1994)
		Immersion 70 min at 0°C, 30 min at 0°C, air at 3°C	9.4	300	Raj (1994)
Turkey stag	2.7	0°C slush ice, wrapped	4.5	220	Esselen et al. (1954)
	2.7	0°C slush ice, unwrapped	4.5	95	Esselen et al. (1954)
	2.7	0°C water, wrapped	4.5	235	Esselen et al. (1954)
	2.7	0°C water, unwrapped	4.5	135	Esselen et al. (1954)
	2.5	−5°C brine, wrapped	4.5	165	Esselen et al. (1954)
	2.5	−5°C brine, unwrapped	4.5	55	Esselen et al. (1954)
Turkey hen	5.3	−18°C brine, wrapped	4.5	215	Esselen et al. (1954)
	5.3	−18°C brine, unwrapped	4.5	110	Esselen et al. (1954)
	5.3	−29°C brine, wrapped	4.5	160	Esselen et al. (1954)
	5.3	−29°C brine, unwrapped	4.5	60	Esselen et al. (1954)
	10.8	−29°C brine, wrapped	4.5	205	Esselen et al. (1954)

Source: James et al. (2006).

that the rate of cooling relates to the wrapping on the product. The time required to chill a 1-kg carcass to 4°C ranged from 25 min at −5 or 18°C to approximately 55 min at 0°C. The corresponding values for a 1.56-kg bird was 38 and 95 min. The ratio of ice to water is also known to affect the rate of chilling. A 100% ice immersion system takes longer.

Sivacheva et al. (1970) reported that a water circulation rate of 0.1 m/s was satisfactory in immersion chilling, and speeding up the circulation was neither technologically nor economically justified. A theoretical analysis of the heat transfer coefficient revealed that product thickness mattered. They concluded that intensification of water circulation would neither greatly increase the heat transfer coefficient nor reduce the chilling time significantly.

Immersion chilling results in a weight gain of 4 to 8% (Veerkamp, 1990). Simeonovova et al. (1999) have reported average weight gains of 0.7 to 1.7% in spray chilling of dressed broilers and up to 3.3% in immersion chilling. Thomson et al. (1975), Veerkamp (1990), and Simeonovova et al. (1999) reported a 7.4, 4 to 8, and up to a 3% weight change in broilers after two-stage immersion chilling. Bigbee and Dawson (1963) studied fryers immersed in slush ice, then ice packaged, held at 1.7°C for 96 h, and reported that those immersed initially in slush ice for 2,4, and 24 h gained 4, 3.7, and 5.6% weight. In their study on different types of poultry, Sivacheva et al. (1970) found that immersion chilling of chicken, hens, ducklings, ducks, turkeys, and geese resulted in 4.3, 3.6, 6.7, 6.1, 5.6, and 7.3% weight gain respectively. The limitation of this method is that it involves large quantities of water.

Spray and Evaporative Chilling

Generally, spray chilling involves a combination of spray and air chilling in the initial stage, with air only for the remaining chilling. The principle of spray chilling is to increase the rate of evaporative heat loss, and by replacing the water lost, to reduce the overall weight loss (James et al., 2006). In a chilling operation the heat removed by evaporation of water is controlled by the water transport in the product. The weight loss in the product can be controlled by periodic spraying of the carcasses with water during the chilling operation. Usually, spray-chilling systems depend on intermittent sprays: for example, after 5 and 15 min of the start of air chilling, four or five times during the entire chilling process (Veerkamp, 1986).

A study by Thomas et al. 1977 revealed that experimental spray chilling installations using very large volumes of refrigerated water produced microbiological results comparable with those obtained in well-operated controlled immersion chilling systems. So far, only one commercial spray chilling system has been reported (Leistner et al., 1972), and that involved continuous spraying of refrigerated water (12 L per bird) on the carcasses.

An increase in the amount of water evaporating from the surface can reduce the cooling time in air-chilling operations (Veerkamp, 1986). Weight loss during evaporative (intermittent sprays combined with air chilling) and air chilling at

3.0 m/s, 0°C, of 16-kg turkey carcasses was 1.1% (Evans et al., 1988). Klose (1975) reported a −5% weight change in broilers that were evaporatively chilled. He reported that a weight change could be made −1 and +1% by dipping in methyl cellulose before chilling and by placing 50 mL of water in the cavity.

A wet surface can result in microbial growth, which in turn can affect the shelf life. Addition of lactic or acetic acid can reduce bacterial contamination (Hamby et al., 1987). Evans et al. (1988) found that weight change in turkey weighing 16 kg was −2% with air at 0.2 m/s, 0°C and −1.1% with air at 3.0 m/s, 0°C. They found a −1.1% weight change in turkey with air at 0.2 m/s, 0°C. Simeonovova et al. (1999) reported a 0.7 to 1.7% change in the weight of broilers. Veerkamp (1986) reported that giving four or five sprays to broilers did not cause a change in weight. However, spraying broilers at 5- and 15-min intervals resulted in a −0.8% change in weight. Chilling times of poultry carcasses in spray and evaporative chilling systems are depicted in Table 2.

Accelerated-Chilling Systems

Usually, accelerated-chilling systems depend on maintaining very low temperatures (−15 to −70°C) during the initial stage of the chilling process and is achieved by a powerful mechanical refrigeration plant (Kerens, 1983; Bowling et al., 1987). At successive stages higher temperature are employed, and at the final stage the temperature is at or above 0°C, so as to equalize the temperature. The initial cost of accelerated-chilling systems is higher than that of conventional plants, so to be cost-effective they must offer substantial savings in terms of increased throughput and/or higher yields of salable meat. Studies (Gerosimov and Malerany, 1968; Gerosimov and Rumyanstev, 1972) have revealed that cooling time can be reduced by increasing the surface heat transfer coefficient (e.g., by using radiative plates in conjunction with blast air).

Plate Cooling

Hannan and Shepherd (1956) reported that plate cooling was not faster than slow-moving air at 0°C. A plate cooling system has the potential to reduce the cooling time substantially compared to that required in an air-blast system. The type of material that can be chilled should be thin. Plate cooling systems are expensive but are low in cost to run.

Modified-Atmosphere Packaging for Poultry

Poultry is usually contaminated with large bacterial populations that consist primarily of spoilage bacteria but can include a significant number of pathogens. Poultry has a higher pH than that of red meat and so provides an ideal environment for the growth of these bacteria. Vacuum packages are difficult to form around whole dressed birds because of their irregular shape. Thus, the shelf life of vacuum-packed poultry is usually short, limited to about 2 weeks. There are now an increasing range of cut-up portions (e.g., breast, wings, fillets) and other

TABLE 2 Chilling Times of Poultry Carcasses in Spray/Evaporative Chilling Systems

Carcass Type	Weight (kg)	Chilling Method	Temperature (°C)		Time (min)	Reference
			Start	Finish		
Unwrapped broiler	0.93	Evaporative (spray) with air at 0.5 m/s	34.9	5.0	50	Mielnik et al. (1999)
Broiler		Evaporative (spray) 15 L per bird		6	30	Großklaus and Levetzow (1967)
		Evaporative (spray) 12 L per bird at 0°C	35	5	35	Peri et al. (1971); Szentkuti et al. (1969)
		Evaporative (spray) at 12 L per bird at 0°C		7	35	Leistner et al. (1972)
		Evaporative (spray)	34.8	8.1	45	Ziolecki et al. (1997)
		Evaporative (spray)		12.0	27.5	Mulder and Veerkamp (1990)
Hen		Evaporative sprays for 15 min, then air −3 to −4°C, 3m/s		<4.0	80	Sivacheva et al. (1975)

Broiler	0.80	Evaporative (spray) 100 L per bird at 2.5°C	32	5	30	Veerkamp et al. (1972)
Broiler hung by wings	0.80	Evaporative (spray) 12 L per bird at 2.5°C	30	13	30	Veerkamp et al. (1972)
Broiler hung by hocks	0.80	Evaporative (spray) 12 L per bird at 2.5°C	30	9	30	Veerkamp et al. (1972)
Broiler	1.00	Evaporative (spray) 12 L per bird air 6°C, 0.9 m/s	30	1	30	Veerkamp et al. (1972)
		Evaporative (spray, light) in spiral ventstream	39.2	1.5	<90	Allen et al. (2000)
		Evaporative (spray, moderate) in clipbar air chiller	38.3	4.4	<90	Allen et al. (2000)
		Evaporative (spray, moderate) in standard ventstream	39.6	3.0	<90	Allen et al. (2000)
		Evaporative (spray, heavy) in standard ventstream	35.1	5.7	<90	Allen et al. (2000)
	1.22	True evaporative dipped in methyl cellulose before	29	2	30	Klose (1975)
	1.00	True evaporative 50 mL water placed in cavity before	26	1	29	Klose (1975)

Source: James et al. (2006).

further-processed products, both raw and cooked. High CO_2 atmospheres increase the product shelf life. For chicken meat, 20% CO_2/70% N_2 can be as effective as an 80% CO_2/20% N_2 mix over 1 week's storage at 2°C, and thus is very useful for retail packs. However, if a longer shelf life is required in bulk packs, higher levels of CO_2 are needed. A storage life of up to 35 days has been achieved under certain closely controlled conditions, although commercially 10 to 21 days at −1 to +2°C would be expected using an 80 to 100% CO_2/0 to 20% N_2 mixture (James, 2003).

Air Chilling

Air chilling involves circulation of refrigerated air around carcasses to reduce their temperature. The time of chilling and weight loss depend on the conditions in the chiller and the spacing between carcasses. Air chilling is suitable for birds that have been soft-scalded (i.e., at 50 to 53°C), as their outer dermal layer remains intact, which retains a pleasant appearance and thus the birds can be sold in a fresh state. However, air chilling is not suitable for those that have been given a high scald (semiscald), as epidermis gets removed in the plucking operation, which makes the surface susceptible to dehydration and discoloration (Jul, 1986).

In immersion chilling, where carcasses are washed with water, the microbial load is reduced. Air chilling–blast, continuous or batch, does not have this advantage. The rate of heat transfer is low in air chilling. This can, however, be overcome to some extent by wrapping the poultry. Use of very low temperatures may result in freezing of the surface. Chilling by air is economical, hygienic, and relatively noncorrosive to equipment. In a batch process the warm poultry is placed in a refrigerated room and air is circulated around, but uneven air distribution can affect the quality. In a continuous system the problem of uneven air distribution is not encountered, as the products are exposed to the same velocity and time.

In automatic plants the dressed carcasses are transferred automatically from the slaughter conveyor to the chill room system. In not-so-sophisticated plants the carcasses are hung manually on long rails that index their chiller. With an increase in throughput there is a trend to move to much larger chill rooms with much more free space above and below the rails to facilitate the cleaning of the structure of the chill room as well as maintaining the rail system (James et al., 2006).

Small cooked poultry products can be chilled continuously on racks in trays that are pulled or pushed through a chilling tunnel using a simple mechanical system. In sophisticated plants, racks can be conveyed through a chilling tunnel in which refrigeration capacity and air conditions can be varied throughout the length of the tunnel. In larger operations it is far better to convey the cooked products than to use a linear tunnel or spiral chiller. Linear tunnels have far simpler constructions than spiral chillers but require more space.

Air chilling results in a weight loss of carcass. Veerkamp (1990) reported a −1 to −3% weight change in broilers. Mielnik et al. (1999) reported −1 to

−3% weight changes in broilers that were air chilled at 0.5 m/s and 0.3°C. A higher change in weight was reported by Skarovsky and Sams (1999): −1.9% in broilers that were air chilled 1°C, 0.75 m/s, 91% relative humidity (RH), 2 h postmortem, and −2.55% in broilers that were air chilled 1°C, 0.75 m/s, 91% RH, 4 h postmortem. Veerkamp (1986) stated that use of sprays at 5 and 15 min during air chilling reduced weight loss to 0.8% in broilers and the application of four or five sprays in the chilling process would eliminate any loss. Chilling times of poultry carcasses in air-chilling systems are reported in Table 3.

Super and Deep Chilling

Superchilling involves chilling the carcasses by water, followed by putting them through an air freezer operating at −15°C for approximately 30 min (Jul, 1986). After packaging, the product is placed back in the air freezer, stored, and distributed at −1 to −2°C. The process results in crust freezing, however. Vacinek and Toledo (1973) reported that crust freezing of poultry carcasses during chilling, followed by allowing them to equalize to approximately 4°C, did not produce any quality problems.

Cryogenic Cooling

Cryogenic cooling involves the use of liquid nitrogen or solid CO_2 for chilling. Avoiding surface freezing of the product is the main problem. Continuous-chilling systems using liquid nitrogen either immerse the product in the liquid, spray nitrogen onto the surface, or vaporize the nitrogen in a forced draft and pass it over the surface of the foodstuff. Direct spraying of liquid nitrogen onto a food product while it is being conveyed through an insulated tunnel is the most common method. A limited number of studies have looked at cryogenic coolants (Arafa and Chen, 1978), but they are reported to have little commercial adoption (Lillard, 1982). Overall, there is a dearth of published data relating the rate of temperature reduction in different parts of poultry carcasses to carcass weight, dimensions, and chilling conditions.

TEMPERATURE

Attaining the Refrigeration Temperature

The purpose of refrigeration is first to reduce the temperature of a food to below a set temperature and thereafter maintain it so as to avoid the growth of both pathogenic and food-spoilage organisms. The speed with which a food can be cooled is limited by either the rate of heat removal from its surface or internal conduction. Heat removal from the surface is a direct function of the surface heat transfer coefficient (h). The values for h range from 5W/m^2·°C for slow-moving air to 500W/m^2·°C for agitated water. Table 4 reveals that at low values of h, a 10-fold increase, 5 to 50W/m^2·°C makes a substantial 3.2- to 4.2-fold reduction

TABLE 3 Chilling Times of Poultry Carcasses in Air-Chilling Regimes

Carcass Type	Weight (kg)	Chilling Method	Temperature (°C)		Time (min)	Reference
			Start	Finish		
Unwrapped broiler	0.91	Air chilling at 0.5 m/s, 0.3°C	33.2	5.4	50	Mielnik et al. (1999)
Uneviscerated broiler	2.5–3.5	Slow-moving air at 0°C	40	10	264	Hannan and Shepherd (1956)
	2.5–3.5	Air blast 2.5 m/s, 0°C	40	10	186	Hannan and Shepherd (1956)
Uneviscerated fowl	1.4	Still air at 1.7°C		3.9	390	Funk (1942)
	2.3	Still air at 1.7°C		3.9	480	Funk (1942)
	2.7	Still air at 1.7°C		3.9	600	Funk (1942)
Uneviscerated cock	1.8	Still air at 1.7°C		3.9	420	Funk (1942)
	3.2	Still air at 1.7°C		3.9	600	Funk (1942)
	4.0	Still air at 1.7°C		7	900	Funk (1942)
Uneviscerated fowl	1.8	Air at 1.7°C, 2.5 m/s		3.9	260	Funk (1942)

Broiler	1.3	Air at −5 to 0°C	30	4	90	Veerkamp (1990)
	—	Air blast at −18°C	38	<3.0	27	Vacinek and Toledo (1973)
	—	Air blast at −40°C	38	<3.0	17	Vacinek and Toledo (1973)
	—	Air 1°C, 0.75 m/s, 91% RH	26.2	<4.0	150	Skarovsky and Sams (1999)
	—	In wire baskets, air at −7°C, 4.1 m/s		4	60	Heimbach and Berner (1969)
	—	Air standard ventstream	35.1	7.0	<90	Allen et al. (2000)
	1.25	Air at −12°C		3.4	65	Craig et al. (1999)
	1.25	Air at 0°C		8.9	95	Craig et al. (1999)
	—	Air 1 h at 5°C 78, then 0°C		1	150	Ristic (1997)
Turkey	6.5	In unevacuated bag in air blast at 1°C	35	4.4	780	Matson et al. (1956)
	6.2	In canvas shroud in air blast at 1°C	35	4.4	520	Matson et al. (1956)

Source: James et al. (2006).

TABLE 4 Predicted Cooling Time (h) from 40 to 2°C at the Center

Cooling Method	h(5 W/m^2·°C)	Meat Thickness (cm)		
		2.0	4.0	8.0
Air (still)	5	5.0	11.0	24.0
Air (5 m/s)	50	1.2	2.8	7.4
Plate	360	0.7	1.8	5.5
Immersion	500	0.4	1.2	4.4

Source: James (2003).

in cooling time. A further 10-fold increase in h (50 to 500W/m^2·°C) decreases the cooling time threefold for a 2-cm-thick slab but results in only a 69% reduction at a thickness of 8 cm. This shows that in thicker material, internal heat conduction controls the rate.

Storage Temperature

Hypothetically, environmental conditions required for cooling and storage are different since the former involves temperature reduction, and the latter involves temperature maintenance at a set product temperature. However, in an actual air-based cooling system, cooling and storage take place in the same chamber. Where two separate chambers are used, all the heat may not be removed in the cooling phase. Failure to remove the required heat could be due to insufficient time allowed, insufficient refrigeration capacity to cater for high initial product load, overloading, variability in size of products, and incorrect environmental conditions.

In commercial practice the aim of the processor is to achieve an endpoint temperature of 0 to 2°C prior to distribution. Barnes et al. (1978) showed the significance of keeping processed carcasses as cold as possible. In their study, eviscerated turkey carcasses wrapped in an oxygen-permeable film were stored at a temperature between +5 and −2°C, and it was found that storing a carcass at 0°C rather than 2°C extended the shelf life by more than 7 days. However, such studies are conducted under laboratory conditions, where the storage temperature is relatively constant, but in actual commercial practice the temperature will inevitably vary to the same extent at different stages of the cold chain. Shelf life under a particular storage temperature is the cumulative effect of fluctuating temperature throughout the storage history of the product. Daud et al. (1978) and Pooni and Mead (1984) studied predictive mathematical models relating temperature and spoilage rate for poultry products, and data for these parameters were shown to fit the Arrhenius equation as proposed by Olley and Ratkowsky (1973). The square-root equation of Ratkowsky et al. (1982) was found to be more appropriate according to tests on 28 sets of spoilage data from 14 published studies (Pooni and Mead, 1984). Temperatures for bulk packs of chilled products in large storage rooms have been found to be much less sensitive to small heat inputs than are single consumer packs in transport or open display. Cooling operations

TABLE 5 Specific Heat of Poultry

Type	Temperature Range (°C)	Specific Heat (kJ/kg·°C)
Chicken lean (73% water)	0–100	3.39
Chicken fat (11.4% water)	0–15	4.44
Chicken bone (35.6% water)	6–21	2.92

Source: Morley (1972).

carried out efficiently ensure that food is reduced below the temperature required before it is placed in storage. In such cases, the storage refrigeration system is only required to extract extraneous heat that enters through doors and wall openings.

In refrigeration, heat has to be extracted from the poultry to reduce the temperature. The rate of heat removal depends on the type of process being used (e.g., air chilling, water chilling). However, the rate of heat flow in the meat depends on its thermophysical property. The amount of heat removed is the specific heat but is not constant with temperature. So the difference in enthalpy between the temperature of interest can be used to provide a value for the energy change required. Poultry is not a homogeneous product, and in the carcasses there are three main components: fat, lean muscles, and bone. The specific heat of different parts of poultry is depicted in Table 5.

Temperature Measurement

Handheld digital thermometers can be used by small producers to check routine tasks such as measuring air temperature between packs or product temperature. Such thermometers should be accurate, easy to use, react quickly, and be robust. At times there could be a requirement to measure the values of temperature at many different positions at the same time. This can be accomplished by attaching a multipole switch to a digital thermometer. Subsequently, temperature sensors can be connected to a switch and the temperature in central plant rooms monitored at different locations simultaneously. The temperature can be monitored as well as recorded over a period of time. However, if a large number of temperature sensors are not put in place, it is difficult to predict the warmest positions in the refrigerated space. The UK code of practice provides ideas about the number and position of sensors in different situations. According to this, the number of sensors should range from two for a 500- to 5000-m^3 cold store to six for a cold store of over 8500 m^3. The places where the probes should be kept, in descending order of importance, are: at the maximum height of food farthest away from the cooler fans or in the air return to the evaporator, along the walls at two-thirds the height of the room away from the doors and not directly in the path of the air outlets from the evaporator, and positioned above the floor level directly opposite the evaporator. The code also recommends monitoring the air

from and returning to the evaporator coil. Infrared radiation thermometers could be of utility in identifying areas of high temperature within cold stores.

REFRIGERATED STORAGE ROOMS

Bulk Storage Rooms

In large-scale commercial operations, poultry and its products are stored in large rooms where air is circulated. The air movement around the unwrapped poultry should be the minimum required to maintain a constant temperature so as to minimize weight loss and appearance changes associated with desiccation. Even in unwrapped products, low air velocities are recommended to minimize energy consumption. While constructing such rooms, care should be taken to provide for air distribution and localized air velocities over products.

Jacketed Cold Stores

An enclosed space can have good temperature control with minimum air movement if the walls, ceiling, and floor are kept cool. It is best suited for unwrapped produce and controlled-atmosphere storage that is very sensitive to air movement or temperature fluctuations.

Controlled-Atmosphere Storage Rooms

There is a growing interest in applying controlled-atmosphere storage to poultry. However, in addition to the normal temperature control, these stores also include special gastight seals to maintain an atmosphere that is normally lower in oxygen and higher in nitrogen and CO^2 than air. An additional plant is required to control the concentration of CO^2, generate nitrogen, and consume oxygen.

Domestic Refrigerators

The period for which consumers store chilled foods after purchase will affect their safety. Recommendations concerning microbial safety of foods advise that maximum temperature in domestic refrigerators should not exceed 5°C (Richmond, 1991). Studies were carried out by James et al. (1989) and James and Evans (1992) on three types of refrigerators: a 6-ft^3 dual-compressor refridgerator freezer, a 6-ft^3 single-compressor refridgerator freezer, and a 4-ft^3 free-standing domestic refrigerator with an ice box compartment. In the ice box refrigerator, more than 2 h is required to reduce the surface temperature of drumsticks and portions to 7°C, compared with more than 5 h in a refridgerator freezer. In a domestic refrigerator the drumsticks cooled faster than did the large portions. In the refridgerator freezer, portions on the middle shelf cooled faster than drumsticks positioned on the top shelf.

Generally, food is loaded "warm" into domestic refrigerators after purchase from retail stores. Achievement of refrigeration temperature by warm food (20°C) (two joints ca. 17.5 × 7.6 × 3.6 cm, 195 ± 10 g) and two drumsticks (ca. 12 × 6 × 3 cm, 120 ± 10 g) of simulated chicken (Tylose) revealed the poor performance of domestic refrigerators.

Designing Refrigerators for Poultry

The following specifications for designing refrigerator equipment should be clear whether it is to be used for reducing temperature, maintaining temperature, or both.

- How the product will be kept, wrapped, unwrapped (drumsticks, whole broiler, cut portions)
- Size of equipment
- Load expected
- Loading and unloading frequency
- Temperature requirement
- Size and position
- Air velocity
- Humidity
- Defrosting frequency
- Cleaning operations
- Lighting
- Future needs

COSTS

Pedersen (1979) compared the relative costs of five different chilling systems and found that the energy costs of an air-chilling system were five times the energy costs of a countercurrent water system. On the other hand, if the cost of water and water disposal are considered, the water-chilling cost was over 50 times that of an air system. The control of refrigeration costs is a major concern for the industry, so there is a strong motivation toward developing ways of predicting heat-load variations over time and the response of the refrigeration system to those load variations. If accurate predictions can be made, a more precise design of the plant itself and of the control strategy to be employed can enable significant cost savings to be made (Lovatt et al., 1993).

CONCLUSIONS

Since refrigeration is an established low-temperature preservation technique, a major section of poultry shelf-life extension relies on refrigeration. Therefore,

refrigeration is one of the important needs of the poultry industry. Over the years the basic design of the refrigerator has not changed much, although its use has increased. Features in the domestic refrigerator have increased and are more sales oriented. User-friendly and cost-effective refrigeration equipment can bring a revolution in poultry refrigeration that can facilitate low-cost mass storage and distribution. The development of cost-effective materials and systems for gas packaging of poultry has widened opportunities for the marketing of products with an extended shelf life in the chilled state. The characteristic feature governing purchase is the cost per unit storage volume. The efficiency of refrigerators also needs to be expanded.

The domestic refrigerators currently available are not efficient enough to maintain the desired temperature for refrigerated foods, especially nonvegetarian, when subjected to frequent door opening and the loading of warm food. There has to be coordination between the regulatory authorities and the industry. There is a paucity of literature on the equipment for poultry and this needs to be taken up by scientists and engineers. A hazard analysis and critical control points (HACCP) program could have much more impact on refrigeration. A basic HACCP approach could improve product performance. Issues such as pollution due to chlorofluorocarbons also need to be addressed.

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19

FREEZING EQUIPMENT AND OPERATIONS

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Handbook of Poultry Science and Technology, *Volume 1: Primary Processing*, Edited by Isabel Guerrero-Legarreta and Y.H. Hui

INTRODUCTION

Freezing is a long-term food preservation method used widely in the poultry meat industry. Freezing is employed to preserve poultry meat products ranging from whole carcasses, cut-up chicken and turkey, ground turkey, duck breast and offal, to processed products. The freezing process combines the favorable effect of low temperatures with the conversion of water into ice, which makes it less available for decaying changes. Freezing of foods is carried out in special cold-producing machines called *freezers*. At present, a variety of industrial freezers of different designs, sizes, and operating modes are available in the marketplace for freezing poultry meat products. The selection of suitable freezing equipment helps to maximize product quality, operating flexibility, and return on investment while minimizing waste, costs, and downtime. Whatever the product, rapid freezing is generally better than slow freezing (Miller and Butcher, 2000). Rapid freezing improves product quality by promoting the formation of numerous intracellular small ice crystals (Li and Sun, 2002a; Fernández et al., 2006). The freezing rate achievable by conventional industrial food freezers and their combinations is controlled by the low thermal conductivity of foods (about 0.5 to 1.5W/m · K) (Sun and Li, 2003). Novel freezing methods such as high-pressure and ultrasound-assisted freezing and chemical aids to freezing, such as antifreeze and ice nucleation proteins, are being proposed and developed to assist in energy saving and/or quality improvement. In this chapter we present industrial freezing equipment commonly used in the poultry meat industry and their operation as well as the principal factors affecting the choice of conventional freezers. Also, it reviews novel food freezing methods with great potential in the poultry meat industry.

FREEZING EQUIPMENT

Freezers used in the poultry meat industry and other food industries can be characterized primarily according to their cooling system or cold source. Vapor-compression refrigeration and cryogenics are the two main artificial cooling techniques used in the industrial freezing of foods (Miller and Butcher, 2000).

Artificial cooling consists of getting temperatures below that of the local environment, which requires energy expenditure. Freezers using vapor compression are commonly called mechanical freezers; the second class of freezers are cryogenic freezers or cryofreezers. The majority of conventional mechanical vapor-compression refrigeration systems operate down to $-40^{\circ}C$, with special applications down to $-80^{\circ}C$ (Richardson and Stone, 2003). Officially, the term *cryogenics* is applied to temperatures below $-150^{\circ}C$, but in food processing the term *cryogenic freezing* is widely used to identify freezers using either liquid nitrogen ($-196^{\circ}C$) or carbon dioxide ($-78^{\circ}C$ as a solid) (Ramaswamy and Marcotte, 2006).

By the type of contact between refrigerant and food, freezing equipment can be classified into direct- or indirect-contact freezers. To freeze a food, its heat must be subtracted and ejected elsewhere by another substance (a primary refrigerant or simply, a refrigerant) whose temperature is lower than that of the food. Direct-contact cryofreezers allow contact between the food and the refrigerant, commonly known as *cryogen*. Direct-contact mechanical freezers use a secondary refrigerant or cooling medium surrounding the food which extracts its heat and transfers the heat to the refrigerant within the refrigeration system. The cooling medium can be cold air or cold brine. Indirect-contact freezers involve the use of metallic surfaces (heat exchangers) which isolate the food from the refrigerant, cooling medium, or cryogen (Karel and Lund, 2003). Indirect-contact cryofreezers generally are not used in the poultry meat industry and so are not reviewed here. A review of indirect-contact cryofreezers has been provided by Khadatkar et al. (2004). In practice, due to close stacking of the product, the radiation contribution is low (Cleland and Valentas, 1997). The effective heat transfer coefficient (h) is a parameter that accounts for all these mechanisms and shows the ability of a freezer to remove heat from the product. Based on their h values, industrial food freezers range from slow freezers ($h = 5$ to 10 $W/m^2 \cdot K$) to ultrafast freezers ($h > 100$ $W/m^2 \cdot K$). Both mechanical and cryogenic freezers can be operated in either batch or continuous mode. The freezing process can be carried out either on- or off-line. Online freezing is a process in which products are frozen as part of a continuous manufacturing assembly line, so that the exit line of the assembly line produces the frozen product. Off-line freezing involves removing the food product physically from the production line in order to freeze it in a separate manufacturing step or location (Ramaswamy and Marcotte, 2006). Several types of industrial food freezers share many features, such as similar design principles or modes of operation, even though they may use different cooling systems (mechanical refrigeration or cryogenics). This feature arranges the freezers by design family (Miller and Butcher, 2000). Freezers within a design family are suitable for many of the same applications. In this chapter, classification of freezer types by design families forms the basis of our discussion.

Mechanical Freezers

Thermodynamic changes that take place in a refrigerant as it alternately vaporizes and condenses, absorbing and rejecting heat, respectively, as it circulates

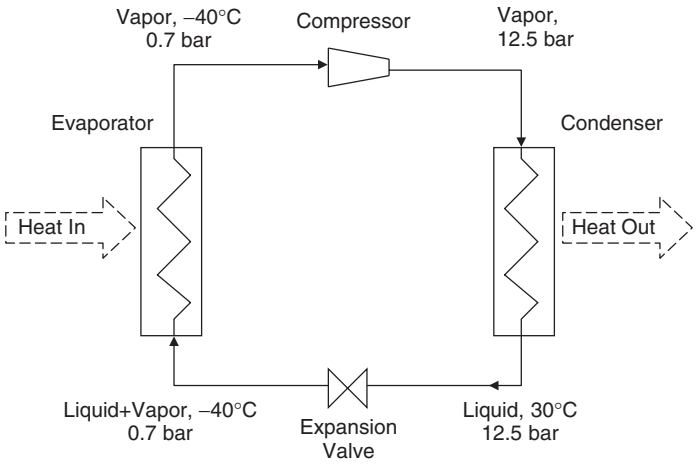

FIGURE 1 Single-stage vapor-compression refrigeration system using ammonia as the refrigerant. It shows the thermodynamic conditions of ammonia in the various components of the refrigeration system.

through a closed circuit is the base of mechanical vapor-compression refrigeration. Sites using mechanical refrigeration often have a central refrigeration plant from which refrigerant is piped to and from the freezers. In agreement with the Montreal Protocol, these refrigerants must be phased out and replaced by refrigerants with zero ozone-depletion potential. Ammonia (R-717) is currently the dominant refrigerant for industrial refrigeration in many countries. It is non-ozone depleting and has no global warming potential. Figure 1 shows a mechanical vapor-compression refrigeration system usually working at temperatures around -40°C with ammonia as refrigerant (Miller and Butcher, 2000). This system has four main components: a compressor, a condenser, an expansion valve, and an evaporator.

In the condenser, ammonia vapor rejects heat from the freezer, condensing into a liquid. The rejected heat is carried away by the water or air. The evaporator is where the circulating refrigerant absorbs and removes heat, which is subsequently rejected in the condenser. The evaporator often forms part of the freezer itself. The heat coming from the freezer and its contents evaporates the liquid part of the cold refrigerant mixture within the evaporator. Now the ammonia returns to the compressor to complete the cycle. Several types of mechanical compressors, condensers, and evaporators are available in the marketplace, and they are chosen depending on the process conditions. A widespread review of these components is provided by Dossat (1996).

Air Freezers

These freezers are used widely in the poultry industry and provide the largest range of designs. Food, packaged or unpackaged, is frozen by exposure to air

at temperatures ranging from −18 to −40°C (Ramaswamy and Marcotte, 2006). In these freezers, the main heat transfer mechanism between the hotter product surface and the colder air moving surrounding it is convection. Furthermore, in the industry, this weight loss becomes an important quality and economic factor (Campañone et al., 2001, 2005). Air freezers can be classified in two wide categories: natural- or forced-convection air freezers. In natural-convection air freezers, the cold air surrounding the food (heat source) is warmed and becomes less dense (and more buoyant) than the bulk of the cold air. The warm air rises, causing the cooler fluid in the bulk to sink, thereby creating very slow natural convection currents (air velocity of less than 0.4 m/s), which supply cool air continually to the food. These slow freezers have h values typically between 5 and 10 $W/m^2 \cdot K$, resulting in an ice front moving at a rate of 0.2 cm/h. An example is the still-air freezer (Cleland and Valentas, 1997; North and Lovatt, 2006). The air immediately adjacent to the surface of the food is stagnant due to the friction between the air and the surface of the product. These factors are related to the performance of forced-convection air freezers, which are equipped with fans or nozzles to increase the air velocity and turbulence degree, reducing the thickness of the boundary film surrounding the food. These freezers can be classified on the basis of the airflow pattern into air-blast freezers, fluidized-bed freezers, or impingement freezers. In air-blast freezers the product is placed in a powerful blast (1.5 to 6.0 m/s) of circulating cold air at between −30 and −40°C, with airflow either parallel or perpendicular to the food surface (without product fluidization). The h values for blast freezers are typically between 11 and 50 $W/m^2 \cdot K$. Most poultry for further processing, consumer portions, and other poultry products are frozen in air-blast freezers. Fluidized-bed freezers are modified blast freezers in which cold air (−25 to −35°C) flows up under a 2- to 13-cm (depth) "bed" of particulate foods at a high enough pressure and velocity (2 to 6 m/s) to "fluidize" the foods. In these freezers, the air acts as both a cooling medium and a transport medium. Typical h values are in the range 120 to 200 $W/m^2 \cdot K$. Products suited to fluidized-bed freezing are small and uniform in size (0.5 to 5.0 cm in diameter). Therefore, a major disadvantage of fluidized-bed freezers is the fact that large or nonuniform products cannot be fluidized at reasonable air velocities. An advantage of fluidized-bed freezers over conventional air-blast freezers is less product dehydration due to a short freezing time and less frequent defrosting of equipment. Impingement freezers consist of jets of high-velocity air (10 to 100 m/s) exiting from nozzles and impinging on the food surface to break the insulating air boundary layer that surrounds the product. This results in heat transfer typically three- to fivefold that of a conventional air-blast freezer using axial-flow fans (h up to 400 $W/m^2 \cdot K$) (Salvadori and Mascheroni, 2002; Sarkar and Singh, 2004). The cooling process is more controllable in forced-convection air freezers than in natural-convection freezers because they can achieve a more uniform air temperature throughout the freezer, and the airflow pattern and velocity can be altered to vary the heat transfer coefficient at the surface of the product.

Liquid Immersion Freezers

Liquid immersion freezers, also referred to as direct-immersion freezers, are used in the poultry industry to freeze commonly packaged products with irregular shapes, such as film-wrapped whole carcasses, and to prefreeze film-wrapped cut-up poultry parts before air-blast freezing. Whole turkeys are so large that a brine immersion freezer is the only practical way to freeze them (Miller and Butcher, 2000). In these freezers, the product is immersed in a secondary refrigerant which remains liquid throughout the process. Aqueous solutions of the following substances can be used as secondary refrigerants: sodium chloride, calcium chloride, ethylene glycol, propylene glycol, and mixtures of salt and sugar. Solutions comprising 23% sodium chloride or 40% ethanol allow operating temperatures of -20 and -30°C, respectively. In -29°C calcium chloride brine, times for the interior to reach -9°C for warm eviscerated packaged broilers, 5.5-kg turkeys, and 11.4-kg turkeys are approximately 1.5, 5, and 7 h, respectively (ASHRAE, 2002). The freezing liquid must be nontoxic and approved by the local government, it should be relatively inexpensive, have a low freezing point, and have good heat conductivity. Comparison of various liquids (methanol, salt brines, and glycols) that might be used in immersion freezing revealed that freezing times depended mainly on the viscosity of the liquids and were maximum in glycerol and minimum in calcium chloride brine (ASHRAE, 2002).

In liquid immersion freezers, only convective heat transfer is important. Increased agitation decreased freezing times in the surface layers by as much as 50%. These freezers are fast or quick freezers. Values of h tend to be greater in liquid immersion than in air freezers for the same degree of fluid movement because of the greater density and thermal conductivities of the liquids compared to air. Typical h values for brine and glycol freezers are 300 to 600 $\mathrm{W/m^2 \cdot K}$ (Cleland and Valentas, 1997). Liquid immersion freezers can be designed to operate in a batch or continuous mode. Some disadvantages of these freezers are that after the product is removed from the freezer, the freezing liquid must be rinsed from the product's surface with cold water or by using air knives to blow the liquid off the product. It results in additional technical difficulties, and costs arise. Also, it is difficult to find secondary refrigerants with suitable properties, and they may also exert corrosive effects on metallic packages. Also, the brine concentration changes during the process, requiring that it be adjusted during the treatment.

Plate Freezers

Plate freezers, also known as contact freezers, are commonly used to freeze foods in regular-sized packages. These freezers are aimed at bulk storage and distribution rather than individual product portions for retail sale. In the poultry industry, plate freezers are used to freeze thinly packed poultry fillets and patties, meat packaged in wrapped trays, mechanically deboned poultry/turkey boxed in plastic-lined or waxed cardboard containers, and offal. In these freezers, the food is frozen by contact with a stainless-steel plate, which is usually cooled by

circulating through it refrigerant at -40°C. Heat transfer occurs from both sides of the package by conduction. For plate freezers, h takes account of the resistance to heat transfer between the refrigerant and the plate, the resistance in the metal plates, and the resistance due to imperfect contact between the plates and the product (or packaging). For a plate freezer with poor contact, h may be as low as 50 to 100 W/m$^2 \cdot$K, and a thin air layer may also be present. For good contact h is typically in the range 200 to 500 W/m$^2 \cdot$K, and there should not be an air layer trapped by the packaging (Cleland and Valentas, 1997). These freezers minimize problems of product dehydration, defrosting of equipment, and package bulging, making the product squarer and easier to stack, with high packing density and stability for subsequent transportation. The main disadvantages are the relatively high capital costs and restrictions on the shape of foods to those that are flat and relatively thin. Packages must be uniform in thickness.

Cryogenic Freezers

Cryogenic freezers or cryofreezers rely on cryogenics to generate cold. Cryogenics is the branch of physics that deals with the production of extremely low temperatures by means of the evaporation or sublimation of liquefied or solidified gases at atmospheric pressure. The upper limit of cryogenic temperatures has not been agreed on, but the National Institute of Standards and Technology has suggested -150°C. This somewhat arbitrary temperature is chosen because the normal boiling points of the "permanent" gases (i.e., helium, hydrogen, neon, nitrogen, argon, oxygen, air) all lie below -150°C. The lower limit is absolute zero at -273.15°C (0 K). In cryogenic freezing of foods, the product is either sprayed with, or immersed in, the cryogen at atmospheric pressure. In the food industry, the most popular cryogens are liquid nitrogen (LN_2) and liquid carbon dioxide (LCO_2). The sublimation of solid carbon dioxide gives a high refrigerating capacity (618 kJ/kg) (Miller and Butcher, 2000). LN_2 has a refrigerating capacity of 384 kJ/kg. As LN_2 is sprayed onto food at atmospheric pressure, the droplets touch the product surface and boil at -196°C, extracting the latent heat of vaporization from the food surface in the process. Vaporization of the LN_2 gives a count of about 48% of the refrigeration effect. The remaining 52% of the refrigerating capacity is available from warming of the resulting cold nitrogen gas to -20°C.

LCO_2 is generally piped to a cryofreezer as a high-pressure liquid at -16°C and 22 bar, giving a total refrigerating capacity of 311 kJ/kg. At the point of use, spray nozzles reduce the pressure of the liquid, and it instantaneously expands and changes to approximately equal parts (by weight) of solid and vapor. The resulting mixture of cold gas and tiny dry ice solid particles is commonly referred to as dry ice *snow*. As CO_2 particles contact the food surface at atmospheric pressure, the solid almost instantly sublimes at -78.5°C instead of passing through the liquid phase, which draws out the latent heat of sublimation of the product (571.3 kJ/kg). This system provides approximately 85% of the refrigeration effect. Therefore, the CO_2 "snow" is usually sprayed onto the product throughout the length of

the freezer, and the gas is not recirculated. The remaining 15% of the cooling is a result of the contact of the product with an air/CO_2 mixture. These cryogens are safe for direct contact with foods, and their vapors are harmless in normal concentrations. Cryogenic freezing is the best way of preserving the freshlike characteristics in a product because of the small ice crystal formation. The main disadvantage is the high cost. h values on the order of 200 to 400 $W/m^2 \cdot K$ are often reported for cryogenic freezers (Karel and Lund, 2003). In the poultry industry, cryogenic freezers are generally used for individual quick freezing (IQF) of small to medium-sized poultry products with little susceptibility to cracking. Such products include battered-breaded poultry products fully or partly cooked, such as cut-up chicken portions (e.g., wings, drumsticks, eight cuts, nine-piece cuts), deboned meat portions such as chicken and turkey skinless breast fillets, chicken cordon bleu products, and chicken nuggets and patties. Direct-contact cryofreezers are the most commonly employed by the food industry and are classified by the method of contacting the food with the cryogen (Khadatkar et al., 2004). Thus, they can be spray or immersion cryogenic freezers.

Cryomechanical Freezers

Cryomechanical freezing consists of a two-step process. During the first step, the foodstuff gets into contact with LN_2 in an online immersion cryofreezer for a few seconds, during which fast freezing of the outer layers occurs, forming a thin crust. This freeze-crusting treatment provides a higher resistance strength to the foodstuff and prevents small and/or wet products from sticking on the conveyor or between them. The cryogenically crust-frozen product is then transferred directly into a mechanical freezer, where the remainder of the heat is removed and the product temperature is reduced to $-18^{\circ}C$ or lower (Agnelli and Mascheroni, 2001). Their most important application is for freezing of delicate products, food pieces that tend to stick or clump, or products that otherwise change their appearance. These products include chicken scallops, diced chicken chunks, meatballs, and meat patties, among others. Hamburgers and chicken scallops exhibit benefits in quality when frozen in cryomechanical freezing systems (Agnelli and Mascheroni, 2002). Hamburgers frozen in a cryomechanical freezer showed a 37% lower thaw–drip loss during thawing at $4^{\circ}C$ than that of conventionally frozen hamburgers. Also, hamburgers frozen in a conventional freezer show typical discoloration suffered by meat after the freezing and thawing cyles. Cryomechanical freezing decreases color deterioration, resulting in hamburgers with a color closer to that of fresh hamburgers. The drip loss of chicken scallops frozen in a mechanical freezer is higher by 85% than that observed for cryomechanically frozen chicken scallops.

TYPES OF FREEZERS AND OPERATIONS

Following is a description of the most important types of industrial food freezers for solid foods, and their operation, arranged by similar design principles or

modes of operation, even though they may use either mechanical refrigeration or cryogenics.

Freezing Rooms

Freezing rooms are basically cold storage rooms that although not properly considered freezers, are sometimes used for this purpose. There is no standard design equipment. The design and size of the freezer room is determined by the volume and type of product to be frozen, the packaging, the method of palletization, the accessibility required, and the equipment used for handling. These freezers consist basically of an insulated room provided with a mechanical refrigeration system wherein the foods are hanged manually or placed on shelves and bulk-stacked. Based on the former, freezing rooms can be classified as still-air freezers or forced-air freezers. In a still-air freezer, referred to historically as a "sharp" freezer, the products are exposed to cold air (-10 to -29°C) which is natural-convective cooled by contact with the evaporator. The extremely slow freezing of the product (3 to 72 hours) tends to produce large ice crystals that damage product quality and might also allow some undesirable activity of enzymes and microorganisms prior to the completion of freezing (Ramaswamy and Marcotte, 2006). Also, dehydration due to slow freezing rate and temperature fluctuations may be excessive. Furthermore, they are not suited to run with high product loadings since the refrigeration capacity is low, and are therefore rarely installed today.

An air-blast freezer room is an improved version of the still-air freezer. This freezing room is equipped with forced-air coolers that force air over refrigerant evaporator coil and then circulate it over the food product at a velocity of 0.5 to 2.5 m/s. A holding freezer usually has product loaded that has already been frozen by another freezing method. In the poultry industry it is used primarily to store previously frozen raw materials and semifinished as well as finished products. Frozen poultry products held at -18 to -29°C and at approximately 85% relative humidity retain product quality for 6 to 10 months (Kotrola, 2006).

Cabinet Freezers

Cabinet freezers are used for freezing a wide variety of foods, normally for lower capacities (a few hundred kilograms per hour). The food products may be frozen either in cartons or unpackaged and spread in a layer on trays. Products are placed on trays which are then placed into racks or carts, and each cart is pushed into the freezer. Cabinet freezers can make use of mechanical refrigeration or cryogenics. A mechanical-refrigeration cabinet freezer is the simplest form of batch air-blast freezer. The cold air (-35 to -40°C) is circulated over the products with the help of axial or centrifugal fans. Heat transfer coefficients are generally in the range 20 to 40 $W/m^2 \cdot K$ (Miller and Butcher, 2000). A cabinet cryogenic freezer uses cryogens combined with a highly efficient gas circulation system to ensure extremely rapid freezing. The cryogen, either LN_2 or CO_2 "snow," is sprayed

into the chamber, and the N_2 vapor or the mixture of CO_2 air is circulated by fans mounted on the cabinet side.

Push-Through-Trolley Freezers

The push-through-trolley air-blast freezer consists of an insulated tunnel equipped with two or three conveyor rails and forced-air coolers. When fully loaded, the wheeled racks or trolleys are pushed manually into the freezer at one end. To obtain high air velocity over the product, the freezing tunnel should be completely loaded across its cross section, with even spacing of the units of the product. These freezers can be operated in batch, semicontinuous, or continuous mode. Usually, the movement of the trolleys is countercurrent to the airflow. The push-through-trolley freezer is used widely in the poultry industry to crust-freeze (quick-chill) whole turkeys or to deep-freeze several types of packaged poultry products. Quick freezing on the surface is used to achieve a lighter appearance for the entire turkey. Most wrapped whole ready-to-cook birds and tray-packaged bone-in and bone-out portions are frozen in air-blast tunnel freezers, with air temperatures ranging from -35 to -40°C and air velocities of 1.5 to 5 m/s and up. It is desirable to have air temperatures at -35°C or below during operation and air velocities over the product surfaces of at least 3 m/s. The packaged birds freeze much faster on open shelves than they do in boxes. In some cases, such as meat for further processing, the whole bird may be packed into cartons or boxes and the cartons stacked on pallets in the blast tunnel.

Belt-Type Tunnel Freezers

Belt-type tunnel freezers are a broad class of food-processing freezers in which the product is conveyed horizontally on perforated stainless-steel belts through a long insulation-enclosed tunnel. These freezers can make use of mechanical refrigeration or cryogenics. There are various designs that include straight belt, multipass straight belt, fluidized-bed, and impingement freezers. These types of freezers are used for individual quick freezing (IQF) of a wide variety of foods.

Straight One-Pass Belt Freezers

The mechanical-refrigeration version of the straight one-pass belt freezer consists of two mesh conveyor belts in series which carry products through the freezing tunnel. This design also is called a *two-stage belt freezer*. The first belt initially precools or crust-freezes an outer layer or crust to condition the product before transferring it to the second belt for freezing and sensible cooling to -18°C or below. Two-stage freezers are generally operated at -1 to -4°C refrigerant temperature in the precool section and at -32 to -40°C in the freezing section. When products to be frozen are hot, another cooling section is added ahead of the normal precool section. Instead of evaporator coils, a straight one-pass belt cryofreezer has nozzles to spray LN_2 or CO_2 "snow" directly onto the foods.

The product and cryogen flows are usually countercurrent and the cryogen vent temperature is kept reasonably close to $-50^{\circ}C$. The LN_2 model is the most common type of this cryofreezer. It consists of three sections: a precooling section (A), a freezing section (B), and an equilibrium section (C). Most LN_2 cryogenic tunnels have a single refrigerant spray zone. Newer designs have multiple LN_2 spray zones, improving the control and eliminating the need for gas transfer fans. In a typical cryofreezer with one spray zone, LN_2 at $-196^{\circ}C$ is sprayed on foods toward the end of the tunnel (section B). As the LN_2 removes heat from the product, it boils and the cold nitrogen vapors at about -30 to $-45^{\circ}C$ are directed toward the start of the tunnel (section A), thereby prefreezing the incoming product before exhausting the vapor from the freezer.

In the poultry industry, it is common to employ N_2 freezing for small particulates such as diced meat and nuggets. Use of a vertical single-belt LN_2 tunnel freezer does not require fans because the natural heat transfer is enhanced in the vertical temperature gradient through which the product flows. The low temperature of the liquid and vaporous nitrogen provides rapid freezing. The LCO_2 straight one-pass belt cryofreezer is configured in a way similar to the LN_2 model. However, CO_2 acts very differently from LN_2 in the freezer (see the section "Cryogenic Freezers"). LCO_2 is sprayed on the foods immediately after they enter the tunnel and almost continuously for about 70% of the length of the tunnel. The vapor generated in a CO_2 freezer does not provide as much refrigeration effect as does vapor generated in a LN_2 freezer because it is at a much higher temperature. Applications for CO_2 freezing include producing IQF diced poultry, pizza toppings, and seafood. A variant of these freezers is the straight dual-belt tunnel freezer.

Multipass Straight-Belt Freezers

The multipass straight-belt freezer is designed for use with any product larger than 1 cm round or thick without surface moisture, with longer freezing times (up to 60 min) and higher capacity requirements (0.5 to 5.4 Mg/h). Both mechanical-refrigeration and cryogenic versions of this freezer contain stacking belts above each other to form either a single-feed/single-discharge multipass system (usually three passes) or multiple single-pass systems stacked one on top of the other. The speed of each belt is controllable independently. The multipass arrangement increases the residence time that the food spends in the freezer and saves processing floor space. Its applications include small portioned boiled, fried, or baked poultry products, such as nuggets, burgers, chicken parts, and ready meals.

Flighted Tunnel Cryofreezer

The flighted tunnel cryofreezer has a continuous serpentine belt or flighted conveyor which gently tumbles the product while continually exposing new surfaces for maximum heat transfer and cryogen efficiency. Product stacking in successive flights allows adequate retention to freeze the product fully to its core. This

is used for diced chicken (cooked), chicken tenders, cut-up chicken, chicken nuggets, and baked, fried, and cooked chicken.

Fluidized-Bed Freezers

Mechanical-refrigeration fluidized-bed freezers are available in batch or continuous models. This design is well suited for the IQF of small (0.5 to 5 cm in diameter) uniform-sized particulate products, such as diced chicken chunck, chicken scallops, and meatballs. Fluidized-bed freezers are characterized by high heat transfer coefficients and good mixing, which ensures excellent product quality. Food entering the machine travels through the first of two freezing zones, where it is crust-frozen to provide strength and to minimize moisture loss. The partly frozen product is then carried into the second zone, where freezing is completed. A cascading tunnel freezer makes use of a cascading twin belt incline for the positive conveying of products. The product is agitated mechanically in a thin layer on the first belt, allowing the product to be crust-frozen. The product is then transferred to the second belt. In this stage the product is further subjected to an upward airflow, and the product is fluidized and quick frozen individually. Two-stage fluidized belt freezers operate at -34 to -37°C refrigerant temperature and in capacity range from 0.9 to 14 Mg/h. The fluidized-bed cryofreezer uses two LN_2 immersion pans to crust-freeze the product, removing as much as 50% of the total heat load, locking in product moisture, and guaranteeing separate product pieces without clumping.

Impingement Freezers

Impingement freezers are designed with single- or multipass straight belts. A mechanical-refrigeration impingement freezer is provided with thousands of air-jet nozzles positioned above and below the mesh-belt conveyor system, which transports the foods through a freezing tunnel. The jet nozzles direct air at high velocity (20 to 40 m/s) perpendicularly to the product surface, which disrupts the boundary layer surrounding the product, resulting in very fast freezing times and minimal dehydration, similar to those provided by cryogenic equipment. Thus, use of this equipment increases the production capacity at a noticeably lower operating cost (Salvadori and Mascheroni, 2002). This freezer is used for thin, flat food products (less than 25 mm thick) such as patties or fillets whose internal heat transfer is not the limiting factor and their flat shapes allow the product to receive multiple jets directed perpendicularly onto its faces (top and bottom). Impingement freezing is generally not cost-effective for thick products (Salvadori and Mascheroni, 2002). Some products, such as fillets, may suffer damage caused by sticking to the perforated belt. The factors affecting the efficiency of impingement systems include the nozzle exit velocity, nozzle design, boundary-layer characteristics on the surface of the product, and the design of the impingement equipment (Sarkar and Singh, 2004). An important aspect in the design of this type of equipment is nozzle configuration. Even more important than tube length is the length/diameter ratio. Other geometric relationships

relevant to the heat transfer between air and product are distance between nozzle and product surface, nozzle diameter, and spacing between nozzles (Salvadori and Mascheroni, 2002). These factors were studied widely by Sarkar and Singh (2004). The impingement cryofreezer is designed to freeze a variety of products easily and quickly, such as chicken breasts, beef patties, fish fillets, and any other relatively flat product. Its unique cryogen delivery mode reduces product dehydration by up to 80% compared with other freezing methods, while also providing consistent gas flow throughout the freezing zone. Another benefit of the LN_2 or CO_2 impingement tunnel freezer is that it has the highest freezing capacity for a given floor space.

Spiral-Belt Freezers

Spiral-belt freezers are one of the commonest freezer types in the food industry. They can make use of mechanical refrigeration or cryogenics. This freezer is advantageous for products with long freezing times (generally, 10 min to 3 h) and for products that require gentle handling during freezing. Typical poultry products quick frozen individually in spiral belt freezers include chicken portions, raw and cooked patties, nuggets, poultry breast fillets, marinated chicken chunks, breaded chicken parts, meatballs, and a variety of packaged products. Spiral-belt freezers are large square box-type freezers inside which a continuous flexible mesh belt is formed into spiral tiers and carries food up through a refrigerated chamber. In modern designs, each tier rests on the vertical sides of the tier beneath and the belt is therefore "self-stacking." This eliminates the need for support rails and improves the capacity by up to 50% for a given stack height. Products are fed evenly from the production line directly onto the loading freezer belt. This freezer provides flexibility for different types of products, because dwell time can be controlled by increasing or decreasing belt movement. In the mechanical refrigeration spiral freezer, the continuous belt enters the spiral at the bottom, via a drive mechanism that supports the entire weight of the spiral. On reaching the top of the spiral, the belt changes direction, discharges the frozen product, and then returns to the feed point at the base of the freezer. The airflow pattern plays a key role on energy efficiency, freezing time, and production rate (Huan et al., 2003). Air flows vertically, from the top to the bottom, through the belt stack in a countercurrent flow, which reduces weight losses by evaporation. The horizontal airflow arrangement minimizes the fan power needed to circulate the air and assures that the coldest air has scrubbed heat continuously from all sides of the product. It also allows delicate products to use a belt with a closely spaced mesh that would cause too high a pressure drop in a vertical-airflow freezer. A variant is the multiple spiral freezer. In cryogenic spiral-belt freezers, the product is normally fed into the top of the spiral and exits at the bottom of the box. The LN_2 or LCO_2 is sprayed directly on the products by a spray header. The spray header is fabricated using stainless-steel tubing. Individual spray nozzles are installed into the spray header as cross members. LN_2 is sprayed down through the belt stack to minimize weight losses due to evaporation. Spiral freezers have several

advantages, including a relatively small floor space, high capacity, automatic loading and unloading, low maintenance costs, and flexibility to freeze a wide range of foods.

Immersion Freezers

Immersion freezers are available in mechanical-refrigeration and cryogenic models. Liquid immersion freezers, also known as direct-contact freezers, use mechanical refrigeration and can be designed to operate in a batch or continuous mode. A typical batch liquid immersion freezer consists of a bath or tank containing cold brine ($-29^{\circ}C$) wherein baskets with products are immersed. The baskets are removed from the liquid after the product is frozen. Although batch systems are simple and easy to install, they are more labor-intensive than continuous systems. Continuous immersion freezers use some type of conveyor system to move the product through the cooling liquid in a tunnel-type freezer. The product can also be conveyed, on a belt, through a freezing tunnel, where it is sprayed continuously with a cold liquid. The brine is refrigerated either by circulation through a heat exchanger or by cooling coils and/or a jacket built into the liquid tank. In the poultry industry, the turkeys are wrapped in polyethylene and dropped into a tank of chilled calcium chloride brine. The control of residence time is simple: As fresh turkeys enter the tank at one end, they displace a similar number of frozen turkeys at the other end. On the basis of construction, they are classified as straight-belt or spiral-belt immersion freezers. The immersion tunnel freezer in turn is available in horizontal or vertical conveyor belt arrangements. The horizontal arrangement consists mainly of a conveying system for the food and a control system for belt velocity and the LN_2 flow rate. The conveyor with food packets passes through the LN_2 bath. The cold gaseous nitrogen goes out as waste. The working principle of the vertical conveyor belt immersion freezer is similar to a horizontal immersion freezer, but the food travels on a vertical conveyor belt. The vertical freezer occupies less floor area and requires more power input than does a horizontal freezer of the same capacity. The spiral immersion cryofreezer is made of a spiral belt around a central drum inside a large insulated square box. Product is fed into the top of the spiral and exits at the bottom of the box.

Contact Freezers

Two classes of contact freezers can be defined: batch and continuous systems. Plate freezers are batch systems in which the product is usually frozen from both sides by plane heat exchangers applying a certain pressure against the product. They use mechanical refrigeration systems. Continuous systems used for solid foods include specialized contact freezers which move the foods through a freezing tunnel in a continuous way. They are available in either mechanical refrigeration or cryogenic models.

Plate Freezers Plate freezers consist of a series of hollow metal plates through which a refrigerant such as R-12, R-22, ammonia, or cold brine is circulated. The plates are mounted parallel to each other and are available in horizontal or vertical arrangements with manual loading and unloading. Horizontal plate freezers are also available in an automatic loading–unloading mode. A hydraulic system is used both to open the space between plates for loading and unloading and to close the plates with a moderate pressure on the order of 10 to 30 kN/m^2, so that effective contact with the food product occurs during freezing. Automatic plate freezers accommodate up to 200 packages per minute, with freezing times from 10 to 150 min. When greater capacities are required, the freezers are placed in series with associated conveyor systems to handle the loading and unloading of packages (ASHRAE, 2002). When closed, the plates make firm contact with the two major surfaces of the packages, thereby facilitating heat transfer and assuring that the major surfaces of the packages do not bulge during freezing. The advantage of good heat transfer in contact plate freezers is gradually reduced with increasing product thickness. For this reason, thickness is often limited to 50 to 80 mm.

In horizontal plate freezers, the bottom layer is loaded first, either manually or automatically. Horizontal plate freezers are commonly used either for product packed into rectangular cartons or product formed into rectangular shapes by metal molds or trays. Horizontal plate freezers are suitable for packaged products such as fillets or meat pulp. In a vertical plate freezer, the product is loaded from the top. Once frozen, the plates are unclamped and the product falls out the bottom of the plate freezer. Vertical plate freezers are best suited to freezing unpackaged or bare deformable products such as offal and meat.

Contact Belt Tunnel Freezers The contact belt tunnel freezer is a variant of the straight one-pass belt freezer, but instead of a mesh belt it has a moving solid stainless-steel belt onto which the product is loaded manually or by spreader shaker. The continuous belt is typically 1.2 to 2 m wide and may be 30 m long. Cold air (-37°C) flows horizontally at high velocity across the top of the product surface and under the belt countercurrently. In the poultry industry, such freezers can be used for IQF of flat cooked or fried products requiring no marking on the product, such as poultry fillets and patties. Another specialized contact freezer is the plate-link-belt tunnel freezer, which conveys food products on a continuous plastic film over a low-temperature (-40°C) refrigerated plate. This freezer is suitable for freezing fragile, flat, wet and sticky soft products, such as poultry fillets, marinated products, and boneless chicken breast. Contact with the film freezes approximately the bottom 1 mm of products in about 1 min (ASHRAE, 2002). Another benefit of contact prefreezing is that it reduces dehydration losses in the subsequent freezing step.

Tumbling and Rotary Cryogenic Freezers

A rotary cryofreezer is a long, insulated, inclined, rotating stainless-steel tube. This cryofreezer combines ultraslow tumbling action with precise CO_2 or LN_2

spray to provide a highly accurate continuous freezing process. Typical applications in the poultry industry are IQF of bulk-packed and boxed meat products such as stripped, minced, or diced meat and excess trim, either cooked or raw. This freezer offers high product quality and high throughput for a given floor area.

SELECTION OF A FREEZER

Several factors affect the choice of food freezers. Initial considerations when choosing a freezer are the financial, functional, and feasibility factors. If more than one freezer design or refrigeration system will do the job, the choice comes down to a detailed comparison among these selection criteria.

Economic Considerations

Economic factors include both the capital investment and operating costs of the equipment. When calculating the capital cost, it is also important to consider the space taken up by the freezer. The operating costs of freezers vary with product throughput and include electricity, labor, maintenance, and cleaning costs. Other financial considerations are the refrigerant and projected losses, such as product damage and dehydration. Product versatility and mobility of operation are two additional factors that should be considered when making an economical analysis of freezing systems. In general, cryogenic freezers have the lowest capital costs, while mechanical freezers are the cheapest to run. Mechanical freezing, especially in continuous belt freezers, has lower operating costs than cryogenic freezing. However, mechanical freezers require higher processing times, due to low heat transfer coefficients, which lead in turn to a lower-quality product. On the other hand, cryogenic freezing has high refrigerant consumption and very high operating costs (Salvadori and Mascheroni, 2002; Chourot et al., 2003). Cryogenic freezers tend to have low capital costs and greater flexibility in throughput because they do not require refrigeration machinery. Effective insulation and/or refrigeration of the storage tank are necessary to prevent excess heat ingress and cryogenic loss. For short trial production runs for very high value products that must be frozen rapidly, cryogenic freezing may be useful. Mechanical freezers have a high investment cost because the cost of materials, installation, and complex conveying and control systems can be considerable. Relatively, the operating cost is lower for cryofreezers. Most freezers can run for two shifts before defrosting becomes necessary, and the defrosting process itself is often automatic. Cryogenic freezers do not usually need defrosting. Cryogenic freezers tend to be more compact than those using mechanical refrigeration. Although a batch air-blast freezer may not be as expensive as a plate freezer of the same throughput, it will take up considerably more space, which may represent a significant cost. It is also important to consider mass and quality loss from the product when comparing the operating cost of freezers. Large variations in product exit temperatures can also cause inconsistent product quality and lead to downgrading of the product.

Functional Considerations

Functional factors include such things as whether a freezer is physically able to freeze the product and whether the freezer is needed for continuous or batch operation. Carbon dioxide freezing of sensitive meats such as mechanically deboned poultry meat will reduce the frozen storage life compared with air-blast freezing, as a result of carbonic acid formation and pH reduction, which can contribute to some lipid oxidation (Barbut, 2002). For large products, the speed of freezing is limited increasingly by internal heat transfer. For items such as frozen turkeys, which need a residence time of several hours, a brine immersion freezer is the most practical choice. Dehydration during freezing is both a quality issue and a direct financial cost in terms of lost product. Hot cooked chicken can lose 8% of its weight when frozen slowly; fast freezing reduces dehydration to 2% or less. A typical arrangement is to use a cryogenic tunnel upstream of a mechanical-refrigeration spiral freezer. By crust-freezing the chicken before it enters the spiral freezer, the cryogenic tunnel greatly reduces dehydration losses.

Feasibility

Feasibility includes taking into account whether it is possible to operate a freezer in the plant location. A LN_2 freezer, for instance, may be suitable in every respect for freezing the product, and the high costs of using this method of freezing may be justified. However, if the location of the plant is such that a supply of liquid nitrogen cannot be guaranteed, the freezer should not be considered.

INNOVATIONS IN FREEZING OPERATIONS

The quality of frozen foods is closely related to the size and distribution of ice crystals. The existence of large ice crystals within frozen food tissue could result in mechanical damage, drip loss, and thus reduction in product quality. One way in which the frozen food industry could enhance the quality of its products is to control the nucleation of ice and ensure that the water-to-ice transition occurs through the formation of lots of small ice crystals (Kennedy, 2000, 2003; Sun and Zheng, 2006). A number of areas of research are beginning to offer control of nucleation, which could achieve this goal. These innovations include high-pressure freezing, ultrasonic-assisted freezing, and applications of antifreeze protein and ice nucleation protein.

High-Pressure Freezing

When water is frozen at atmospheric pressure, its volume increases. This increase in volume is contributed to the ice I formed, which uniquely has a lower density than that of liquid water, resulting in a volume increase of about 9% on freezing at $0^{\circ}C$, about 13% at $-20^{\circ}C$. This causes tissue damage in freezing. However, under high pressure, several types of ices (ices II to IX) are formed, their densities

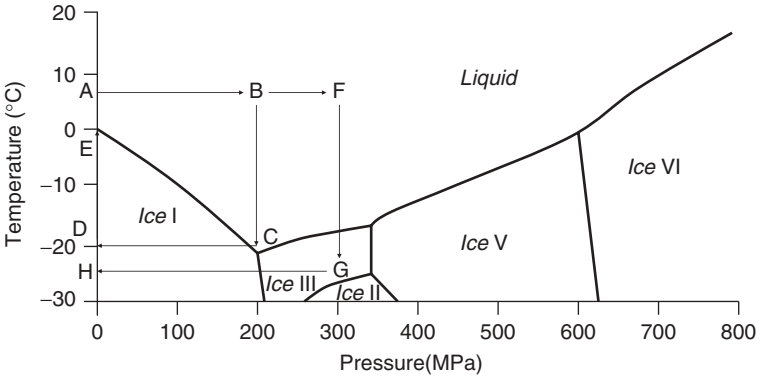

FIGURE 2 Phase diagram of water and principles of PSF (ABCDE) and PAF to obtain ice III (ABFGH) processes. (Adapted from LeBail et al., 2002; Otero and Sanz, 2003.)

being greater than that of water. During phase transition, high-pressure ice (ices II to IX) does not expand in volume, which may reduce tissue damage (Li and Sun, 2002b). As shown in the water phase diagram (Figure 2), changing the physical state of food can be achieved using external manipulation of temperature or pressure.

Two types of high-pressure freezing processes can be distinguished, essentially different but frequently confused in the literature: high-pressure shift freezing (PSF) and high-pressure assisted freezing (PAF) (Otero and Sanz, 2003; Picart et al., 2005; Fernández et al., 2006). In the *PSF process*, the product is kept initially in the liquid state at subzero temperature combined with high pressure (Figure 2: ABC). The freezing point of water can be reduced to a minimum of −22°C at 210 MPa (Luscher et al., 2005). Phase transition occurs as a result of a pressure release (Figure 2: CD), which promotes a large degree of supercooling and thus rapid ice nucleation (Figure 2: DE). Because of this large degree of supercooling, the initial formation of ice is instantaneous and homogeneous throughout the entire volume of the product, not only on the surface as occurs in conventional freezing methods. The temperature in the samples increases according to the temperature–pressure equilibrium relationship of liquid water and ice I. Only partial freezing can be obtained during PSF, as experiments show that the ice/water ratio can only reach 0.36 for a sample of pure water at the end of the pressure-release step. Freezing must thereafter be completed at atmospheric pressure (Zhu et al., 2005).

In the *PAF process* (ABFGH in Figure 2), phase transition occurs under constant pressure, higher than atmospheric, while the temperature is lowered to the corresponding freezing point. In this way, ice I or the other known ice polymorphs can be obtained (Figure 2). Cooling of the sample proceeds from surface to the center, so the freezing process is governed by thermal gradients as occurs at atmospheric pressure (LeBail et al., 2002; Otero and Sanz, 2003). Substantial reductions in freezing times of high-pressure-assisted freezing experiments have

been described in comparison with the times required to complete the process at atmospheric pressure, but the opposite has also been reported. Reduction in time can be attributed to a decrease in the latent heat values of water with pressure (Otero and Sanz, 2003). PSF technology can be especially useful for freezing large items of foods in which a uniform ice crystal distribution is required. Such large items are difficult to freeze even using efficient classical freezing methods, including cryogenic freezing (Otero and Sanz, 2003; Chen et al., 2007; Otero et al., 2007), as under very low to medium freezing temperatures, thermal gradients within the foods are pronounced and freeze-cracking damage would be possible. The use of high pressure facilitates supercooling and promotes uniform and rapid ice nucleation and growth, thus producing smaller crystals (Chevalier et al., 2000b,c, 2001; Zhu et al., 2005). Improvements in texture and histological damage have been reported by many authors in different high-pressure-shift frozen products (Otero and Sanz, 2003, 2006; Otero et al., 2007). Microscopic observations also indicate that the microstructures of foods can be preserved as long as no ice is formed before depressurization. However, texture measurements have revealed that denaturation might occur under pressure, resulting in modification of the texture of foods containing high protein. Drip-loss reduction is variable from one product to another. Pressures above 4 kbar have been shown to inhibit enzymatic activities, which causes undesirable changes in seafood quality, making products more stable during frozen storage (de Lamballerie-Anton et al., 2002; Li and Sun, 2002). Comparing with traditional air-blast and liquid freezing, it was found that PSF samples have small, uniform ice crystals both at the surface and at the central zones, whereas air-blast and cryogenic frozen samples, having thermal gradients, showed nonuniform ice crystal distribution (Chevalier et al., 2000a, 2001; LeBail et al., 2002; Urrutia-Benet et al., 2005). In the commercialization of PSF technology, the biggest obstacle is the high capital cost (Li and Sun, 2002b). As the operation of high-pressure equipment is at subzero temperature, the use of special steel is needed for vessel design, and suitable pressure transmission fluid is required. Furthermore, precise monitoring is also necessary to improve product quality and the stability of the operation (Otero et al., 2007).

Ultrasound-Assisted Freezing

The use of power ultrasound to assist food freezing is a relatively new subject, and recent research advances indicate that its potential is promising (Li and Sun, 2002a; Knorr et al., 2004; Zheng and Sun, 2006). Power ultrasound, ultrasound waves of low frequency and high intensity, has proved to be useful in controlling the crystallization process. It plays an effective role in the initiation of nuclei and subsequent crystal growth. Under the influence of power ultrasound, much more rapid and even nucleation occurs. In freezing, this would lead to fine ice crystals and to shortening of the time between the onset of crystallization and the complete formation of ice, thus reducing damage to cellular structure (Li and Sun, 2002a; Chow et al., 2006).

The beneficial use of sound energy is realized through the various effects that ultrasound generates on the medium where it transmits. Among them, cavitation,

which can lead not only to the production of gas bubbles but also the occurrence of microstreaming, is perhaps the most significant. The basic components of a freezing food are ice crystals and aqueous phase. When subjected to the action of acoustic energy, the compression and rarefaction of the sound waves can cause cavitation in the aqueous phase (Zheng and Sun, 2006). Cavitation leads to the production of gas bubbles that will continue to grow and act as nucleating agents to promote nucleation. Experiments with a concentrated sucrose solution showed that the number of nuclei increased with the use of power ultrasound. In a sucrose solution treated with power ultrasound, 32% of the water exists as crystals with a diameter of 50 mm or larger, compared with 77% for a solution without acoustic treatment (Zheng and Sun, 2006). Microstreaming, another significant acoustic phenomenon associated with cavitation, occurs because of the vigorous circulatory motion of the cavitation bubbles in the sonic field. The violent agitation that ultrasound provides can benefit in increasing heat and mass transfer rate, which can therefore accelerate the freezing process. Similar to other dense and incompressible materials, ice crystals will fracture when they are subjected to alternating acoustic stress. This will lead to products with smaller crystal size distribution.

The use of power ultrasound in assisting food freezing is promising, as it not only enhances the freezing rate but also leads to a product of better quality. Much less intercellular void and cell disruption was observed in potato subjected at high-powered ultrasound-assisted immersion freezing. This was attributed to the high freezing rate obtained at a high ultrasonic level and thus the domination of intracellular small ice crystals (Sun and Li, 2003). The future development of this technology is still strongly related to the availability of cost-effective and easily operated equipment. Instead of being a new freezing technique, ultrasound is an aid to existing freezing processes. Therefore, it is preferred that ultrasonic devices be designed such that they can easily be connected to existing freezing equipment, which will require further research effort. As with PSF, this will need to be followed by rapid removal of heat to ensure that these crystals grow to provide a lattice of small ice crystals throughout the frozen food structure (Zheng and Sun, 2006).

Antifreeze Proteins and Ice Nucleation Proteins

When a living organism is cooled to a temperature below the equilibrium freezing point of its tissue fluids, ice may form in the tissues, an event that is usually lethal. Organisms that are cooled to subfreezing temperatures in nature must interfere with their body water in such a way that freezing is either prevented or becomes tolerable. This is done by means of ice nucleating proteins (INPs) and antinucleating or antifreeze proteins (AFPs), which in various ways promote or counteract the formation of ice (Zachariassen and Kristiansen, 2000). AFPs and INPs can potentially be added to food to interact with ice. Although both AFPs and INPs influence ice crystal size and structure within food, they are very different substances in structure and function distinctly and oppositely during freezing.

AFPs are used to lower the freezing temperature and retard recrystallization on frozen storage and these proteins may serve as plasma membrane protectors at low temperatures (Wang, 2000; Tomczak et al., 2001). On the other hand, INPs raise the temperature of ice nucleation and reduce the degree of supercooling.

AFPs were first identified in the blood of antarctic and arctic fish species (areas susceptible to ice formation) (Evans and Fletcher, 2004; Kristiansen and Zachariassen, 2005; Wharton et al., 2005). These proteins served to lower the freezing point of the blood of the fishes (-1.9°C) to below the freezing point of seawater (-1.0°C), without significantly increasing the osmotic pressure of the plasma. AFPs have also been reported to be present in many invertebrates, including most insects and in higher plants as well as in fungi and bacteria (Meyer et al., 1999; Crevel et al., 2002; Atici and Nalbantoglu, 2003; Zhang et al., 2004). The most studied proteins with antifreeze activity are from fish. Based on the presence or absence of carbohydrates and structural characteristics, AFPs are classified into two main types: antifreeze glycoproteins (AFGPs) and nonglycoproteins (Barrett, 2001; Kobashigawa et al., 2005; Sun and Zheng, 2006). For convenience, nonglycoproteins are still called AFPs, which can be further subdivided into four distinct antifreeze subtypes: the alanine-rich AFPs of right eye flounders and sculpins (type I), the cystine-rich AFPs of sea raven smelt and herrins (type II), an AFP (type III) found in ocean pout and eelpout wolfish, and the glutamine and glutamate-rich AFPs of long horn sculpin (type IV) (Sun and Zheng, 2006). AFGPs consist primarily of repeating units of two amino acids, in which one is glycosylated. AFPs depress the freezing temperature of a solution in a noncolligative manner, by arresting the growth of ice crystals (Chapsky and Rubinsky, 1997; Liu and Li, 2006).

It is generally accepted that AFP functions by binding to ice and interfering with water molecule propagation to the crystal surface. At low concentrations, AFP molecules bind individually to the surface; at sufficiently high concentrations, AFP molecules pack together in a cooperative manner to exert maximal activity. For the inhibition of ice crystal growth, patches or aggregates of AFP molecules are assumed to bind tightly to the ice surface, so that the ice lattice is allowed to grow only in the spaces between AFP molecules, hence decreasing the stability of the surface at the ice–water interface. Therefore, the addition of water to an ice surface is unfavorable, and growth of the crystal is inhibited. Moreover, when the AFP is adsorbed to ice surfaces, it tends to bind to ice prism faces. The dipole nature of the AFPs might account for their preferential binding. It is postulated that the dipole field of the α-helix would align dipole moments of individual water molecules in the ice crystals; therefore, a dipole–dipole interaction is induced between the protein molecule and the ice crystals. These interactions would lead to specific adsorption on the prismatic facets of ice. Mixtures of AFP types I, II, and III produced ice crystals of hybrid shapes and dimensions, consistent with the various antifreeze types binding to the same ice surfaces. The activity of the mixtures was independent of the proportions of the isoactive AFP stocks present, indicating that the different antifreezes neither attenuated nor potentiated each other's activity (Chao et al., 1995). The function of AFP in

suppressing the freezing point and inhibiting recrystallization may be very useful in maintaining the high quality of chilled and frozen meats, including poultry. However, practical applications are still seldom reported.

There are many organisms that live in environments where the temperature is just too cold to avoid freezing altogether. These organisms have evolved methods of controlling where in their bodies ice forms so as to minimize the damage from their annual freeze–thaw cycle and allow them to repair and function in the spring. These are lipoproteins (ice-nucleating proteins) which are usually generated on the outer surface of the cell membranes. They act as a template for ice growth and encourage ice formation to occur in the gaps between cells, where the organism is least sensitive to damage. There exist various types of INPs in plant bacteria, insects, intertidal invertebrates (frogs), plants, and lichen. The INPs from some ice-nucleating bacteria are the highest level of ice nucleation activators. When water is cooled under atmospheric pressure, it can keep a liquid state even below 0°C, which is known as the *supercooling state*. In this state of water, a number of embryo ice crystals are naturally created which assemble the water molecules onto their surfaces. Accordingly, the ice crystals become larger and contact with each other to construct a multicrystalline state of ice, leading to the entire freezing of water. Ice nucleation protein (INP) itself serves as a template to assemble the water molecules to act as an effective embryo ice crystal. The most common species of ice nucleation–active bacteria that have been found to produce INPs belongs to the genera *Pseudomonas*, *Erwinia*, and *Xanthomonas*. Some strains of *Fusarium* and related genera of fungi are also active during ice nucleation. These bacteria can catalyze ice formation at temperatures as high as −2 to −3°C, resulting in frost damage of many important crops. The bacterium *Pseudomonas syringae* uses INPs to initiate freezing on the leaves of plants. In the food industry there is a trend toward developing rapid freezing techniques to preserve the high quality of frozen foods. The addition of bacterial cells that produce INPs in food products can elevate ice nucleation temperature, thus reducing freezing time and improving the quality and cost-effectiveness of the rapid freezing process. However, one major concern in their use in the food industry is that bacterial ice nucleators must be robust, environmentally safe, nontoxic, nonpathogenic, and palatable. If entire bacterial cells are used, it is very important to make sure that inedible microorganisms are killed completely before the food is consumed.

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REFRIGERATION AND FREEZING IN CENTRAL FACILITIES AND RETAIL STORES

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Handbook of Poultry Science and Technology, *Volume 1: Primary Processing*, Edited by Isabel Guerrero-Legarreta and Y.H. Hui

INTRODUCTION

The refrigerator–freezer is the core of poultry-processing operations, including central facilities and retail stores. Central facilities are an important part of the overall cold chain, which runs from poultry-processing plants to consumers (DITC, 1971). The primary purpose of central facilities is to preserve and store surpluses of raw or processed poultry and poultry products. Apart from this primary purpose, they also provide additional services, known as *value-added logistics* (VAL). These activities involve chilling and freezing fresh poultry, packing, transport, order picking, distribution, stock control, supply to supermarkets and retail food stores, and the like. This means that central facilities are no longer limited to storage but also provide a wide range of divergent activities. A central facility is active at the beginning and a distribution central cold facility at the end of the cold chain. They play an important role in in-transit bulk storage. A complete refrigeration cold chain for poultry will contain many of the following unit operations: prechilling preparation, primary or secondary chilling, freezing, storage, transportation, and display (James, 1996, 2004, 2006; James and James, 2002; James et al., 2006). During storage, transport, and display, the principal aim is to maintain the set temperature. Following transportation, the cold chain continues through the central facility and the retail store to the customer. For this purpose, a wide range of chilled storage equipment may be seen around the world in different sizes, each suited to the particular requirement for which it is designed (Sandra and Zey, 1980a). Losses at this stage waste all the effort and energy that was expended earlier in the chain. Hence, continuity of refrigeration should be employed successively to ensure the refrigerated preservation of perishable poultry from production to consumption (IIR, 1986, 2000; ASHRAE, 1998). A wide variety of commercial refrigeration systems are being used in central facilities and retail food stores (Pruthi, 1999). These include a central refrigeration system connected to food display cases, self-contained display cases, and walk-in refrigerators and freezers. These systems account for 40 to 50% of a supermarket or retail store's total energy.

CENTRALIZED SYSTEMS

Centralized systems are in very common use in supermarkets and hypermarkets. Focusing on central supermarket systems, a prototypical system includes various refrigerated and frozen-food display cases connected to a central refrigeration system, typically located in a mechanical equipment room or in a rooftop enclosure. There are two options:

1. *Direct systems*. The typical direct central refrigeration system consists of several sets of rack-mounted compressors that independently serve a portion of the refrigeration load in the store. Often, there are two racks for medium-temperature fresh-food loads and two racks for low-temperature

frozen-food loads, but the exact configuration varies depending on store size and other factors.

2. *Indirect systems*. There is a growing interest in indirect systems to lower the refrigerant charge by 50 to 75% compared with classic direct systems, to enable use of flammable or toxic refrigerants located in a machinery room separated from the sales area, and to easily modify the disposition of display cabinets in the sales area. Initial costs are about 15% higher than those of the usual direct systems. Indirect systems are also used in which a primary refrigeration system cools a secondary fluid that circulates through a secondary loop to the display cases.

Distributed systems are used in large supermarkets and comprise several smaller plants that reduce refrigerant circuit length and charge. This concept, launched in 1997 in Ushers stores, did not secure a significant market share. New designs that place refrigerator, compressor, and associated components near the display cases being refrigerated are distributed systems.

In each case the choice of refrigerant will depend on the specific requirement of the application. Commercial refrigeration systems have traditionally used R-12, R-22, and R-502, all chlorofluorocarbon (CFC) refrigerants. The type of equipment employed in commercial refrigeration is very different in terms of size, the logistics of the specific refrigeration circuit, and the refrigerant charges used.

PRINCIPLES OF A REFRIGERATION SYSTEM

The refrigeration system in central facility and retail stores is usually a vapor-compression system comprising a compressor, a condenser, a receiver, air-cooling units, and associated piping and controls (Woolrich, 1968c; Sandra and Zey 1980b). At its simplest, heat is removed from product display cases and discharged outdoors. Excellent details of refrigeration cycles and full details of component may be found in several refrigeration textbooks (Woolrich, 1968b; 1968aSHRAE, 1998). A brief outline of the vapor-compressor cycle and its primary components follows.

- *Evaporator*. An evaporator is a heat exchanger inside a display case in a sales area. Heat removed from the conditioned space within the case causes the liquid refrigerant to boil away at a very low temperature, producing a low-temperature low-pressure gas.
- *Compressor*. The refrigerant enters the compressor in the vapor state at low pressure and temperature. The compressor raises the pressure and results in a much higher temperature for the gas. Compressors are located mainly in a mechanical equipment room or rooftop enclosure. The most common type of compressor used in commercial refrigeration systems is the

reciprocating compressor. Reciprocating compressor types include single-stage (booster or high state), internally compounded, and open, hermetic, or semihermetic.

- *Condenser*. The function of the condenser in a refrigeration system is to transfer heat from the refrigerant to another medium, such as air or water. After rejecting heat, a refrigerant become a high-pressure liquid. Various types of condensers are used, such as evaporative, water cooled (shell and coil, shell and tube, tube in tube), and air cooled (fan forced or natural convective, which could be of plate or fin type).
- *Expansion valve*. An expansion valve, is essentially a metering device that releases high-pressure liquid in a controlled manner. As the liquid moves to the refrigerated display case, it becomes vapor and hence absorbs heat and enters the evaporator ready for the next cycle.
- *Ammonia absorption system*. Another system used in the refrigeration of poultry is the absorption refrigeration system (Woolrich, 1968c). Those based on ammonia especially offer an alternative to the vapor-compression system.

REFRIGERATION AND FREEZING SYSTEMS COMMONLY USED FOR POULTRY

Air-based chilling systems are generally used for refrigeration and cold storage while a number of ways are available to accomplish quick freezing or other rapid extraction of heat. Chilled poultry has obvious limitations as to shelf life, due to microbial growth (Kloss, 1968). Frozen poultry has a shelf life of months to years, compared to chilled poultry's shelf life of days or at most weeks. Freezing systems can be broadly divided into groups with regard to the basic method of extracting heat from poultry (James, 2002).

- *Air-blast freezing*. Air-blast freezing utilizes convection heat transfer to remove heat from foods using air as the convention medium. Plastic bagged poultry is placed in the room and low-temperature air at high velocity (4 to 7 m/s) is allowed to circulate around the poultry for the desired residence or freezing time.
- *Contact freezing*. Poultry (wrapped or unwrapped) is placed between metal plates or surfaces, and heat is removed by direct conduction through the metal surfaces.
- *Liquid immersion freezing*. Food is immersed in a low-temperature nonfreezing solution that is cooled by evaporators in a conventional refrigeration system.
- *Cryogenic freezing*. Cryogenic freezing may utilize convention or conduction heat transfer to remove heat from poultry, and it can be achieved by spraying liquid nitrogen (LN_2) or liquid carbon dioxide into the freezing chamber.

All the refrigeration and freezing methods available can be employed for poultry processing (Kloses, 1968; Tressler, (1968a, 1968b); Jul, 1986; Veerkamp, 1990); however, most commercially frozen poultry is produced in air-blast systems, which vary widely in design, capacity, and operating characteristics. The choice of freezing equipment is primarily a matter of cost; such factors as product quality and operation flexibility are secondary conditions. The various freezing methods available for freezing poultry (James et al., 1979; Creed and James, 1981; Fleming et al., 1996; Gomez and Rubio, 1998; Everington, 2001; Lammertz and Brixy, 2001; Newman, 2001) include:

- Continuous conveyor: sharp or belt freezer
- Spiral freezer
- Tunnel freezer (stationary and push-through tunnels)
- Blast freezer
- Fluidized-bed freezer
- Plate freezer
- Immersion freezing
- Cryogenic freezing

Many small products, such as cubes and strips of ham and poultry meat, poultry pieces, cooked products, slices of poultry meat, and deboned and minced meat, can be individually quick frozen in a rotary cryogenic freezer (Thumel and Gamm, 1994).

REFRIGERATION APPLICATIONS

Refrigeration applications in the commercial sector involve a wide range of technologies, from stand-alone residential refrigerators to large central supermarket refrigeration systems. The most common commercial refrigeration application is the supermarket refrigeration system, which consists of display cases (Woolrich, 1968b; Cortella and d'Agaro, 2005) and walk-in refrigerators and freezers equipped with several sets of rack-mounted compressors connected via long runs of liquid and suction vapor lines to refrigerated and frozen-food display cases in the store. Commercial refrigeration systems maintain cold and freezing temperatures for storing food and displaying it for self-service sales. Poultry is stored prior to transfer to the store area in walk-in storage areas. The cases are generally located at the periphery of the store near their associated walk-in storage. This type of equipment has a vapor compression–based refrigeration system. Display cases come in a variety of configurations and maintain different temperatures depending on what is being displayed. They range from very small display cabinets to large merchandizing door-type displays with walls.

DISPLAY CASES

Refrigerated or frozen displays of poultry in retail premises is an important part of the cold chain. The purpose of supermarket cases is to display food for the self-service style of supermarket shopping. Hence, they are evaluated based on two major criteria: preserving poultry quality, and sales enhancement through persuading the consumer to buy poultry and poultry products (MLC, 1992). Achieving both criteria without compromising is very difficult. Presenting poultry to consumers in the most attractive way while maintaining the desired storage conditions is a very difficult task (Spiess et al., 1986, 1997; BFFF, 1994; Anon., 1992; Bobbo et al., 1995).

In general, display cabinets are meant to accommodate three types of poultry products (James and James, 2002; James, 2004): (1) chilled wrapped, (2) chilled unwrapped, and (3) frozen wrapped. After the temperature of displayed poultry has been reduced to a desired value, it is likely to remain at that temperature for a period that may range from a few hours to a week for chilled poultry and for a few months for frozen poultry (James, 2002). A survey carried out in a number of European Union (EU) countries revealed retail display cabinets to be the weakest link in the chill chain (Malton, 1972; Moerman, 1972; Bøgh-Sørensen, 1980; Lyons and Drew, 1985). The display life and required environmental conditions for wrapped poultry (Brolls, 1986; James and James, 2002) differ from those for unwrapped poultry. The desired chill display life is limited by microbial considerations and appearance-related factors (James and Swain, 1986).

Chilled Display of Unwrapped Poultry and Poultry Products

Display of chilled unwrapped poultry and poultry such as sliced meat and pâté requires a display life of at least one working day. A temperature close to the initial freezing point ($0 \pm 1.0^{\circ}C$) can provide a long display life for unwrapped poultry products. During retail display, relative humidity (RH) and air movement are the most critical factors, along with temperature. RH and air movement may result in changes in appearance due to variable dehydration, hence reducing consumer appeal (James and Swain, 1986) and also account for considerable economic loss to the retailer because of weight loss in the product displayed (Cutting and Malton, 1974; James and Swain, 1986; Fulton et al., 1987; Malton, 1986; Swain and James, 1986; Evans and Russell, 1994a, 1994b). For the display of unwrapped poultry, refrigerated display cabinets with gravity- or forced-connection coils and glass fronts that are nearly vertical or angled up to 20° are used primarily.

Chilled and Frozen Display of Wrapped Poultry and Poultry Products

The display life of chilled and frozen wrapped poultry may be a few day and many weeks, respectively. For chilled wrapped poultry the temperature maintained in displayed cabinets should be as close as possible to its initial freezing point,

-1.5°C, while for frozen retail display the real temperature should be -18°C. All frozen poultry and poultry products are usually shrink-wrapped before retail display to minimize moisture losses. Therefore, in chilled and frozen wrapped poultry display, air movement and RH are of less significance than they are for unwrapped poultry. But temperature is the most critical factor governing the display life of wrapped as well as unwrapped poultry during display.

TYPES OF DISPLAY CABINETS

There are a number of different types of display cabinets (Woolrich, 1968e; James and James, 2002). Under the EU save program "Energy Labeling of Supermarket Refrigerated Cabinets" on the basis of service rendered, display cases with and without doors have been broadly categorized as:

- Open top/glass top well type
- Island type
- Multideck open-fronted
- Multideck glass-fronted

On the basis of their geometry, they can be classified as horizontal open-top and vertical multideck cabinets (Gac and Gautherin, 1987; Rigot, 1990; Morillon and Penot, 1996). Both glass door and open display cases are used, but open-top display cabinets are the most common.

Other common case types are glass door reach-ins, open multideck, coffin/open tub freezers (single/multi-level), and deli display cases. A typical supermarket will have from 60 to 80 or more display cases. About half of these will be low-temperature or very low temperature cases. Another important display cabinet commonly used for retail display of poultry is served-over display. These cabinets display food on a base over which cold air flows and normally have glass fronts. Mainly unwrapped food is kept in such cabinets, and airflow can be either fan assisted or gravity fed. Such display cabinets are common in small shops.

LAYOUT AND DESIGN OF DISPLAY CABINETS

Retail display cabinets are meant to maintain the temperature of displayed products. They are neither designed to freeze food nor to reduce its temperature. Display cabinets provide a combination of storage space and display capability. They are basically assemblies operating as a vapor compression system to extract heat from within the cabinet. They comprise:

1. *A thermally insulated cabinet*. This is the vehicle for merchandizing a chilled or frozen foodstuff.

2. *A refrigerating unit*. Self-contained cabinets meant for particular applications use an integral refrigeration unit, However, remote refrigeration unit cabinets are commonly used in supermarket and large retail store applications.
3. *Heat exchangers*. The load volume is refrigerated through one or more heat exchangers, which can be fin- or plate-type coils or a combination, and the mechanism of heat convention could be convection or forced-drauft type. Usually, refrigeration is achieved through forced circulation of cold air.
4. *A defrosting system*. Frost formulation is a common phenomenon in display cases and more prevalent in frozen display cases. Timely defrosting of coils is important, as frost buildup reduces heat transfer and affects the plant capacity. The system used to defrost display cabinets can be manual, semiautomatic, or fully automatic, and the most common methods used for defrosting are water defrosting, hot gas defrosting, and electric defrosting (Datta et al., 1998; Pruthi, 1999; Baxter and Mei, 2002; Datta and Tassou, 2002; Gage and Kazachki, 2002).

The ability of a display case to maintain even product temperature requires entry of chilled air which is considerably colder than the poultry (Brolls, 1986; James and James, 2002). The refrigeration unit is placed behind the display area, and the chilled air from the refrigeration unit is blown by a fan and delivered to the product area by a duct behind the display area. After chilled air is delivered to the display area, it is returned to the duct through the grill and recycled for refrigeration.

Various types of single- and multideck display cases are now available with single and twin air curtain systems. An air curtain provides a thermal barrier between the customer and the product. The air curtain is created by a jet of chilled air at around -4°C at 1 m/s velocity that exists the duct at the top of the cabinet and falls down the face of the cabinet to the return grille. The temperature of the surrounding air is higher than the air curtain temperature, which results in a density gradient between the two, and hence the air curtain is aided by natural convention, a downward motion. Air curtain efficiency can be influenced by various factors, such as the temperature and pressure gradient between ambient and the air curtain, the velocity and thickness of the air curtain, and obstructions in the path of the air curtain. To maintain the correct temperature and efficient operation of display cases, it is very critical that the air curtain work properly (Marriot,1992; Gigiel and James 1992). Twin/dual air curtains are more efficient than single air curtains due to the protective effect of the first air curtain. Glass-fronted service counters can also be used to display poultry products. These types of display cases fall into two main types (Brolls, 1986; James, 1996; James and James, 2002):

1. *Fan-assisted*. Air movement is created by forcing air through the evaporator; better suited for display of chilled and frozen wrapped poultry.

2. *Gravity-cooled*. Cold air falls by convection from a bunker coil located on the back wall of the cabinet. This type of display case is better suited for the display of unwrapped poultry and poultry products as it could prevent severe moisture loss and subsequent drying of product to a greater content due to continual air movement (Malton, 1972).

Other key factors of immense importance in the design of refrigeration display systems are relative humidity levels, the efficiency of airflow patterns, and proper insulation (Woolrich, 1968; Gautherin and Srour, 1995; Tassone, 1997; Axell and Fahlen, 2002; James and James, 2002).

Relative Humidity

Maintaining proper levels of humidity within the product zone in display cases is essential because poultry quality can be retained or deteriorate through prevailing relative humidity (RH) conditions in the display area. If the RH is maintained at a higher moisture level than the poultry, it will result in a soft, mushy surface and microbial growth will occur, and if the RH is maintained below the moisture level of the poultry surface, desiccation and appearance-related defects will be seen. These types of defects are more prevalent in unwrapped poultry and poultry products, so proper RH from 85 to 90% is required for the display of unwrapped poultry and poultry products.

Airflow Patterns

The basic operation of a refrigerator or freezer is to remove heat from the air in the product zone and from the poultry as displayed. The refrigeration system relies on forced convection to achieve this heat transfer. Air is moved through the product zone by fans or blowers (Woolrich, 1968d). The faster the airflow, the more thoroughly and quickly heat is removed. The practical problem that occurs during the use of refrigeration system is blockage of airflow, creating flow resistance, by food and containers stored in the product zone and by the support apparatus used to hold these items. The greater the resistance or blockage, the slower the heat of removal. This can result in case freezing of product as well as spoilage within the same storage zone. Therefore, efficient and even airflow in a crowded refrigeration system is necessary if uniform humidity and temperature levels are to be maintained. Refrigeration systems having air outlets will result in quicker and uniform cooling. Usually, airflow patterns used are vertical and horizontal. The vertical airflow pattern circulates air in a top-to-bottom flow through the product zone. This flow pattern is most common back to front, but front-to-back flow patterns are also used sometimes. It is claimed that a front-to-back flow pattern creates an air curtain, preventing the migration of warm air across the food product shelves when the door is opened. This reduces cold-air spoilage from the product zone, reduces warm-up and possible spoilage, and conserves energy by reducing compressor running time for air recovery. Horizontal airflow

patterns are produced by fans or by an air duct mounted perpendicular to the storage shelves within the product zone. The air duct is usually positioned on the back of the wall of the storage compartment and contains strategically positioned air-discharge holes. Fans mounted in the top housing force air down the ducts and direct it across the food shelves. The warmed air is drawn back up through a top-mounted cooling coil.

Insulation

A good insulator is a necessity; heat naturally flows from an area of higher temperature to one of lower temperatures. A good thermal-resistant material must be able to reduce or block this transfer (Woolrich, 1968e). Throughout the evolution of commercial refrigeration design, several materials have been used to provide insulation, such as cardboard, wood fiber, cork, mineral wool, and glass fiber. Today, manufacturers use either fiberglass or polyurethane. Generally, polyurethane insulation is most widely used in the form of rigid foam slabs affixed between the wall cavities, or frothed or poured foamed between the wall cavities of the refrigeration system.

FACTORS AFFECTING RETAIL DISPLAY LIFE

Retail display life of poultry and poultry products is dependent on several independent variables, the main ones being factors associated with display cases and others being the quality of poultry and poultry products being displayed as well as the type of packaging material used for wrapping. The factors associated with retail display cases (Brolls, 1986; James, 1996; James and James, 2002) are categorized broadly as case or store parameters.

Case Parameters

- *Air temperature and humidity*. These factors are of considerable importance in determining the display life of product (Bøgh-Sørensen, 1980; Fulton et al., 1987; Evan and Russell, 1994a,b; James and Swain, 1986). Moreover, it is well documented that products displayed in fluctuating temperatures do not have the same shelf life as products stored under ambient conditions. It is not only the quality that can decrease at fluctuating temperature, but the safety of product for the consumer can also be at stake. Contamination with toxin-producing bacteria such as *Listeria monocytogenes* and *Yersinia enterocolitica* as well as other microorganisms can occur. A modified atmosphere during display has been reported to improve the quality and shelf life of displayed products (Watts, 1954; Lanier and others, 1978; Wolfee, 1980; Renerre, 1985).
- *Air velocity and distribution*. A desirable air velocity (ca. 0.2 to 0.5 m/s) and its uniform distribution within the display case is necessary for maintaining product temperature and thereby preventing fluctuations.

- *Display case lighting*. Illumination with either a fluorescent or an incandescent lamp is extremely important for persuading consumers to buy products, but this may result in raised product temperature through the greenhouse effect (Malton, 1971). Light-catalyzed oxidation reactions can also cause quality to deteriorate.

Store Parameters

The effects of store parameters are related primarily to the efficiency of display cases and may also have an influence on product quality. The main store parameters affecting display case efficiency are:

- *Heat gained by display cases*. This may be from different sources (Rose, 1986; Billiard and Gautherin, 1993; Clodic and Pan, 2000), such as heat conducted to the airstream through the walls and bottom of cases; sensible heat gain cause by air entrainment; the latest heat deriving from moisture in entrained air; fan power; radiant heat falling on the top layer of food (Malton, 1971; Bøgh-Sørensen, 1980; Nesvadba, 1985).
- *Merchandising and placement of the display case*. Poor merchandising and poor product layout, such as different shapes of product, can deflect the airstream and hence subsequently deteriorate product quality (Foster, 1997). It is very important and determined precisely. It is usually away from drafts, excessive energy inputs, warm-air velocity areas, and so on, although areas close to the entrance are favorite sites, but these should be avoided.
- *Refrigeration system control*. This depends on several independent variables, the main ones being refrigerating temperature, condensing temperature, type of refrigerant, and ambient temperature; different types of compressors and evaporators may also influence the efficiency of the refrigeration system control. Good control of all variables, especially temperature, results in a longer display life and quality of displayed poultry (Gortner et al., 1948; Dawson, 1969; Van Arsdel, 1969; Jul, 1982; Bøgh-Sørenson, 1984).

FUTURE THRUST

A great deal of improvement have evolved in the design and construction of commercial retail cabinets during the last two decades. These improvements are based on various simulated mathematical and computer-based models, the most important being computational fluid dynamics (CFD) (Baleo et al., 1995; Foster, 1995; Oort and Gerwan, 1995; Penot et al., 1995; Stribling et al., 1997; Cortella et al., 1998; Foster and Quarini, 1998; Schiesaro and Cortella, 1999; Cortella, 2002) and experimental techniques such as laser doppler anemometry (LDA) and particle image velocimetry (PIV), the main objective being modification of the air circulation pattern in the display area (Field et al., 2002).

Refrigerant choice has shifted to new ones that have a reduced environmental impact (Infante Derreira and Soesanto, 1998; Eggen and Aflekt, 1998; Mao et al., 1998; Russell and Fitt, 1998; Russell et al., 1998; Christensen, 1999; Schiesaro and Kruse, 2002), and significant efforts to reduce energy consumption (Sandra and Zey, 1980c; Evans et al., 1998; Howell et al., 1999; Maidment et al., 1999; Maidment and Tozer, 2002) have also been given marked consideration for improvement in the design and construction of display cases.

CONCLUSIONS

In the last decade, the food-service industry has witnessed many changes in methods. The wide use of chilled and frozen poultry and poultry products (Kennedy, 2000a,b) has made commercial refrigerators and freezers one of the most pieces of equipment in central facilities and retail stores. Different types of refrigeration systems have evolved in recent years. A central refrigeration system maintains cold and freezing temperatures in food display cases, walk-in storage coolers in supermarkets, convenience stores, and other locations, using a vapor-compression system. Refrigerated display is probably the most important part of the cold chain from producer to consumer. They serve two main purposes: preserving the quality of food poultry as well as sales enhancement. A wide variety of display cases are available to accommodate frozen wrapped, and chilled unwrapped and wrapped, poultry and poultry products. The display life of poultry and poultry products is restricted mainly by appearance and microbial considerations. The display life of chilled products is a few days or at most weeks, but frozen poultry and poultry products have a shelf life of months to years. Display shelf life and efficiency of display cases are affected by a number of factors. Proper control over all the factors (principally temperature) is necessary to preserve the quality of poultry and poultry products and to deliver them to the consumer in an appealing condition. Various attempts have been made to improve the design and construction of display cases, the most important being CFD and experimental techniques such as LDA and PIV. Much work is also being done toward refrigerant choice to reduce environmental hazards and to reduce energy consumption by modifying display design and construction.

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INTERNET RESOURCES

http://www.abc-supermarket.com. Single-level wide aisle open display case and glass door reach-in display case, multilevel display cases.

http://www.aps.com/aps_services/energysurvey/Default_BUSRES.html?type=b. Energy-efficient refrigeration system.

http://www.fridgesolution.com. Central refrigeration guide.

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REFRIGERATION AND FREEZING IN INDUSTRIAL FOOD FACILITIES (HOSPITALS, RESTAURANTS, FACTORIES)

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Handbook of Poultry Science and Technology, *Volume 1: Primary Processing*, Edited by Isabel Guerrero-Legarreta and Y.H. Hui

INTRODUCTION

Refrigeration has long been a standard method for the preservation of meat. The use of cool conditions for food storage dates back to the dawn of recorded history (Woolrich, 1968a). Refrigeration maintains the sensory characteristics of products close to those of fresh meat, and efficient refrigeration can preserve poultry and poultry products in conditions approaching the natural ones for a period adequate to meet commercial requirements. Furthermore, the relatively low price of poultry and shifting consumer preference have expanded poultry meat's share of global output. As a consequence of market globalization, the production and marketing of poultry and poultry products is at the stage of innovative dynamics. The demand for an oven-ready carcass has been superseded by diverse convenient products processed further. Present market trends reflect a rapidly growing demand for ready-to-cook and ready-to-serve convenience products. The current market trends and significant achievements in refrigeration have resulted in tremendous innovations in restaurants and industrial food facilities (Klose, 1968; Lyons and Drew, 1985; Anon., 1986, 1990; MLC, 1992; Heap, 2000) and account for a significant contribution to economic growth (Table 1).

Nowadays, consumers demand convenient high-quality meat products with natural flavor and taste as well as a very fresh appearance and prefer convenient high-quality, safe, and natural food products without additives. So, harmonizing or blending the modern consumer's demands without compromising food safety, refrigeration, and freezing has a vital role (Kennedy, (2000a, 2000b)). Refrigeration and freezing constitute a vital link between the processors and eventual consumers for the safe delivery of products through various stages of processing, storage, transport distribution, and marketing (IIR, 1986, 2000; ASHRAE, 1998; James, (1996, 2002, 2006); James et al., 2006).

RESTAURANTS AND INDUSTRIAL FOOD FACILITIES: REASONS FOR GROWTH

Food sales and food-service facilities represent the majority of refrigeration applications. Food sales to consumers typically take place in grocery stores, meat

TABLE 1 Food Industry Sales Projection

	2008 Sales (billion dollars)
Commercial	510.4
Eating places	376.7
Drinking places	16.5
Managed services	38.3
Hotel/motel restaurants	27.6
Retail, vending, recreation, mobile	51.4
Other	47.8

Source: www.restaurant.org.

markets, delicatessens, supermarkets, and food lockers. Food-service facilities include restaurants, cafés, drugstores serving food, taverns, grills, tearooms, cafeterias, canteens, dining rooms, carryouts, delicatessens, and stadium concession stands. Other common refrigeration uses are for serving food in taverns, bars, service stations, offices, employee-break rooms, stores, service establishments, public buildings, recreation areas, theaters, and hotels/motels (Van Dress and Freund, 1967; Enochian, 1968; MLC, 1992). In general, restaurants and industrial food facilities are complex sociotechnical organizations involving both people and machines in the production and service of food. Such a system serves the particular sector with the chief purpose of transforming the diverse requirements of a specified group of consumers to their desired expectations. Different types of industrial food facilities have evolved over the past few years. Various important food-service sectors include:

- Health care (e.g., hospitals)
- Education [e.g., institutions, schools (for lunch programs), colleges]
- Business and industry (e.g., staff feeding operations)
- Public service (e.g., police operations, the armed forces)

Many cook–chill systems are involved in the supply of food to institutional (e.g., hospitals, schools, canteens) catering operations (Glew, 1985; Armstrong, (1985, 1986); Mottishaw, 1986a,b). In these systems the food is prepared, cooked, and cooled in a central facility near the institute before being distributed to various places. It is stored and transported to the institute under refrigeration, after which it will be reheated (not cooked) or consumed. A similar system is used in chilled ready-to-eat meals. Other important industrial food systems are mobile food facilities (MFFs) and temporary food facilities (TFFs). According to the definition of the Pennsylvania Department of Agriculture (2003), a MFF is any stationary, movable, or temporary food facility, such as a stand, vehicle, cart, basket, box, or similar structure through which food is prepared, processed, distributed, or sold which remains physically at one site or location for no more than 14 consecutive days, whether operating continuously or not. The term does not include a food facility located at one site for more than 14 consecutive days. A TFF is defined as a food facility that operates for a period of no more than 14 consecutive days in a fixed location and in conjunction with a single event or celebration (such as a fair, festival, carnival, or other transitory gathering). Lockers and freezers are specialized facilities engaged in a wide variety of food-service operations, ranging from slaughter to all other commercial operations dealing with frozen products (Madiera, 1968).

Other highly profitable subsectors include hotels, restaurants, fast-food establishments, cafés and take-aways, public houses, travel organizations (on-board and in-flight refrigeration), and leisure operations. In addition, refrigeration is commonly used in such special applications as cold storage of flowers, medicines, candies, fresh fruit and vegetables, photo processing, laboratory supplies, fishing bait, and morgues.

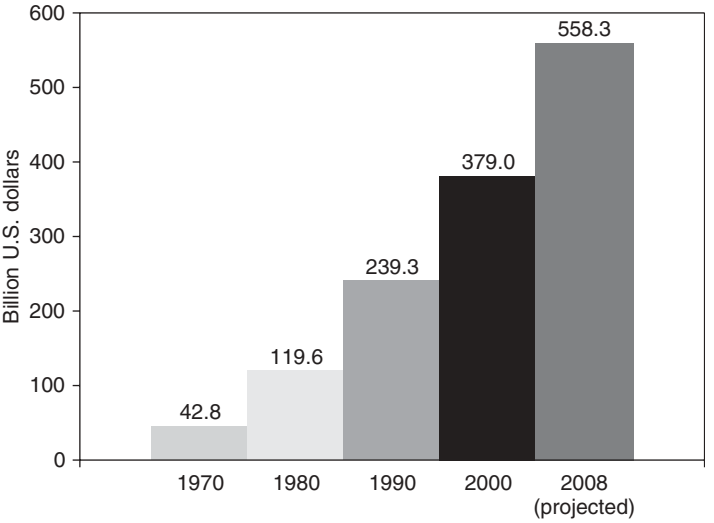

FIGURE 1 Increase in restaurant sales since 1970. (From www.restaurant.com.)

The reasons behind the increase in the sales and growth of restaurants and industrial food facilities (Figure 1) are attributed mainly to the changing lifestyle of consumers due to the convenience and better living standards provided by refrigerated and frozen foods (Mountney et al., 1960; Spencer et al., 1961; May and Saffle, 1964; Michener and Elliott, 1964; Winawer and May, 1964; Brant et al., 1965; Branson et al., 1966; Khan and Van den Berg, 1967; Enochian, 1968; Fremer and Sayre, 1968; Evans et al., 1991). Frozen processed ready-to-eat and ready-to-cook foods can save time, as the food is ready for the table. It is remarkable to see the shift from a basic array of raw agricultural commodities to so many ready-to-eat foods that has occurred in recent years (Lavay et al., 1994). During the last 30 years there have been dramatic changes in eating patterns (e.g., no or minimal breakfast, a tremendous increase in foods consumed outside the home in restaurants or fast-food outlets) and a great demand for convenience foods and in-home preparation. Key factors involved in the growth of restaurants and industrial food facilities in developed countries include massive urbanization, growing economies, higher disposable incomes, growing consumerism, increased nuclear families, changing food habits, high numbers of working women, media proliferation, rising awareness levels, brand profusion, and traveling by working groups in a society.

PRINCIPLES OF CHILLING AND FREEZING POULTRY PRODUCTS SUPPLIED TO RESTAURANTS AND INDUSTRIAL FOOD FACILITIES

Ready-to-eat delicacies and other processed poultry products are a popular option on many restaurant menus and in fast-food outlets as well as being demanded

by other food facilities. Many small poultry products, such as cubes and strips of ham and poultry meat, poultry pieces, cooked products, slices of poultry meat, and deboned and minced meat, can be individually quick frozen (IQF) in rotary cryogenic freezers (Thumel and Gamm, 1994). In many industrial cooking preparations the products processed are often cooked and cooled intact and then supplied to restaurants or retail shops for food-service operations (Sandra and Ley, 1980d). Before supplying cooked products or raw products to food-service facilities, a number of methods are used in cooling processed meat products (Cook, 1985; James, (1990a–1990c); Gaze et al., 1998; McDonald et al., 2000).

Basically, two types of chilling processes are used: mechanical air-blast and cryogenic systems. The options available for the purpose include upright cabinets, roll-ins with carts, or reach-in shelves. Freezing systems are similar to chilling systems and are meant for cooling and then freezing of food (Tressler, (1968a, 1968b); Sandra and Dey, 1980d). The majority of freezing systems used in industrial food facilities are mechanical air-blast freezers with or without a cryogenic gas booster and individual quick freezing. The major categories of poultry products supplied to food-service operations include (Fletcher, 2004):

- *Traditional product form:* raw, whole bird, cut-up parts, deboned meat, and commodity-based products.
- *Whole-bird product form:* whole, ready-to-eat rotisserie, smoked broilers, turkey and speciality birds, and fully cooked broilers.
- *Poultry parts:* halves, quarters, or fully portioned carcasses. Parts can be supplied, mixed by front or rear half (for light and dark meat preparations), or as one specific part. Certain parts, such as wings, drumsticks, breast fillets, or thighs, either raw partially or fully processed, are also supplied. Before being supplied, the products can also be marinated, coated, or cooked into specified meat recipes.
- *Boneless or skinless meat:* boneless or skinless breast fillets, whole and strips, nuggets, and cubes from breast fillets; could be supplied raw, marinated (e.g., lemon pepper, barbeque, Italian, mesquite, Teriyaki products), or in a processed form.
- *Formulated products:* various tenderized, battered, breaded, prefried, and grilled ready-to-prepare products of poultry.
- *Ready-to-eat or heat-and-eat products:* chicken potpies, chicken fettuccini, chicken fajitas, and chicken pizza, ready-to-cook (e.g., diced chicken cubes), beans and other vegetables to make soup, and other forms may be ready to prepare, such as heat-and-eat products and completely ready-to-eat and take-home food.

The various forms of poultry being supplied for food-service operation differ slightly to provide variety and convenience to processors making the desired products.

GENERAL REQUIREMENTS FOR REFRIGERATION AND FREEZING EQUIPMENT INTENDED FOR FOOD SERVICES

Refrigeration and freezing equipment for restaurants and industrial food facilities is used to preserve the small volumes of different types of foods and drinks simultaneously following the desired requirements for food service. This equipment may contain a wide variety of food materials having variable requirements for storage conditions (temperature and relative humidity being most important) and storage life. Of all the equipment used in food-service facilities, refrigeration is the one system that operates on a 24-h basis. So, before designing the equipment, all considerations regarding its intended use should be noted (Dana and Miller, 1939; Montfort, 1943; Anon., 2002; James, (2002, 2003)). In general, pieces of refrigeration and freezing equipment used in restaurant and industrial food facilities have some common requirements:

1. They are used primarily for food storage (James, 2003).
2. They are usually handled by untrained people, so their handling operation and maintenance need to be very simple, preferably with less maintenance over a long period of time.
3. They should withstand more frequent use and deal effectively with constant opening and closing.
4. They should be economical and easily repairable in case of malfunction and damage, to assist in smooth functioning and continuity of operation.
5. The overall appearance and design must be in compliance with the requirements of consumers.
6. The operation should be noise-free or low noise.
7. Energy requirements should be reduced and economical.
8. They must use nontoxic and nonflammable refrigerants.

CRITERIA FOR SELECTION OF REFRIGERATORS AND FREEZERS FOR FOOD-SERVICE OPERATIONS

Refrigerators and freezers are in increased demand for restaurant and industrial food applications. Various types of freezers and refrigerators are currently being used to store and preserve foods in food-service operations (Table 2); however, the actual choice depends on the individual situation. In determining the type and options of refrigerator and freezer equipment needed, size and capacity are the factors that must be considered carefully because in most cases their requirements are restricted by available space. When selecting a refrigerator or freezer, several points must be considered in meeting the desired operating requirements. The first step is to determine the range of refrigerator or freezer equipment required to meet a specific application of food service. A simple method of accomplishing this is by categorizing service needs into the following major areas:

TABLE 2 Typical Refrigeration Applications

Application	Freezer Space Required (L)	Volume Required (L)	Critical ?	Refrigerant Used
Institutional and commercial food preservation	50–550	200–1000	Yes	R-404A, R-507, HFC-134a
Institutional and commercial drinks, etc. cooling	—	200–300	No	R-410A, R-407C, R-507, HFC-134a
Dedicated freezing (institutional or commercial)	500–1000	—	Yes	HFC-134a, R-404A, R-507
Household refrigeration/freezing	15–250	200–550	No	HFC-134a

1. *Interim storage*. When primary storage refrigerators are located outside the main kitchen (such as on a different floor), an interim storage refrigerator (or "day cooler") is required to stage the day's or shift's refrigerator requirements in the actual kitchen.

2. *Production requirements*. Refrigerated working and preparation coolers are always needed at the points of preparation, both cold and hot, within the kitchen and server areas. These may take the form of walk-in coolers or reach-in or roll-in refrigerators and provide a safe food supply to chefs and cooks at the point of preparation. Also, somewhere between the points of preparation and service, holding or "ready" refrigerators are required to hold the food products safely prior to serving.

3. *Service requirements*. At the points of service, presumably in the café server and smaller retail venues, there are requirements for both ingredient coolers and finished product refrigeration. The ingredient units are typically reach-in and under-counter refrigerators. Open ingredient rails or cold pans are utilized at sandwich, made-to-order, grill, pizza, and salad and dessert stations. The use of both closed-front and open-air refrigerated merchandisers is most evident; they increase merchandising opportunities as well as promoting customer self-service. Open-air units require careful engineering to ensure proper food temperatures and safety concerns.

4. *Specialty needs*. This category includes units such as blast chillers, temperature-monitoring systems, and food bank refrigerators designed for special temperature holding and refrigerated drink and condiment dispensing systems.

Freezers are also selected on the basis of a star rating system (Ware, 1974; Sanderson-Walker, 1979; Evans et al., 1991) (Table 3). Other factors of prime importance in selecting refrigerator and freezer systems for specific applications

TABLE 3 Star Rating System

	Storage Temperature	Storage Time	Capability of Equipment
*	Not warmer than −6°C	Up to 1 week	Storage only
**	Not warmer than −12°C	Up to 1 month	Storage only
***	Not warmer than −18°C	Up to 3 months	Storage only
****	Not warmer than −18°C	Up to 3 months	Can freeze fresh food down from room temperature to −18°C, as well as store

Source: Evans et al. (1991).

include particular refrigeration needs, such as for hospitals, schools, or restaurants. Their needs may vary with their specific requirements, power requirements or energy consumption, location of the food-service establishment (warm locations requires more energy), running cost, and defrosting method.

However, no one size or type will answer all requirements, which is indicated by the vast number, sizes, and types of equipment being offered today, and continuous improvements in existing equipment (Beltran Cortes, 1983; Radermacher and Kin, 1996; Zoughaib and Clodic, 2003; Pearson, 2004). A hard and fast rule cannot be given; the actual choice depends on the individual situation.

PRINCIPAL COMPONENTS OF REFRIGERATION AND FREEZING EQUIPMENT

Refrigerators and freezers may be seen around the world in a wide range of sizes, each suited to the particular operation for which it is designed (Pruthi, 1999). In general, refrigerators and freezers can be regarded as cooling appliances comprising a thermally insulated compartment and a mechanism to transfer heat from the insulated section to the external environment. Various methods are used for refrigeration in equipment utilized in restaurant and industrial food facilities, and on the basis of their refrigeration mechanism, these methods can be classified as noncyclic, cyclic, and thermoelectric.

1. *Noncyclic refrigeration:* can be accomplished by melting ice or by subliming dry ice. These methods are generally used for small-scale refrigeration, such as in laboratories and ice boxes.
2. *Cyclic refrigeration:* consists of the basic component of the refrigeration cycle and can be accomplished by:
   a. A vapor cycle
      (1) Vapor-compression refrigeration
      (2) Vapor-absorption refrigeration
   b. A gas cycle
3. *Thermoelectric refrigeration:* uses the Peltier effect to accomplish cooling.

Other refrigeration methods include magnetic refrigeration, an air-cycle machine, a vortex tube for spot cooling, and thermoacoustic refrigeration. The principal refrigeration system used in refrigerators and freezers for restaurants and industrial food facilities is a vapor-compression system (Sandra and Ley, 1980b; Woolrich, 1968c; Radermacher and Kim, 1996; Heap, 2000; Anon., 2002) The details of refrigeration cycles may be found in several excellent refrigeration textbooks (Woolrich, 1968b; ASHRAE, 1998).

Refrigerators and freezers for restaurants and industrial food facilities have some components in common (Woolrich, 1968f). The basic components are a thermostat, an evaporator, a condenser, a compressor, insulation, and a refrigerant gas. Their other common features include:

1. *Evaporators.* Evaporator coils used include two types of refrigeration systems: the flooded evaporator, and direct expansion. For direct expansion systems, two of the most commonly used refrigerant liquid metering devices are the capillary tube and the thermostatic expansion valve. In addition, proper provisions are made for periodic defrosting of evaporator air-side surfaces. Defrosting may be accomplished using refrigerant compressor discharge hot gas, water spray, or manually as selected to meet the user's objectives. Suitable drain connections are also provided to carry off water from defrosting operations.

2. *Coils and condensing units.* Coils and condensing units can be either self-contained or remote. In a self-contained system the condensing unit is attached to the cabinet, and in a remote system the compressor and condenser are located separate from the cabinet. To ensure maximum coil life and to prevent leaks, surfaces should be plasticized to eliminate corrosion. Condensing carts are generally air cooled, but under high-temperature conditions, a water-cooled unit is used. The type of condenser selected depends largely on the size of the cooling load, the refrigerant used, the quality and temperature of the cooling water available (if any), and noise considerations.

3. *Capillary and expansion valves.* These valves are the controlling or metering apparatus of refrigerant flow into an evaporator coil. Both types of systems are employed; the choice depends mainly on the use of equipment and on operational and maintenance cost considerations. A capillary tube is generally used in a self-contained refrigeration unit; whereas large remote-installation refrigeration cabinets and walk-in systems require expansion valves.

4. *Compressors.* Self-contained compressors are generally air cooled, whereas a remote compressor can be either air or water cooled. The most common type of compressor used in commercial refrigeration systems is the reciprocating compressor. Reciprocating compressors include single-stage (booster or high state), internally compounded, and open, hermetic, or semihermetic compressors.

5. *Construction material.* The most durable material available for construction is high-quality stainless steel, which provides durability, sanitation, and beauty. Aluminum is used only as a finish for interior and exterior walls of equipment. Colored interiors can be made by spraying on a vinyl coating, fiberglass, or

vacuum-formed polystyrene. Such coatings also provide seamless construction, which facilitates cleaning and sanitation. Corner door lines may be made of metal or molded reinforced fiberglass.

6. *Door and floor.* Door design is an extremely important feature. Most commonly in refrigerators, the door will remain open at a 95° angle for loading operations and will close with a slight nudge. In other applications, doors can be sliding or moving. Floors should be made of galvanized steel, which provides the structural strength to withstand heavy, uneven weight distribution. All floors are insulated and covered with a nonskid finish. These features of floors are commonly seen in large walk-in systems.

7. *Sanitation.* For sanitation purposes, all vertical and horizontal corners are rounded, since square corners are more difficult to clean. All metal surfaces should have smooth, nonporous surfaces, to prevent the accumulation or harboring of microorganisms.

8. *Alarm.* An alarm may be used as a power indicator when the electrical supply is interrupted, or as a temperature sensor if a product zone exceeds safe limits.

9. *Shelves.* Wire shelves, solid shelves, and solid shelving with ventilation slots are all acceptable. According to the shelving designed, an appropriate air circulation pattern and relative humidity should be provided.

10. *Insulation.* A good insulator is a necessity, as heat flows naturally from an area of higher temperature to one of lower temperature. A good thermal-resistant material must be able to reduce or block this transfer.

Throughout the evolution of commercial refrigeration design, several materials have been used to provide insulation, such as cardboard, wood fiber, cork, mineral wool, and glass fiber. Today, manufacturers use either fiberglass or polyurethane. Polyurethane insulation is most widely used in the form of rigid foam slabs affixed between wall cavities or as frothed or poured foam between the wall cavities of a refrigeration system.

TYPES OF RESTAURANT AND INDUSTRIAL FOOD FACILITY REFRIGERATORS AND FREEZERS

Food-service refrigeration applications vary widely in size and temperature level (Sandra and Ley, 1980a; Pruthi, 1999). Domestic refrigerators require 60 to 140 W of electrical power and contain 40 to 180 g of refrigerant. Industrial and cold storage refrigeration systems have power requirements up to several megawatts and contain thousands of kilograms of refrigerant. Refrigeration temperature levels range from +15 to −70°C. Domestic refrigerator temperatures should not exceed 5° C (Richmond, 1991). Walk-ins, step-ins, reach-ins, roll-ins, under-counter units, sandwich/pizza open tops, cold pans, display cases (closed- and open-air, self-service), blast chillers, mobile units, and beverage

chillers are the types of refrigerators and freezer used in food-service operations (Sandra and Ley, 1980a). The type of equipment is combined with such options as self-contained, remote rack, indoor vs. outdoor, individual vs. parallel systems, water-cooled vs. air-cooled, various door configurations, roll-in, and pass-through. According to the definition given by Energy Star (2001), refrigerators and freezers can be defined as follows:

1. *Commercial refrigeration cabinet:* a refrigerator, freezer, or combination refrigerator–freezer for storing food products or other perishable items at specified temperatures and designed for use by commercial or institutional facilities.
2. *Commercial refrigerator:* a cabinet designed for storing food or other perishable items at temperatures above 32°F and below 40°F.
3. *Commercial freezer:* a reach-in cabinet designed for storing food or other perishable items at temperatures below 0°F and above −5°F.
4. *Commercial refrigerator–freezer:* a cabinet with two or more compartments, at least one of which is designed for storing food or other perishable items at temperatures above 32°F and below 40°F and at least one of which is designed for storing food or other perishable items at temperatures below 0°F and above −5°F.

Since more emphasis is being given to the energy consumption (Sandra and Ley, 1980c) of commercial refrigerators and freezers, the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) Standard 117–1992, "Method of Testing Closed Refrigerators," will be used to measure the daily energy consumption of commercial reach-in refrigerators and freezers with the following temperature specifications:

- *Commercial solid-door refrigerator:* initial product temperature 38 °± 1°F, maximum product temperature 40°F
- *Commercial solid-door freezer:* initial product temperature 0°± 1°F, maximum product temperature 2°F

General Refrigerator and Freezer Equipment Used in Food Service

Self-Contained Systems Many upright models and designs are available to suit various storage requirements. These systems are used primarily for short-term storage of limited food quantities with immediate access to the preparation and assembly and service areas.

Reach-in Refrigerators and Freezers These refrigerators and freezers provide shelf or pan slide storage in preparation and serving areas. They are generally used for storing prepared or portioned foods and for storing food ingredients in work areas. They are available in one-, two-, or three-section capacities, and other model design modifications may include full-length doors, half-length doors, and pass-through doors for energy saving and smooth working.

Roll-in Refrigerators and Freezers Roll-in refrigerators and freezers are designed for mobile cart storage; upright commercial refrigeration cabinets with one to three solid doors that allows wheeled racks of product to be rolled into or through the refrigerator or freezer. They promote efficient material flow and easy storage of large food quantities. In addition, they facilitate food removal from inside to a temporary storage area in preparation and service centers. They are available in one-, two-, or three-section capacities, and other model design modifications may include full-length doors, half-length doors, and pass-through doors for energy saving and smooth working.

Under-the-Counter Refrigerators and Freezers These are upright commercial refrigeration cabinets with one to three solid doors, intended for installation under a counter and thermally isolated from the counter. These refrigerators have shelves and are designed for installation under preparation, assembly, and serving counters. They keep ingredients immediately available while maintaining them under temporary safe storage temperatures. Under counters provide ideal storage for proportioned recipes such as chicken pizza, which may require variable proportions of diced chicken and vegetables.

Griddle Stand Refrigerators and Freezers These refrigerators may have drawers that provide immediate access to short-order items. Drawers aid in separating different types of foods, such as raw vegetables and chicken strips, and eliminate odor transfer. Griddle stands are usually installed under fryers and griddles and are used to store products such as portioned ground chicken patties, French fries, chicken fillets, breaded chicken, and similar items.

Display or Merchandising Refrigerators and Freezers These refrigerators and freezers have sliding or hinged glass doors and provide safe temporary storage and merchandising appeal for prepared foods. They are usually located in cafeteria and self-service areas. They may be available as upright models, wall-mounted units, and countertop cabinets.

Mobile Refrigerators These are portable, insulated refrigerators that usually have electrically controlled air temperatures and are equipped with a self-contained refrigeration system. These are used primarily for storing prepared foods and for distributing foods to service areas. They are ideal for catering and satellite services where storage refrigeration is lacking. Mobile systems are used to increase the ease of material handling for transportation and holding of prepared foods under safe, temporary storage conditions until required for cooking.

Household Refrigerators A home freezer is defined as a self-contained refrigerator for home or restaurant use in storing frozen foods or in freezing and storing frozen foods. The freezer cabinet in which the food is stored consists of an outer shell or walls and inner walls or lines with insulation between the two. Two general types of home freezers are available today: Designated as horizontal chest or

top opening and vertical or upright types (Woolrich, 1968d; Mascheroni and Salvadori, 2005). Customer preference at present indicates an increasing demand for the upright type. Bottom- and top-freezer variations are available, but top freezers are preferred since bottom freezers have more problems related to breakage, clogging, and dripping on the floor (Woolrich, 1968d).

Pass-Through Refrigerators These are upright commercial refrigeration cabinets with one to three solid sliding or hinged doors on both the front and rear of the refrigerator or freezer.

Remote or Self-Contained Walk-in Coolers and Freezers Walk-in-boxes are used in a wide variety of applications, but their use in food sales and service facilities dominates all other uses. There are two major classes of walk-ins: low temperature (-10 to -20°F) and medium temperature (-10 to 30°F). Reach-in refrigerators and freezers are upright refrigerated cases with solid doors whose purpose is to hold refrigerated and frozen-food products, respectively (Woolrich, 1968d). These cases are commonly used in commercial and institutional food-service establishments. The refrigeration system is located at the top of the unit. This keeps refrigeration components away from spills and other debris unique to food-service establishments and reduces accumulation of dust on the condenser serve-over cabinet while keeping these components readily accessible for maintenance and servicing. The refrigeration components of a reach-in freezer consists of a $\frac{1}{2}$-hp hermetic compressor, an evaporator farn, and a condenser fan. Refrigerant flow is governed by a thermostatic expansion valve.

Ice Machines Ice machines are used to produce a variety of ice types used in the food-service, food-preservation, hotel, and hospital industries. The various types of ice produced include cube ice, flaked ice, crushed ice, and nugget ice. Primary applications include chilling of procured raw poultry and poultry products in small restaurants by keeping them under ice or under bags of ice. Ice is also added to meat mixtures during mixing and grinding operations to maintain their temperature.

Refrigerated Vending Machines Refrigerated vending machines are upright refrigerated cases whose purpose is to hold refrigerated drinks and food products and vend them in exchange of currency. These cases can be found anywhere. According to vending times, the most common locations are inside or outside factories, offices, health care institutions, schools, hotels, colleges, and other public locations (Lavay et al., 1994). The entire refrigeration system is built into the machine, and heat is rejected from the refrigeration cycle to the surrounding air.

Multifunctional-Performance Refrigerators or Freezers

Dual-Temperature Cabinets These refrigeration systems are designed with separate, isolated compartments of refrigeration and freezer storage. They are used primarily in situations where both refrigeration and freezing are necessary, but

space to accommodate both is limited. Dual-temperature cabinets have two compartments stacked vertically: a freezer compartment with a refrigerated section underneath. They are available as two- and three-section models.

Tri-temperature Cabinets These cabinets can be converted to a 0°F freezer, a 28°F deep chiller, or a 40°F refrigerator. They are used in operations where menu components vary and quantities change continually. A tri-temperature cabinet has a key switch that converts the temperature. These systems provide ideal storage flexibility.

Other Important Processing and Storage Refrigerators and Freezers

Chilling Refrigerators Chilling refrigerators are used for processing hot precooked foods through the 130 to 45°F danger zone by means of high-velocity convected air. The cabinets can then be converted to 38°F conventional storage cabinets when storage is not required.

Thawing Refrigerators These refrigerators are designed to thaw frozen foods quickly and evenly in refrigerated air that never exceeds 45°F. The cabinets used high-velocity convected air and introduce heat to increase thawing speed. These systems can be converted to conventional storage refrigerators when processing thawed foods is not required.

Mechanical Air-Blast Freezers These cabinets use −40 to −20°F high-velocity convected air to freeze foods quickly. When not required for freeze processing, the cabinets can operate as conventional storage freezers.

Combination Cryogenic and Mechanical Freezers Cryogenic refrigerant, either liquid nitrogen or carbon dioxide, is mixed with high-velocity air to obtain an air temperature of −40 to −100°F for freezing foods rapidly. When the systems are not in use, they can be used as storage freezers.

GENERAL GUIDELINES FOR THE USE OF REFRIGERATORS AND FREEZERS

The following precautions should be considered during the use of refrigerators and freezers in their food-service operations:

1. They should not be exposed to strong drafts, direct sunlight, or heating from any other equipment.
2. The temperature should be checked regularly and the cabinet should be defrosted as and when necessary.
3. Frozen foods should be put into the cabinet or storage room immediately following their receipt from the distributor.
4. Packages should not be stacked above the line in the cabinet.
5. Stock should be rotated so that it is sold on a first in, first out basis.

6. Cabinets should always be kept clean and orderly, and damaged packages should be removed immediately after being detected.
7. Unfrozen products should never be put in the cabinet for freezing or storage, as this could cause an increase in the temperature of the cabinet and cause harm to other stored frozen foods in the cabinet.
8. Temperature is the most critical factor determining shelf life and product quality, and fluctuations in temperature should be kept as small as possible in order to have high-quality, safe, and wholesome products (Gortner et al., 1948; Dawson, 1969; Van Arsdel, 1969; Jul, 1982; Bøgh-Sørensen, 1984). The refrigerated shelf life expected for some poultry products is given in Table 4.

LEGISLATION

Since the mid-1980s there has been a considerable increase in legislation governing temperature requirements during production, processing, distribution,

TABLE 4 Expected Refrigerated Storage Life of Some Poultry Products

Product	Refrigerator Storage Life
Fresh chicken, giblets, or ground chicken	1 to 2 days
Cooked chicken, leftover	3 to 4 days
Chicken broth or gravy	1 to 2 days
Cooked chicken casseroles, dishes or soup	3 to 4 days
Cooked chicken pieces, covered with broth or gravy	1 to 2 days
Cooked chicken nuggets, patties	1 to 2 days
Fried chicken	3 to 4 days
Take-out convenience chicken (rotisserie, fried, etc.)	3 to 4 days
Restaurant chicken leftovers brought home in a "doggy bag"	3 to 4 days
Store-cooked chicken dinner, including gravy	1 to 2 days
Chicken salad	3 to 5 days
Chicken luncheon meat	
Deli-sliced	3 to 5 days
Sealed in package	2 weeks (but no longer than 1 week after a "sell-by" date)
After opening	3 to 5 days
Vacuum-packed dinners, commercial brand with USDA seal	Unopened 2 weeks, opened 3 to 4 days
Chicken hotdogs	Unopened 2 weeks (but no longer than 1 week after a "sell-by" date), opened 7 days
Canned chicken products	2 to 5 years in pantry

transport, retailing, and other food-service operations. This legislation has come forward due to the increased incidence of food poisoning caused by mishandling of food in food-service operations with insufficient refrigeration or cooling (Mottishaw, 1986a; Bryan and Kilpatrick, 1971; Goodfellow and Brown, 1978; DHSS, (1980, 1986); Evans et al., 1991; WHO, 1992). Various types of standards, specifications, regulations, and codes have been formulated to provide high-quality safe and wholesome foods to consumers (Fen, 1968; IIR, 1986, 2000). In the UK and the United States various regulations have been given for cooling meat products to ensure their safety before being supplied to restaurants or retail shops (Gaze et al., 1998). The meat products (hygiene) regulations (1994) have also set special conditions for cooling of meat-based prepared meals; similar criteria have also been mentioned in European Commission meat product directives. In the UK, the Department of Health published guidelines for cook–chill food systems in 1989. A number of cities and states, under their limited regulatory authority, have adopted mandatory requirements for the handling of frozen foods (Schmitt, 1964). The National Association of Frozen Food Packers (1965) have also summarized regulatory frozen-food-handling temperature requirements in its Technical Service Bulletin 7.

CONCLUSIONS

From the onset of refrigeration, refrigeration and freezing of poultry in food-service operations became a common practice. The poultry industry share in the global market has seen tremendous growth in past years, attributed to increased consumer preference for poultry meat compared to its other meat counter parts. Moreover, during the last three decades there have been dramatic changes in eating patterns and consumer lifestyles which have resulted in increased numbers of restaurants and industrial food facilities. Consumers are now more conscious about the quality of products they are eating and demand high-quality, additive-free, convenient meat products with natural organoleptic qualities. To harmonize or blend modern consumer demand, refrigeration is a vital tool in providing wholesome, high-quality, safe, close-to-fresh products.

Food sales and food-service facilities represent the majority of refrigeration applications, such as health care (e.g., hospitals), education [e.g., schools (for lunch programs) and colleges], business and industry (e.g., staff feeding operations), and public service (e.g., police operations, the armed forces). A wide range of poultry products are being supplied to restaurants and industrial food facilities: whole carcasses, cut-up carcasses, portions, boneless meat, and products processed further.

Refrigeration and freezing in restaurant and industrial food facilities have some common requirements, as they are used to preserve small volumes of various types of food and drink according to the requirements of the food service. Various types of freezers and refrigerators are used to store and preserve foods in food-service operations, with the actual choice depending on the individual situation.

So before the selection of a refrigerator or freezer for specific applications in food service and for interim storage, production, and service requirements, specialty needs should be kept in mind.

The two most common methods used to produce low temperatures in refrigerators and freezers are vapor compression and absorption refrigeration. The six basic components of refrigerators and freezers used in restaurants and industrial food facilities are a thermostat, an evaporator, a condenser, a compressor, insulation, and a refrigerant gas. All refrigerators and freezers also have common components: for example, doors, shelves, floors, and alarms.

Walk-ins, step-ins, reach-ins, roll-ins, under-counter units, sandwich/pizza open tops, cold pans, display cases (closed- and open-air, self-service), blast chillers, mobile units, and beverage chillers are the types of refrigerators and freezers used in food-service operations. The type of equipment is combined with such options as self-contained, remote rack, indoor vs. outdoor, individual vs. parallel systems, water-cooled vs. air-cooled, various door configurations, roll-in, and pass-through. Other refrigerators and freezers with added functions include dual-temperature cabinets, tri-temperature cabinets, chilling refrigerators, thawing refrigerators, mechanical air-blast freezers, and combination cryogenic and mechanical freezers. Certain guidelines should be practiced for efficient use of refrigerators and freezers. Legislation is another important aspect that needs to be considered carefully to achieve high-quality, safe food products.

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PART IV

PRESERVATION: HEATING, DRYING, CHEMICALS, AND IRRADIATION

22

HEATING, DRYING, AND CHEMICALS

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HEATING

Heat Transfer in Meat and Meat Products

Using heat treatments to preserve food by reducing microbial counts is commonly employed in food processing. Heat also causes protein coagulation, enzyme inactivation, and desirable changes in several sensory characteristics (i.e., color, aroma, texture, etc.). Heating reduces microbial counts to safe levels, and heat transfer must also be considered, as it affects food quality. However, thermal destruction of microorganisms does not occur immediately; it follows an

Handbook of Poultry Science and Technology, *Volume 1: Primary Processing*, Edited by Isabel Guerrero-Legarreta and Y.H. Hui

TABLE 1 Destruction of *Streptococcus* sp. in Meat Cured at 70°C

Time (min)	Number of Microorganisms	Population Reduction (%)	*D*-Value
0	10^6	—	0
3	10^5	90	1
6	10^4	90	2
9	10^3	90	3
12	10^2	90	4
15	10^1	90	5
18	10^0	90	6
21	10^{-1}	90	7
24	10^{-2}	90	8
27	10^{-3}	90	9

exponential process, indicated by *D*-values, as shown in Table 1 for a given *Streptococcus* strain at 70°C. The ability of microorganisms to survive heat treatment is expressed at a given temperature (i.e., $D_{121.1}\,^{\circ}\mathrm{C} = 1$ min).

Thus, the larger the initial microbial population, the higher the survival rate; if the initial count is 10 million microorganisms per gram, and assuming elimination of 99.9% of the initial population, a survival population will be 10,000 microorganisms. Heat treatment severity is defined as an *F*-value, defining the deadly effect of heat treatment on microorganisms. Several authors call this *time thermal destruction* (TTD) or *thermal death time*, with *F* defined as the time required to destroy a number of microorganisms under specific conditions (e.g., temperature, type and number of microorganisms, environmental conditions). *F*-values at given temperatures are summarized in Table 2.

At present, food industries require real heat-processing conditions that assure destruction of bacteria and spores, which otherwise would be able to germinate but without considerable product alteration. In this concept, called *commercial sterility*, heating is between 65 and 75°C; sterilization is carried out above 100°C. At this temperature range, proteins are able to form gels, while enzymes are inactivated. Enzyme inactivation and bacteria death are followed by thermal death

TABLE 2 *F*-Values at Various Temperatures

Temperature (°C)	Time (min)	*F*-Value
95	1	0.003
100	1	0.008
105	1	0.025
110	1	0.079
115	1	0.251
121	1	1.00
125	1	2.51
130	1	7.94

curves at different food depths. Heat penetration curves depend on the size and composition of the product, heat transfer properties, and packaging type, if used. Steam has also been used as a means to provide sterile surfaces. This method notably reduces microbial populations in poultry skin; if used together with refrigeration, shelf life is extended considerably.

Sensory properties are also affected by heat processing; if applied to obtain cooked products, these changes are positive. However, excessive heating sometimes reduces consumers' acceptance, due primarily to protein reaction with sulfur compounds, producing unpleasant odors and flavors. Raw poultry quality also affects sensory properties due to heating as well as package type and shape (surface area/weight ratio) after heat processing. It is also recommended that two-stage cooking be carried out, as it increases poultry water-holding capacity, mainly in mechanically deboned chicken meat. The effect of heating on nutritional value, the temperature/time ratio, affects protein, peptides, and lipids in a similar manner, as it affects bacterial survival and enzyme inactivation.

Heat processing in foods is based on heat transfer by one or more of the following processes: conduction, natural convection, forced convection, radiation, and microwaves. In all cases the process is due to the presence of temperature differences between the heating source and the product; however, microwaves lack the uniformity in temperature distribution that occurs in other processes, affecting the final product quality. On the other hand, meat substrate being extremely variable, a number of interdependent factors also affect the overall process, making it difficult to predict the precise thermal profile. One of the main problems in calculating meat thermal processes is the amount of fat present in raw meat or meat products; lean products require less heating to achieve process temperatures; in semifluid meat products such as páté or luncheon meat, which tend to become solid when heated, temperature increases faster than cooling. This must be considered to calculate the overall processing time. Surface area/weight ratio must also be considered for meat heat processing; high ratios are heated more rapidly that those with less exposed surfaces.

Meat Changes During Heat Processing

As meat is a dynamic system, several changes occur during severe thermal processing. These changes are summarized in Table 3. Muscle heating brings physical changes such as tissue contraction, fluid releasing, muscle discoloration, and substrate shrinking. Chemical changes occur concurrently: Above 40°C, myofibrillar protein solubility decreases, becoming insoluble at 60°C. Temperature increase also results in pH increase and myofibril pH rises from 5.4 to 6.0, although this increase also depends on the meat initial pH. The Maillard reaction rate increases strongly at 90°C or more, resulting in the development of a bitter taste due to the formation of — SH groups above 70°C, which becomes an exponential formation rate at 80°C or more. Conversely, enzyme activity decreases with increasing temperature: Proteases are inactivate between 70 and 73°C, phosphatases at 70 to 73°C, and actomyosin ATPase at 45°C; pH also increases if

TABLE 3 Changes in Meat Subjected to Heating

Temperature Range (°C)	Meat Changes
20–30	No change in the chemical-colloidal properties
	Myosin ATPase activity when heated at 30°C or above
30–50	Changes in myofibrillar proteins
	Changes in water-holding capacity, hardness, protein solubility, pH, —SH concentration, color, Ca^{2+} and Mg^{2+} retention; ATPase is inactivated
50–55	Reduced myofibrillar protein functionality
	Water-holding capacity and pH reduction; color changes
55–80	At 65°C, increased protein aggregation; collagen gelation
Above 80	Increases sulfhydryl bonding
	Basic amino acid groups start linking; Maillard reaction takes place; tenderness increases

heating is stopped between 50 and 55°C while water-holding capacity decreases. Zhu and Brewer (2002) reported that the combined effect of temperature and pH on metmyoglobin denaturation occurs at 70°C, when the pH is around 7. But when the pH is below 6.5 at 50°C, denaturation is caused by pH, not by temperature. Other mechanisms, such as actomyosin, begin depleting at 30 to 35°C; however, this protein starts aggregating if heated above 35°C. Globular proteins start denaturing at 50°C, begin aggregating at 62°C, and are fully aggregated at 80°C.

Meat becomes tenderer when heating at 65°C, due mainly to collagen gelatinization, although elastin does not denature, due to its polypeptide chain structure. The color of cured meat is also affected by meat heating, as shown in Table 4. Studying chicken breast nuggets, Murphy and Marks (2000) reported a reduction in protein solubility when product temperature increased from 23°C to 80°C; they observed myofibrillar protein dissociation, collagen solubility increase, and increased cooking losses affecting the texture.

TABLE 4 Cured Meat Color as Affected by Heating

Temperature	Scalding Time (min)					
(°C)	15	30	45	60	75	90
75	Gray	Very pale pink	Very pale pink	Pale pink	Pink	Deep pink
80	Very pale pink	Pale pink	Pale pink	Deep pink	Deep pink	
100	Pale pink	Pale pink	Deep pink			
110	Pink	Deep pink				

DRYING

Meat Dehydration Physical Factors

Dehydration as a means of meat and meat product preservation has been used for more than 5000 years in Egypt and other cultures; in fact, it is considered to be the first process developed by humankind. Originally, solar energy was used; today it can be a high-technology process, based on water activity reduction to levels where food deterioration is avoided. The process used in meat preservation is designed to prevent deterioration caused by microorganisms, enzymes, and chemicals without notably affecting the product. The most widely used method employs hot air in the form of an air current at constant temperature and time. Sometimes, salt (NaCl) is added to the raw meat before drying; salt avoids microbial growth and enzymatic reactions while providing flavor to the product.

As water is the most abundant constituent of food, it largely determines the physical, chemical, and sensory characteristics of a food. Water also has a direct influence on food stability; therefore, its control is of particular interest during the drying process. *Water activity* (a_w) is the relationship between water vapor partial pressure of the food and vapor partial pressure of pure water at the same temperature; it is also defined as the amount of water available in the food, and depends on the type and quantity of water interactions with other food components. The a_w value influences microbial growth and survival and the reaction rate of food components.

Foods are divided in three groups based on a_w: low a_w (0 to 0.60); intermediate a_w (0.60 to 0.90), and high a_w (0.9 to 1). Water activity in meat is around 0.97, making it a suitable substrate for microbial growth. Bacteria require a minimum a_w value of 0.91, yeast 0.88, molds 0.80, halophilic bacteria 0.75, and osmophile yeasts 0.60. The important food pathogens need the following minimum a_w: *Salmonella* spp. 0.95, *Clostridium botulinum* 0.95, and *Escherichia coli* 0.96.

Meat products generally have high a_w values, making them highly perishable, requiring preservation processes. Intermediate-moisture foods are relatively stable at room temperature but are susceptible to microbial contamination, needing additives that inhibit their growth; conversely, low-humidity meat products are very stable at room temperature.

Water is also required for chemical and enzymatic reactions that accelerate food deterioration. Meat components (i.e., protein, fat, carbohydrates, vitamins, enzymes, and organic salts) contain considerable proportions of hydration water, water bound in structures such as gel or emulsion, forming solid systems. Major physical changes occurring during meat drying depend largely on the product size; as a rule of thumb, products between 3 and 8 mm in diameter, weighing 1.2 to 4 lb, will take between 3.5 and 6.5 h to lose up to 5% moisture content. If moisture is decreased at a relatively high temperature (above 50°C), sensory deterioration occurs.

Mass transfer as referred to drying processes is moisture migration from inside the product to the surface and moisture evaporation from the surface toward the surrounding drying medium, generally air. Moisture migration from the product interior depends on product temperature, composition, moisture content, and product water-holding capacity; moisture evaporation from the product surface is the differential in moisture between that of the product surface and that of the drying medium. To calculate process conditions it is necessary to know the humidity in the dryer as well as the temperature and time of the process. As mentioned, product size is also an important factor: The larger the drying surface and the thinner the product, the shorter the drying time. The fat content also reduces the drying rate, as it acts as a barrier to water removal from the product; during the process, fat becomes liquid and covers the meat surface, preventing moisture migration.

The water-holding capacity is obviously decreased, as meat ultrastructure (i.e., myofibrils, filaments, muscle fibers, etc.) undergoes size shrinkage; also, on the muscle periphery, potassium accumulates in the dehydrated fibers, altering the muscle chemistry. Finally, at 80°C, sulfhydryl compound concentration increases drastically, altering muscle biochemistry. Sensory characteristics are also altered during the drying process. High temperature and low humidity cause Maillard reactions, which lead to dark color and bitter taste; in high-oxygen partial pressure environments at high temperature, yellowish discoloration occurs in addition to fat oxidation and the development of a cooked meat odor.

Insect Contamination

Depending on the product type to be dried (e.g., fillets, nuggets, ground), product processing is different. In this respect, habits and local traditions are also important, as is considering all aspects of hygiene recommended by *Codex Alimentarius* and local regulations. In meat considered for dehydration, contamination with insects is probably the main concern due to the low water activity, which does not permit microbial growth. Dried meat products are an excellent source of nutrients to insects. Therefore, preventing insect entry to a factory is vital, since access can be given through any opening, such as doors or drains, especially in areas where wastes are accumulated or by the introduction of contaminated materials.

It is necessary that walls and floors be of smooth building materials to facilitate washing and sanitation. Special care must be taken with ceilings, as they are difficult to clean properly and therefore are an important source of dust, which favors the presence of arthropods. Wooden structures must be avoided, as they provide material for nesting. The color of walls and roofs must be clear, to permit detection of dirt and insects. The use of waiting rooms with light traps (black light) contributes significantly to reducing insect passage toward the plant; these traps should be placed strategically throughout the plant. In all equipment and facilities it is necessary to prevent the presence of remnants of raw meat and nonmeat materials, as they can be substrates for insect eggs. Every product batch must be handled separately, to avoid cross-contamination.

The most common species of insects associated with dried beef are mites, flies, and beetles. With respect to mites, temperature and relative humidity have a direct effect on infestation. A decrease in the incubation period occurs as a combination of these two factors:

- At 16°C and 80% relative humidity (RH), the incubation cycle is completed in 22 days
- At 25°C and 80% RH, in 14 days
- At 30°C and 95% RH, in 9 days
- At 25°C and 60% RH, in 17 days

At 10°C and below, or above 35°C, growth stops; at an RH below 50%, growth also stops and high mortality occurs. In the case of flies, an RH above 90% or below 30% is detrimental to their life cycle; adults cannot survive below 5°C, while larvae and pupae are heat resistant up to −10°C. *Lucilia* (green flies) are resistant to 80°C. Flies can long remain in a state of lethargy. Beetles, although less frequent than insects, are a potential danger, as they can survive between 17 and 22°C. They are very sensitive to relative humidity; their egg survival is greater than 50% at 20°C, with an 8-day incubation cycle.

CHEMICALS

Curing

Basically, there are two curing methods: dry and wet (brine), although there are variations. Dry curing began as a method that used only salt, but today, a number of ingredients are used, mainly nitrites, phosphates, stabilizers, and flavorings. Curing salts are rubbed on the meat surface, and meat pieces are left standing for several days covered with the curing salts until they penetrate the tissue. The main advantage of this method is its ease of use; it requires only basic equipment and little quality control and is very safe to operate. However, depending on the region where it is used, appropriate facilities are necessary, such as the need for low relative humidity in the environment. This method had the disadvantage of requiring considerable labor and space to maintain the product immersed in the curing brine, the product flow is slow, and refrigeration is required occasionally.

The wet curing, or brine method, uses the same ingredients as for the dry method, but in this case the ingredients are dissolved in water. Therefore, water quality is fundamental; the water must have a low concentration of salts such as calcium, which can promote off-flavors. Meat is immersed in brine until it penetrates completely; immersion time depends on the type of product to be processed. At the industrial level, brine injection is carried out using multiple needles. Brine incorporation varies from 5 to 100% of the meat cut, depending on the product. Multiple-needle injection allows processing the cuts within a few hours; multiple needles also result in a uniform brine distribution within the cut,

providing homogeneous quality. Curing time also depends on brine concentration and temperature; with 25°C brines, stability is achieved in 48 h. As the concentration increases, the stabilization time decreases. Curing time can be reduced by increasing brine temperature above 40°C; however, at this brine temperature, proteins denature. pH also affects brine curing; at high pH, fibers undergo excessive swelling, preventing brine penetration as well as possible bacteria growth; the pH range recommended for curing is 5.8 to 5.9. Massaging during curing allows better curing salt penetration, rendering a more homogeneous product and making it possible to use brines with lower salt concentrations. Restructured product cohesiveness is increased, as massaging extracts proteins from the meat. A mixed curing method comprises massaging the meat surface with curing salts, then further immersion in brine.

Curing Ingredients

The main objective of using curing ingredients is to improve the sensory characteristics and to extend the product shelf life. The main sensory characteristics improved by curing are color, flavor, aroma, water-holding capacity, and stability, extending shelf life and improving sliceability. The main curing ingredients are described below.

Salt (NaCl) Initial curing operations used only salt, acting mainly on brine's osmotic pressure and decreasing water activity. The main effect of chlorine is against microorganisms, as an inhibitor of bacterial enzymes. However, salt can promote product dryness. Salt is used in 2.4% of products.

Nitrites In the United States and Mexico, sodium nitrite is allowed in meat products below 156 mg/kg, while *Codex Alimentarius* suggests a maximum residual limit of 125 mg/kg. The main role of nitrite is in color development; contribution to flavor; microbial growth inhibition, especially *Clostridium botulinum*; and oxidation delay. Nitrites, reaction product is nitrous oxide, which combines with myoglobin to produce the characteristic bright pink color of cured products and simultaneously inhibits microbial growth. Nitrites are rapidly depleted, however, and their efficiency is reduced. Indiscriminate use of nitrite results in white or green discoloration known as "nitrite burn." Nitrites inhibit *C. botulinum* when present at 100 ppm; they also produce the characteristic cured color at 5 ppm, although it is stable at 60 to 150 ppm. Cured flavor is produced with nitrites at 5 to 100 ppm. A controversial point in the use of nitrites is that they are precursors of nitrosamines, a carcinogenic compound formed at high temperatures, such as during frying.

Phosphates Phosphates are products of phosphoric acid partially or completely neutralized with alkali metal ions. There are two types of phosphates: acid and basic; the most widely used are the basic salts (calcium or potassium). These compounds are divided into two groups: orthophosphates (NaH_2PO_4), the most

common used; and condensed phosphates. Phosphates in solution are polyvalent anions, binding to sites with positive charges and interacting with muscle constituents; the main functional effects are to improve the emulsifying capacity effect and thus promote a tenderer product. Phosphates also increase protein solubility and act as an antioxidant and dispersing agent. They also improve the color, texture, and flavor of the meat product. But the main use of phosphates in the meat industry is to increase the water-holding capacity, thus controlling the loss of muscle fluids during the process. The legal phosphate concentration limit is 8000 mg/kg in the final product. The main problems associated with phosphates in meats are its off-flavor and the fact that it causes iridescence in the final product. Hexametaphosphate may reduce the formation of nitrosamines during frying.

Ascorbate Several reagents are used to accelerate the curing reaction; these are catalysts for color development reactions. The most widely used is sodium ascorbate; it also protects nitromyoglobina against discoloration; ascorbates are also used for emulsion stabilization. The maximum ascorbate concentration in meat products is 0.210 or 0.250 kg of ascorbic acid or sodium ascorbate, respectively, per 100 kg of product.

Sugar Sugar is an auxiliary curing agent, counteracting the harsh flavor of salt. It is also used in fermented products.

Liquid Smoke Liquid smoke is produced by distillation and fractionation of smoke's vapor-phase compounds, not including compounds in the smoke particle fraction. Liquid smoke does not contain hydrocarbons, but its phenol concentration is higher than in natural smoke. It is easier to apply than natural smoke, its concentration is easier to control, and it is environmentally acceptable and affordable. Liquid smoke products are of several forms:

- *Primary smoke*. With high concentration, this is used in very low proportions or is diluted.
- *Secondary smoke*. This is similar to primary smoke, but diluted. Nonetheless, it is a highly concentrated product, recommended for use only in low proportions, as a spray on the product; it provides a traditional smoked appearance.
- *Soluble smoke*. This is a water-based emulsified product; due to its high solubility, it can be included in the brine formulation.
- *Buffer smoke*. This is contained in a liquid base, at controlled pH. It prevents nitrite loss during curing.
- *Oil-based smoke*. The base is a vegetable oil; it gives fumes that provide desirable features to the product.
- *Powder smoke*. This allows direct flavoring to the product, or it can be added during emulsion formulations.

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IRRADIATION

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INTRODUCTION

Irradiation technology involves exposing foodstuffs to controlled amounts of ionizing irradiation to decontaminate them and is now considered to be one of the most effective methods of eliminating pathogens such as *Escherichia coli, Campylobacter*, and *Salmonella*. The process can also be used to control insects and parasites, to reduce spoilage, and to inhibit ripening and sprouting.

Handbook of Poultry Science and Technology, *Volume 1: Primary Processing*, Edited by Isabel Guerrero-Legarreta and Y.H. Hui

The overall hygienic quality of irradiated food is improved, while the treatment causes negligible detrimental effects on its nutritional value. For this reason, the irradiation of foodstuffs by ionizing radiation to control microorganisms and extend product shelf life has become a highly successful technique for preserving foodstuffs and food commodities worldwide (Henkel, 1998; Obana et al., 2005; Rababah et al., 2005; Balamatsia et al., 2006; Aymerich et al., 2008).

Irradiation was promoted by the Food and Agriculture Organization (FAO) in the *Codex Alimentarius* in 2003 and was accepted in 50 countries, especially in the United States, Latin America, Egypt, and China. Reluctance in consumer acceptance in Europe has postponed its application, for the moment allowing only dried aromatic herbs, spices, and vegetable seasoning to be irradiated, although on the approximation of national laws of the member states, the European Union (EU) commission has authorized the treatment of poultry products in some countries (EC, 1999a,b, 2001; Wai-mei sin et al., 2005; Aymerich et al., 2008).

The authorization of irradiation may affect the image of these products negatively, so hazard analysis and critical control points (HACCP) systems should have priority in hygiene control. The irradiation of fresh fruit and vegetables to inhibit sprouting and delay ripening might mislead consumers with regard to the age and freshness of products. Food irradiation must, therefore, never be used as a substitute for good hygiene practices, because it could lead to unfair trade practices (EC, 2001).

The irradiation of meat products results in a dose-dependent decrease in the total viable counts of pathogenic organisms. Irradiation in conjunction with chilled storage inhibits microbial growth and extends product shelf life without compromising product safety. For example, low-dose irradiation in combination with aerobic packaging has been shown to extend the shelf life of fresh chicken fillets compared to that of nonirradiated fillets. Thus, irradiation processing can be used to the advantage of processors, retailers, and consumers (Rababah et al., 2005; Sweetie et al., 2005).

The unit currently used for measuring absorbed radiation is the gray (Gy), which is 1 joule of energy absorbed per kilogram of absorbing material. The unit of absorbed radiation used previously was the rad, which is equal to 100 ergs absorbed per 100 g of absorbing material. One hundred rads is equal to 1 gray (Pauli, 1999).

FOOD IRRADIATION

Ionizing radiation occurs when one or more electrons are removed from the electronic orbital of an atom. It can be produced by three different techniques (Table 1):

1. *Gamma rays from the radionuclide* ^{60}Co or ^{137}Cs. In the industry, the majority of facilities use ^{60}Co because it produces stronger gamma rays and is insoluble in water.

TABLE 1 Depth and Efficiency of Three Ionized-Irradiation Technologies Used in Food Processing

	Gamma Ray	X-ray	E-Beam
Power source (kW)	50	25	35
Source energy (MeV)	1.33	5	5–10
Processing speed (metric tons/h)	12	10	5–10
Penetration depth (cm)	80–100	80–100	8–10
Dose uniformity ratio	1.7	1.5	Moderate
Dose rate (kGy/h)	Low	High	High

Source: Koutchma (2006).

2. *X-rays generated from machine sources operated at or below a maximum quantum energy level of 5 MeV*. This technique offers the possibility of processing packaged meat products in great quantities, although it requires high investment and maintenance costs.
3. *Electrons generated from machine sources operated at or below a maximum quantum energy level of 10 MeV*. Because electrons have a limited penetration capacity, this technique can be used directly for small items such as grains or to remove surface contamination (EC, 2001; Ahn and Lee, 2006; Aymerich et al., 2008).

For treatment, the food is packed in containers and moved by conveyer belt into a shielded room, where it is exposed briefly to a radiant-energy source, the level of energy depending on the food in question. Energy waves passing through the food disrupt the DNA molecular bonds in bacteria, fungi, parasites, insects, and other pathogens. Enzymes may also be denaturalized, and cell membranes may undergo alterations. Thus, due to their death or inability to reproduce, the numbers of these organisms are reduced considerably or even eliminated, although the quality of the food is left virtually unchanged. The effectiveness of the treatment depends on the dose absorbed, the sensitivity of the microorganism, the characteristics of the environment (e.g., pH, temperature), and the nature of the food (e.g., composition, additives, salt content) (Henkel, 1998; Aymerich et al., 2008). Years of research have proved the efficacy and safety of the food irradiation process to increase food quality, extend shelf life, reduce common food-spoilage organisms, and reduce the chances of illness because of postprocessing contamination.

Irradiation of food up to an overall dose of 10 kGy is accepted in several countries for commercial food processing. Many researchers have reported that gamma irradiation in doses below 10 kGy kills most organisms without harming food quality (Javanmard et al., 2006). The problem with food irradiation is that most meats develop detectable off-odors when irradiated at ambient temperature, but this can be avoided in high-moisture foods such as meat by irradiating them while frozen. A combination of gamma irradiation and frozen storage results in a significant reduction of bacterial growth and stabilizes the biochemical characteristics of food.

Irradiation doses of 5 kGy can be effective in the control of bacterial pathogens in chicken meat and extend its frozen shelf life to 9 months without producing any chemical or significant sensory changes to its quality. Therefore, this method will enable food processors to deliver larger amounts of high-quality chicken while improving the safety of its storage (Lacroix and Quattara, 2000; Johnson et al., 2004).

IRRADIATION OF CHICKEN MEAT

Reduction of Common Microorganisms

Irradiation is a well-known method of controlling microorganisms. In the food sector two processes are defined as irradiation:

1. *Radurization*, or radiation pasteurization, which is the inactivation of non-spore bacteria with a low absorbed-dose requirement (1 to 10 kGy).
2. *Radapperdization*, or sterilization irradiation, to ensure the elimination of *Clostridium botulinum*. The dose required is between 40 and 50 kGy, a dose much higher than that permitted for commercial food (10 kGy) (Aymerich et al., 2008).

The efficiency of irradiation in meat products and ready-to-eat meals has been proved and reported in a series of reviews and articles. In general, gram-negative bacteria are the most sensitive to irradiation, followed by gram-positive and molds. Yeast, spores, and viruses are, however, more resistant to irradiation. Low water activity (a_w) and low temperature promote resistance, while the presence of oxygen enhances irradiation action (Franqueira De Toledo et al., 2005; Horvatovich et al., 2005; Aymerich et al., 2008). Table 2 shows the effects of irradiation on the main microorganisms in poultry products.

Radiation doses required to inactivate 90% of colony-forming units of the most common foodborne pathogens associated with meat and meat products are in the range 1 to 4 kGy. In addition to spoilage bacteria, meat products may contain parasites and pathogenic bacteria, which can be eliminated by irradiation (Sweetie et al., 2005). Irradiation may effectively control the presence of all the main foodborne pathogens, such as *Escherichia coli* O157:H7, *Listeria monocytogenes, Staphylococcus aureus, Salmonella* spp., and *Trichinella spiralis*, as well as yeasts and molds. Thus, low-dose irradiation kills microorganisms of significance to public health and extends the shelf life of meat products (Farkas, 1998; Ahn et al., 2006; Aymerich et al., 2008).

According to Min et al. (2007), irradiation at 0.5 kGy resulted in a 2-log reduction in *Bacillus cereus, Enterobacter cloacae*, and *Alcaligenes faecalis* in both raw chicken breast and thigh meat. No viable cells were counted below 100 CFU/g when raw chicken breast and thigh meat were irradiated at 2 kGy, whereas a dose of 2.0 to 5.0 kGy of irradiation was required to destroy the vegetative *B. cereus*. Gamma irradiation was not very effective against gram-positive,

TABLE 2 Effects of Irradiation on Various Microorganisms According to the Dose

Bacterium	Dose	Effect	Reference
All	1–4 kGy	Inactivates 90% of the colony	Farkas (1998)
Bacillus cereus	0.5 kGy	2-log reduction	Min et al. (2007)
	2 kGy	<100 CFU/g no viable cells	Min et al. (2007)
	2–5 kGy	Destroyed	Min et al. (2007)
	2% acetic acid + 3 kGy	Significant reduction	Min et al. (2007)
Enterobacter cloacae	0.5 kGy	2-log reduction	Min et al. (2007)
	2 kGy	<100 CFU/g no viable cells	Min et al. (2007)
Alcaligenes faecalis	0.5 kGy	2-log reduction	Min et al. (2007)
	2 kGy	<100 CFU/g no viable cells	Min et al. (2007)
Staphylococcus aureus		D_{10} values 0.36 kGy	Min et al. (2007)
Clostridium sporogenes		D_{10} values 3 kGy	Min et al. (2007)
E. coli	0.75 kGy	46.6% *E. coli* positive	Javanmard et al. (2006)
	3–5 kGy	Not detected	Javanmard et al. (2006
Staureus	1 kGy	2-log cycle reduction	Shay et al. (1988)
Salmonella	>2.5 kGy	Complete elimination	Al-Masri and Al-Bachir (2007)

spore-forming bacteria such as *B. cereus* and *Clostridium* spp. The radiation sensitivities of *S. aureus, Clostridium sporogenes*, and *B. cereus* in intermediate-moisture mutton kebabs were studied by Chawla and Chander (2004). As in chicken, the D_{10} values of these microorganisms were 0.36, 3.0, and 0.29 kGy, respectively. A 2.5-kGy irradiation dose resulted in the complete elimination of *S. aureus* and *B. cereus* inoculated at 10^6 CFU/g. Acid presensitization to low-dose gamma irradiation (e.g., 2% acetic acid pretreatment followed by 3 kGy of irradiation) resulted in significant *B. cereus* reduction in sheep and goat meat (Shay et al., 1988; Bhide et al., 2001).

The effects of gamma irradiation of whole chicken carcasses and its effect on extending shelf life when combined with freezing was studied by Javanmard et al. (2006). They found that the number of aerobic plate counts decreased concomitantly with an increase in the irradiation dose and during storage time. Mean bacterial loads and coliform counts were high in nonirradiated control samples.

An irradiation dose of 2.0 kGy (or higher) inactivated 99% of the microbial content of chicken carcasses. Irradiation of fresh chicken and meat products with doses of 2.5 kGy was effective in reducing *Salmonella* contamination, although a higher dose was required for its complete elimination in chicken (Sanos et al., 2003). On the other hand, irradiation at 1.5 and 3 kGy significantly reduced the counts of aerobic mesophilic bacteria, psychophysics bacteria, molds, and yeasts. These treatments also prolonged the shelf life of refrigerated samples to 12 and 21 days for 1.5 and 3 kGy treatment, respectively, compared to 6 days for nonirradiated controls (Franqueira De Toledo et al., 2005).

Physicochemical Effects

Undesirable physicochemical and sensory quality changes, such as lipid oxidation, off-flavor, and a pink/red color, may occur during irradiation, all of which affect product quality and acceptability by the consumer. According to Franqueira De Toledo et al. (2005), compared with nonirradiated chicken meat, irradiated meat when stored showed a slight increase in lipid peroxidation in terms of thiobarbituric acid values. The presence of oxygen was the most critical factor influencing lipid oxidation during the storage of irradiated meat. Lipid oxidation and the discoloration of meat are increased in the presence of oxygen, although the antimicrobial action of irradiation is enhanced (Lacroix et al., 1991). In the presence of oxygen, polyunsaturated fatty acids undergo autoxidation. The overall result is a chain reaction that occurs in three phases: the initiation or formation of free radicals; propagation; and finally, the termination or formation of nonradical products. Free radicals can react with oxygen, causing the formation of hydroperoxides, which will yield a great variety of compounds, such as alcohols, aldehydes, hydrocarbons, keto acids, and ketones. This leads to the formation of warmed-over flavors and the destruction of essential fatty acids and some fat-soluble vitamins (Giroux and Lacroix, 1998).

Irradiation in the presence of oxygen accelerates the autoxidation of fats by one of the following three possible reactions:

1. Formation of free radicals, which combine with oxygen to form hydroperoxides
2. Breakdown of hydroperoxides
3. Destruction of antioxidants

According to Johnson et al. (2004), when chicken meat was irradiated at 5 to 10°C, there was a threshold dose of 2.5 kGy, resulting in a slight irradiation flavor. Doses from 2.5 to 5.0 kGy were observed to produce a slight irradiation odor that dissipated during 4 days of storage, after which a fresh chicken odor reappeared. Volatile compounds associated with irradiation odor were dissipated from mechanically deboned, irradiated chicken-meat samples during refrigerated storage. Irradiated samples had a more pronounced oxidation odor than that of nonirradiated samples (De Azevedo Gomes et al., 2003). Nevertheless,

other studies showed no significant changes in meat lipids at low irradiation doses (<10 kGy). According to Javanmard et al. (2006), there was no significant relationship in peroxide and iodine values when the irradiation dose level was increased from 1 kGy to 10 kGy in breast chicken meat (Al-Masri and Al-Bachir, 2007).

The irradiation of poultry meat products under anaerobic conditions not only provides a longer shelf life but also prevents off-flavors and odors because of the absence of oxygen necessary to form peroxides. Sensory quality can also be maintained by irradiating them while frozen (Johnson et al., 2004). Hence, irradiating meat in a frozen state or in a modified atmosphere, packing/vacuum packaging, or adding antioxidants can minimize or prevent the development of rancidity (Kanatt et al., 1997; Al-Masri and Al-Bachir, 2007).

Sensory Effects

Irradiated meat will be successful in the marketplace only if consumers are satisfied with its sensory quality. Alterations to the texture, color, rancidity, and odor of irradiated foods can be eliminated at the time of irradiation with low temperatures, the application of absorbent substances, and the use of condiments (Fernández-Ginés et al., 2002). Gamma irradiation of chicken meat, either marinated or vacuum treated, had no significant effects on the initial sensory attributes of the raw meat samples. Panelists gave similar preference scores for irradiated and nonirradiated samples, which indicated that all were highly acceptable as far as their appearance and odor were concerned. Moreover, both irradiated and nonirradiated samples gave similarly acceptable scores for sensory attributes during refrigerated storage until rejection. Panelists' scores for odor, flavor, and color intensity were neutral for both control and irradiated samples (Mahrour et al., 2003; Johnson et al., 2004; Javanmard et al., 2006).

After a sensory analysis of irradiated, fresh, and stored frozen chicken breast, Franqueira de Toledo et al. (2005) concluded that:

1. The fresh chicken breast samples were negatively affected by the irradiation treatment, which left them shredded and spotted, as well as less fresh and typical. Their color was more intense after irradiation. The irradiated samples took on a strange smoked, salty flavor and became less tender, moist, and juicy.

2. For the frozen stored samples of chicken breast, the sensory modifications produced by the irradiation treatment improved the appearance, aroma, and flavor. The 8-kGy dose differed the most from the nonirradiated control, and changes were positive in some cases, mainly when the meat was frozen afterward.

As far as chilled chicken is concerned, immediately after irradiation the appearance, flavor, and texture of the irradiated samples were no different from the nonirradiated control, and all the samples were acceptable. Irradiation extended

the life of chicken carcasses in cold storage without any notable deterioration in organoleptic quality. In general, no change could be perceived before or after roasting the meat or on storing it at 1 to 4°C (Lacroix et al., 1991; Mahrour et al., 2003; Franqueira De Toledo et al., 2005). Irradiating uncooked chicken produced a sweet, bloody aroma that remained after the meat was cooked. The ratings for overall acceptance toughness, flavor, and texture were equal for irradiated and nonirradiated fresh meat (Rababah et al., 2005).

Selected natural antioxidant extracts have been used to reduce the development of warmed-over flavor in cooked breast meat and assessed by sensory analysis. Green tea and grapeseed extracts have been described by Rababah et al. (2005) as having antioxidant properties. Irradiation with the addition of a combination of these extracts increased the toughness and cohesiveness and decreased moisture release. Infusing plant extracts into skinless, boneless chicken breasts proved to be an effective technique for minimizing undesirable changes in sensory properties during irradiation. Consumer and instrumental measurements indicated that whereas irradiation decreased tenderness, infusion increased tenderness, and the addition of grapeseed extract increased the darkness and redness of the samples. Infusion of chicken meat with 3000 ppm green tea extract effectively combated any negative sensory changes caused by irradiation.

Nutritional Effects

In general, low-dose irradiation is associated with insignificant changes in proteins, amino acids, and fats. Oxidative and nonoxidative changes in lipids can be observed. Ionizing radiation causes the radiolysis of water, which is present to a great extent in meat. This generates free radicals, which react with food constituents, initiating a chain reaction that produces even more free radicals. The most susceptible site for free-radical attacks in a lipid molecule is at a double bond. Thus, the lipids most affected during irradiation are the polyunsaturated fatty acids. In general, the concentration of unsaturated fatty acids decreases concomitantly with increases in radiation doses; conversely, the concentration of saturated fatty acids increases as radiation doses rise (Lacroix et al., 1991; Poste et al., 1991; Giroux and Lacroix, 1998; Mahrour et al., 2003).

Marinating has the potential to control oxidation of unsaturated fatty acids in chicken. The antioxidant properties of a thyme and rosemary marinade reduced the generation of initial free radicals in the fatty acids and caused a substantial reduction in volatile hydrocarbons generated by between 3 and 9 kGy radiolysis of unsaturated fatty acids (Mahrour et al., 2003).

Irradiation of raw chicken either in air or under vacuum favored oxidation of unsaturated fatty acids into lower-carbon-number saturated fatty acids. The significant interactions between radiation doses and pretreatment suggest that the effect of radiation doses on the concentration of fatty acids depends on the pretreatment in question. A combination of marinating and vacuum packaging might be a good alternative for controlling oxidation and degradation of high-carbon-number unsaturated fatty acids during the irradiation of chicken (Lacroix et al., 1991; Mahrour et al., 2003).

Similar to lipids, protein damage due to irradiation is catalyzed by free radicals formed by the radiolysis of water. Damage includes deamination, decarboxylation, the reduction of disulfide linkages and oxidation of sulfydryl groups, breakage of peptide bonds, and changes in the valency states of the coordinated metal ions in enzymes. Nevertheless, these changes take place at much higher doses than those permitted in food products (<10 kGy). With the low doses used, the range of possible chemical and physical changes is similar to that seen with other treatments of foodstuffs (Giroux and Lacroix, 1998).

Although there are no significant changes to the macronutrients at low levels of radiation, γ-tocopherol was found to be sensitive to radiation. Tocopherol is the most labile of the fat-soluble vitamins. γ-Tocopherol has been found to be more stable than α-tocopherol against the effects of ionizing radiation in food and to autoxidation, whereas α-tocopherol is the most labile to oxidation. Therefore, it is not surprising that the effects of radiation upon γ-tocopherol in muscle tissue were less pronounced than on the α isomer. The loss of unesterified tocopherols in chicken breast muscle at 3.0 kGy was found to be 15 and 30% for the γ and α isomers, respectively (Lakritz and Thayer, 1994).

Lakritz and Thayer (1994) concluded that there was only a 6% loss in the tocopherols, the most labile of the fat-soluble vitamins, when chicken breast muscle was irradiated at 3 kGy. The minimal loss of tocopherols is significant in that it indicates that there would also only be a negligible reduction in the levels of the other more stable fat-soluble vitamins (A, D, K). In addition, the shelf stability of poultry against autoxidation should not be compromised by processing with gamma radiation since the process resultes in only a minor reduction in the total tocopherols (Giroux and Lacroix, 1998).

Meat can be a significant source of thiamin. In has been shown that thiamin is the most irradiation-labile water-soluble vitamin. Oxidative damage is responsible for its loss. These vitamin contents are, however, much more affected by the temperature of the meat during irradiation than by the irradiation process itself. Other soluble vitamins, such as riboflavin and niacin, are stable during irradiation (Giroux and Lacroix, 1998; Chung and Yook, 2003).

The effects of irradiation and storage of chicken meat on the heme iron, nonheme iron, and total pigment contents were investigated by Marques de Souza et al. (2007). Chicken thighs and breast were irradiated (0-, 1-, and 2-kGy doses) and then refrigerated for 14 days at 4°C. Levels of heme iron were influenced by both irradiation and storage, falling during the storage period. The nonheme iron content was also influenced by the irradiation dose and length of storage, but this time increasing as the storage period progressed, due to the conversion of heme iron into nonheme iron.

Lee et al. (2003) studied raw and cooked samples of chicken thigh packaged under aerobic or vacuum conditions, irradiated by an electron beam, and analyzed them for the formation of cholesterol oxidation products after 0 and 7 days of storage. 7β-Hydroxycholesterol, α, β-epoxide, cholestanetriol, and 7-ketocholesterol were detected in raw, irradiated chicken meat samples from the

onset of storage, and their concentrations were significantly higher in aerobically packaged samples than in vacuum-packaged samples. The concentration of cholesterol oxidation products also increased with storage time. Both cholesterol oxidation and lipid oxidation products in cooked chicken subjected to irradiation increased significantly with storage time for all treatments, although the values were significantly lower with vacuum packaging than with aerobic packaging. It may be concluded, therefore, that the formation of cholesterol oxidation products and lipid oxidation products is controlled more by packaging conditions than by irradiation.

PROTOCOLS FOR THE DETECTION OF IRRADIATED FOODS

The development of analytical methods for the correct identification of irradiated food samples is important for upholding regulatory controls, checking compliance with labeling requirements, facilitating international trade, and reinforcing consumer confidence. Since an agreement on promoting food irradiation adopted by delegates from 57 countries at the International Conference on the Acceptance, Control of, and Trade in Irradiation Foods in 1988, the governments involved have given their full support to intensive research into the detection of irradiation. Significant progress in irradiation detection has been achieved in the past decade through national and international collaborative programs. Reliable routine methods to confirm the irradiation history of foods would help in the enforcement of labeling regulations and encourage consumers to accept food irradiation. Various methods have been proposed to detect irradiated foodstuffs (Toyoda and Miyahara, 1998; Pauli, 1999; Obana et al., 2005; Wai-mei Sin et al., 2005). Since 1996, the European Committee for Standardization (CEN) has published 10 official protocols for the detection of irradiated foods: EN1784 to EN1788, EN13708, EN13751, EN13783, EN13784, and EN14596, thus enabling food-quality-control laboratories to distinguish between an irradiated and a nonirradiated foodstuff. These tests now allow for the control of international trade with regard to appropriate legal labeling, thus giving consumers a guarantee of freedom of choice (CEN, 1996, 2000, 2004; Wai-mei Sin et al., 2005; Horvatovich et al., 2006).

Table 3 is a summary of 10 official protocols for the detection of irradiated food. Of these methods, analyses of 2-alkylcyclobutanones and volatile hydrocarbons during irradiation of fat-containing foods have been accepted by the European Committee for Standardization. 2-Alkylcyclobutanones (2-ACBs) are formed from triglycerides by irradiation treatment and may be used as markers for this type of food processing. Nevertheless, the analytical method EN 1785, which has been adopted in European countries as an official method, requires lengthy sample preparation consisting of two stages: fat extraction by the Soxhlet method for 6 h, and Florisil column chromatography for cleanup, which takes considerable time and requires large quantities of solvents. To reduce the extraction time and encourage selective extraction for 2-alkylcyclobutanones, supercritical fluid extraction (SFE) has been adopted instead of Soxhlet extraction and has succeeded in greatly reducing extraction time, to about 30 to 60 min. The method

TABLE 3 Official Protocols for the Detection of Irradiated Food Approved by the European Committee for Standardization

Standard No.	Title	Date of Publication	Description
EN13708:2002	Foodstuffs. Detection of irradiated food containing crystalline sugar by ESR spectroscopy.	1/14/02	Food products; dried fruit; irradiated foods; processed foods; sugar (food); crystals; food testing; chemical analysis and testing; electron spin resonance (ESR) spectroscopy; spectrochemical analysis; spectroscopy; ionizing radiation
EN13751:2002	Foodstuffs. Detection of irradiated food using photo-stimulated luminescence.	10/15/02	Food products; food testing; irradiated foods; processed foods; luminescence; luminous intensity; optical measurement; chemical analysis and testing
EN13783:2002	Foodstuffs. Detection of irradiated food using direct epifluorescent filter technique/aerobic plate count (DEFT/APC). Screening method.	1/24/02	Food products; food technology; food testing; irradiated foods; microbiological analysis; biological analysis and testing; counting methods (microbiology); herbs, spices
EN13784:2002	Foodstuffs. DNA comet assay for the detection of irradiated foodstuffs. Screening method.	1/31/02	Food products; irradiated foods; processed foods; food testing; biological analysis and testing; chemical analysis and testing; deoxyribonucleic acid
EN14596:2005	Tanks for transport of dangerous goods. Service equipment for tanks. Emergency pressure relief valve.	4/21/05	Tanks (containers); dangerous goods transportation; relief valves; safety valves; valves; filling devices; dangerous materials; liquids; petroleum products; freight transport; road transport; dimensions; type testing; performance testing

(*continued overleaf*)

TABLE 3 (*Continued*)

Standard No.	Title	Date of Publication	Description
EN1784:2003	Foodstuffs. Detection of irradiated food containing fat. Gas chromatographic analysis of hydrocarbons.	8/12/03	Food products; fats; lipids; ionizing radiation; chemical analysis and testing; food testing; determination of content; radiation-induced chemical reactions; aliphatic hydrocarbons; gas chromatography; fatty acids; fat extraction methods; preserved foods
EN1785:2003	Foodstuffs. Detection of irradiated food containing fat. Gas chromato-graphic/mass spectrometric analysis of 2-alkylcyclo-butanones.	8/12/03	Food products; fats; lipids; ionizing radiation; chemical analysis and testing; food testing; determination of content; radiation-induced chemical reactions; methyl ethyl ketone; alkyl compounds; gas chromatography; fatty acids; fat extraction methods; Pr
EN1786:1997	Foodstuffs. Detection of irradiated food containing bone. Method by ESR spectroscopy.	6/15/97	Food products; preserved foods; ionizing radiation; meat; meat products; fish (meat); bones; contaminant determination (food); electron spin resonance spectroscopy; spectrochemical analysis; food testing; radiation-induced chemical reactions; chemical analysis
EN1787:2000	Foodstuffs. Detection of irradiated food containing cellulose by ESR spectroscopy.	10/15/00	Food products; irradiated foods; cellulose; electron spin resonance spectroscopy; chemical analysis and testing; ionizing radiation; spectrochemical analysis; radiation-induced chemical reactions; food testing; food technology; pistachio nuts; nuts (food)

TABLE 3 (*Continued*)

Standard No.	Title	Date of Publication	Description
EN1788:2001	Foodstuffs. Thermoluminescence detection of irradiated food from which silicate minerals can be isolated.	12/3/01	Food products; preserved foods; ionizing radiation; herbs; spices; shrimps; fruits; vegetables; potatoes; dried foods; food testing; radiation-induced chemical reactions; silicate minerals; silicates; contaminant determination (food); chemical analysis

Source: Data from EN1784–EN1787 (1996), EN13708, EN13751, EN13783, EN13784 (2000); EN14569 (2004).

has been tested on chicken meat in interlaboratory trials. Other studies suggest that the method is applicable to a wide range of foodstuffs (CEN, 1996; Ndiaye et al., 1999; Horvatovich et al., 2000, 2006; PKN, 2003; Obana et al., 2005).

Electron paramagnetic resonance (EPR) spectroscopy is a versatile technique for detecting free-radical signals induced by high-energy irradiation in the bones of chicken, pork, beef, lamb, fish, and mollusk shells. After a significant decrease of about 20% in the first 2 days, the EPR signals of irradiated chicken and pork bones (1 kGy) remained fairly constant. Similar losses of the EPR signals in these two matrices were not observed when the ionization dosage was increased to 3 and 5 kGy. Statistical changes were not noted in other dosed samples within a 2-month storage period at ambient temperature. The intensity of the signals in all samples was found to increase concomitantly with the irradiation dose. Results of the dose–response relationships established using blind samples clearly showed that EPR spectroscopy was a promising technique for providing accurate, rapid, convenient quantitative measurements of irradiated samples of the food types under study (De Azevedo Gomes et al., 2003).

Solid-phase extraction (SPE) is the most popular technique used for sample pretreatment prior to gas chromatographic analysis and has many advantages, such as the need for less organic solvent, less time, and ease of automation; it is also more cost-effective. The hydrocarbons in the irradiated chicken were isolated by the SPE method. Hexanal, octanal, nonanal, 2,4-decadienal, and γ-butyrolactone are the main volatile compounds produced by the oxidation of lipids in raw chicken thighs. Other nonidentified volatile compounds were detected as the gamma-radiation dosage increased. There was a clear sigmoid relationship between the gamma-radiation dosage and volatile hexanal (Whitcomb and Campiglia, 2001; Theodoridis and Manesiontis, 2002; Kima et al., 2004; Thomazini et al., 2006).

Another method is electron spin resonance (ESR) spectrometry, which involves measuring the hydroxyapatite or cellulose radicals in food samples.

Irradiation produces many radicals in foods, some of which, when trapped in bone hydroxyapatite, are fairly stable and can easily be detected several years after irradiation. In principal, ESR spectroscopy is very sensitive and reliable. It is used, for instance, with alanine as the standard dosimetric method for correcting irradiation machine power (10 Gy to 100 kGy). The alanine dosimetric system is the method adopted to test irradiation equipment according to standards established by Japanese Industrial Standards (JIS). But practically, the detection limits in foods are higher than those expected. These problems arise from the nature of radicals themselves: ESR signals are easily reduced if the foods are stored at high temperature under humid conditions; contaminants also produce radical signals that interfere with the analysis; the signal may well disappear inadvertently during pretreatment for analysis. Practically speaking, this method can identify only a few types of irradiated foods and needs 2 or 3 days to produce results. Notwithstanding, the IAEA and British Standards Institute (BSI) recognize the ESR methods as qualitative analytical testing methods (BSI, 2000a,b; JIS, 2001; Miyahara et al., 2002).

Several reports have addressed the o-tyrosine evaluation method. *o*-Tyrosine is a radiolytic product of phenylalanine, which exists widely in food samples. Therefore, irradiated foodstuffs that contain proteins can be detected by this method (i.e., the *o*-tyrosine detection method can be used to detect a much wider range of irradiated food than that detectable by ESR methods) (Miyahara et al., 2000, 2002).

LEGISLATION

The U.S. Food and Drug Administration (FDA) has approved the irradiation of meat and poultry. Food irradiation is allowed in nearly 40 countries and is endorsed by the World Health Organization, the American Medical Association, and the European Parliament, among many other organizations. In the United States, poultry products are also subject to the Poultry Products Inspection Act. Thus, anyone intending to irradiate meat or poultry is also subject to the regulatory authority of the Food Safety and Inspection Service of the U.S. Department of Agriculture (USDA). The FDA currently requires that irradiated foods be labeled with either the statement “treated with radiation” or “treated by irradiation” and the radura, the international symbol for irradiation (Figure 1). If irradiated ingredients are added to foods that have not been irradiated, no special labeling is required on retail packages because it is obvious that such foods have been processed. Nevertheless, special labeling is required for foods not yet on the retail market that may undergo further processing to ensure that foods are not irradiated more often than is necessary or legally possible. When passing this regulation the FDA advised that other truthful statements, such as the reason for irradiating the food, could be added to the statement and encouraged food manufacturers to do so. It approved the first use of irradiation on a food product in 1963, when it allowed radiation-treated wheat and wheat flour to be marketed.

FIGURE 1 The radura, international symbol of irradiation.

TABLE 4 Authorized Uses of Radiation at the Given Maximum Dose

Product	Country	Dose (kGy)
Chicken meat	The Netherlands	7
Poultry	Finland	5
Poultry (domestic fowls, geese, ducks, guinea fowls, pigeons, quails, and turkeys)	UK	7
Mechanically recovered chicken meat	Finland	5
Chicken offal	Finland	5

Source: EC (2001).

When approving any particular use of radiation, the FDA sets the maximum radiation dose to which the product can be exposed. Table 4 lists all approved uses of radiation on foods to date and the radiation dose allowed (Henkel, 1998; Pauli, 1999).

EU legislation is based on Directive 1999/2/EC of February 22, 1999 on the approximation of the laws of the member states concerning foods and food ingredients treated with ionizing radiation, and on Directive 1999/3/EC, on the establishment of a community list of foods and food ingredients treated with ionizing radiation. The food irradiation directives 1999/2/EC and 1999/3/EC became applicable on September 20, 2000. Since March 20, 2001, all irradiated foods and food ingredients on the market in the EU must comply with the provisions of these directives, which apply to the manufacturing, marketing, and importation of foods and food ingredients treated with ionizing radiation.

Conditions for Authorizing Food Irradiation (EC, 1999b)

1. Food irradiation may be authorized only if:
   - There is a reasonable technological need.
   - It presents no health hazard and is carried out under the conditions proposed.
   - It is of benefit to the consumer.

- It is not used as a substitute for hygiene and health practices or for good manufacturing or agricultural practice.

2. Food irradiation may be used only for the following purposes:
   - To reduce the incidence of foodborne disease by destroying pathogenic organisms.
   - To reduce spoilage of foodstuffs by retarding or arresting decay processes and destroying spoilage organisms.
   - To reduce loss of foodstuffs by premature ripening, germination, or sprouting.
   - To rid foodstuffs of organisms harmful to plants or plant products.

Only a single food category is listed on the EU-wide positive list for irradiation treatment: "dried aromatic herbs, spices and vegetable seasonings." A requirement was introduced in Directive 1999/2/EC that the EC should forward a proposal by December 31, 2000 to complete this community-positive list of foodstuffs authorized for irradiation, to be adopted through the co-decision procedure. Meanwhile, member states can maintain existing national authorizations for the irradiation of certain foodstuffs and can continue to apply existing national restrictions or bans in compliance with the treaty.

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PART V

COMPOSITION, CHEMISTRY, AND SENSORY ATTRIBUTES

24

QUALITY CHARACTERISTICS OF POULTRY PRODUCTS

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INTRODUCTION

Poultry consumption has more than doubled over the last 40 years and continues to grow. In the 1970s the average person consumed 48.4 lb of poultry every year (National Chicken Council, 2007a). In 2008 that number was projected to be 102.7 lb per person according to the Economic Research Service and the United States Department of Agriculture (USDA). Of this total, it is predicted that 86.2 lb will be chicken and 16.5 lb will be turkey.

According to the National Chicken Council (2007c), *poultry* is defined as any type of domesticated fowl raised for meat and/or eggs. Chicken and turkey are among the most commonly consumed types of poultry. Other types of

Handbook of Poultry Science and Technology, *Volume 1: Primary Processing*, Edited by Isabel Guerrero-Legarreta and Y.H. Hui

poultry that are available for consumption include duck, geese, guineas, and pigeons. Within each poultry group are individual classes according to age and weight.

All chickens raised for consumption are produced to meet specific requirements of the customer. Chickens for consumption can weigh anywhere between 2 and 11 lb and be 5 to more than 10 weeks of age (USDA, 2007). Typical retail cuts of chicken come from birds referred to as "3's and up," a term used by the industry referring to a bird that weighs 3 lb or more. These birds usually come with the neck and giblets and are between 40 and 45 days of age. A bird of this same size is sold in the retail market as a whole bird. Birds produced for the fast-food market can weigh 2 lb 4 oz to 3 lb 2 oz and are usually sold as cut-up pieces, without necks and giblets, and may have tail and leaf fat removed. Another class of chicken consumed is a capon. These birds were once consumed regularly but are a specialty item in today's market. A capon is a surgically desexed male broiler that can weigh anywhere between 7 and 9 lb, and is about 14 to 15 weeks in age. What makes this class of chicken a specialty item is that it is plump and tender compared to other classes, due primarily to its age (National Chicken Council, 2007b).

The poultry market has grown substantially due to various marketing practices, such as selling individual cuts. A prime example of this is the chicken wing, which has become very popular in recent years. In 2007, 2.25 billion pounds of chicken was marketed solely as wings (National Chicken Council, 2007c). Another reason for the increased popularity of poultry is its low fat and cholesterol contents. White meat from the breast with the skin removed is a very lean cut. Poultry products are especially lean compared to other animal products, such as pork or beef.

Turkey was once thought to be solely a holiday product that was in demand only a few times in a year. The turkey industry is now a booming business that offers more than the conventional whole bird. Now, whole breasts, breast cutlets, tenderloins, and legs, along with ground turkey, are seen regularly in retail stores. The popularity of these products has made them a competitor of other protein products year round. Turkey consumption has increased more than 100% since the 1970s, and production has doubled to accommodate this increase (National Turkey Federation, 2006).

Consumer interest in natural or organic products is increasing at a fast rate and has contributed to the increase in poultry consumption. Some consumers believe that natural or organic products have a superb quality, far above that of traditional products. Many poultry producers have met consumer needs by producing new products, such as antibiotic- or hormone-free meat. Another facet of which some consumers are conscious is whether or not birds are raised by the free-range method or by more traditional means. Many retail packages have the "free range" claim right on the product. There are many critera that drive a consumer decision to purchase certain products, including appearance, taste, aroma, and texture.

SENSORY ATTRIBUTES OF POULTRY PRODUCTS

Color Characteristics

Color is a very important quality attribute considered by consumers when choosing a meat product. Poultry skin and muscle color are affected by a variety of factors, including age, environment, diet, and feed withdrawal. The color of poultry skin can vary from cream-colored to yellow. The color of raw muscle ranges from pink to red due to hemoglobin and myoglobin within the muscle. The more a muscle is used, the more myoglobin is present in the muscle. When cooked, the meat from frequently used muscles is known as dark meat. Dark meat typically comes from the legs or thighs of a bird. Muscles that are used less, like the breast, are lighter in color and thus referred to as light meat.

The color of both muscle and skin is greatly affected by the type of feed the bird consumes. Feed used in the industry consists of various seeds and grains, which all contain certain levels of carotenoids. Carotenoids provide pigmentation in skin and muscle and are used regularly in industry (Koutsos et al., 2003). The effect of diet on the color of breast fillets was evaluated by formulating the diet of 28-day-old broilers with three different carbohydrate sources in a study by Lyon et al. (2004). Each diet consisted of either corn, milo, or wheat as the primary carbohydrate source added to a base feed. The level of carbohydrate incorporated into the base feed was 69.5% corn, 69.7% milo, and 73.6% wheat. The birds fed strictly wheat diets tended to have breast fillets that were lighter in color, whereas birds fed strictly milo seed diets tended to have fillets that were more red. Birds on strict corn diets tended to have breast fillets that were slightly yellow in color (Lyon et al., 2004).

The addition of a dietary supplement to feed can also affect the color of muscle. A study done by Du and Ahn (2002) evaluated the effect of conjugated linoleic acid (CLA) on the color of meat. Three-week-old broilers were fed diets containing 0, 0.25, 0.5, or 1% CLA for 3 weeks in experiment 1, while 3-week-old broilers were fed diets containing 0, 2, or 3% CLA for 5 weeks in experiment 2. Cooked meat from broilers fed 2% and 3% conjugated linoleic acid had darker breast muscles with decreased redness. The changes in color were attributed to decreased levels of unsaturated fatty acid in meat from broilers fed CLA.

Another important factor affecting color is the pH of the meat. Lower pH levels in the muscle are associated with lower water-holding capacity, due to alterations in the structure of myofibrils within the muscle when in a low-pH environment. If a muscle can hold more water, it typically will be lighter in color. Broilers produced by organic methods had a lower pH and a lower water-holding capacity, which may have been responsible for producing meat that appeared more yellow as well as less red than broilers produced by a traditional system (Castellini et al., 2002).

Processing has a significant influence on color. Feed withdrawal, irradiation, and chilling times are some of the processes that affect color. Feed withdrawal is the time from when the bird last has access to feed to the time of slaughter. Feed withdrawal stresses the bird physically, due to the short-term lack of nutrients

available, which reduces the glucose available. This can ultimately lead to a change in muscle and skin color as a result of a drop in pH. The feed withdrawal time period usually ranges from 0 to 8 h. To observe how feed withdrawal affects color, Smith et al. (2002) placed broilers on diets at 28 days of age. The broilers were separated into three different groups and assigned a diet with a strict carbohydrate source. The diet regimen included either a corn, wheat, or milo diet. All feed was withdrawn 12 h prior to slaughter. The feed withdrawal increased fillet lightness significantly, from an average of 46.1 to 48.9, decreased redness from 4.1 to 3.1, and increased yellowness from 2.8 to 3.7. Raw broiler breast fillet color was affected significantly by both diet and feed withdrawal. The longer this time period, the lighter (*L* value) and less red (*a* value) the muscle was, with the skin of these birds being significantly more yellow (*b* value) (Smith et al., 2002).

Stunning is an premortem procedure used to immobilize a bird for automated killing and to render it insensible to pain or stress (Sams, 1999). Electrical stunning is the most used stunning method because it is inexpensive, convenient, and safe (Fletcher, 1993), while an alternative form, gas stunning, is available. After stunning, birds are "bled out" by cutting the neck to allow the blood to drain. A delay in doing so can result in increased discoloration in breast muscle color. The frequency of the current used during electrical stunning in combination with the amount of bleed-out can have a significant effect on development of discoloration. In a study by Raj et al. (2001), broiler chickens were stunned for 1 s. The neck was cut and the bird was bled at 20, 60, or 180 s postmortem. When neck cutting was performed 20 s postmortem, there was less bleed-out. Neck cutting at 20 or 60 s postmortem resulted in a greater bleed-out than when performed 180 s postmortem. Delayed neck cutting (180 s) increased the occurence of discoloration in breast muscles.

Another processing procedure that influences the quality of meat is carcass chill time. If the carcass is not chilled down within a reasonable amount of time, there are many defects in the muscle that may occur. A rapid chilling time can ensure that no defects are present. Postmortem, biochemical changes occur in the muscle that cause rigor mortis to develop along with a drop in pH. The decline in pH is a result of lactic acid being produced in the muscle when oxygen is not available. If the pH of the muscle declines rapidly while the temperature of the carcass is still high, there will be protein denaturation in the muscle fibrils, causing the meat to be pale. This defect, known as *pale, soft, and exudative* (PSE) *meat*, is a growing problem in the turkey and poultry industry. It has been reported by several investigators that the incidence of PSE in meat from broiler chickens can range from 0 to 28% to as high as 47% (Barbut, 1997; Woelfel et al., 1998, 2002). The paleness occurs due to increased sarcoplasmic protein denaturation, which in turn leads to increased scattered light, causing the meat to be lighter (Sams, 2004).

A relatively new preservation method, irradiation, is used to reduce microbial numbers. Although this method is an excellent way to control foodborne illnesses typically associated with poultry, it does influence the color of poultry meat. The change in color depends on the species, irradiation dose, muscle type, and

packaging environment (Ahn et al., 1998). In a study done by Nam and Ahn (2002), aerobically and vacuum-packaged turkey breasts received irradiation at three different doses (0, 2.5, or 5.0 kGy) using a linear accelerator (electron beam). The samples were evaluated for color using the CIE L,a,b color scale, with a LabScan spectrophotometer that had been calibrated against a black-and-white reflectance tile covered with the same packaging as the samples. The samples had increased redness throughout the whole meat sample that increased with higher irradiation dosage. The vacuum-packaged turkey breasts were more intensely red than the aerobically packaged samples. The redness of both meat samples was stable during the 2-week storage period and continued to increase thereafter. The lightness of the samples was not affected by the irradiation treatment, regardless of dosage. The irradiation process generates carbon monoxide gas, which affects the heme pigments in turkey breasts. The combination of carbon monoxide gas and myoglobin found in the muscle is responsible for the pink or red color in irradiated turkey breasts, which is considered a defect (Nam and Ahn, 2002).

Age is an important factor that affects meat quality. As chickens and other animals age, the level of myoglobin in the muscle increases, resulting in darker colors (Nishida and Nishida, 1985). Results of a study by Smith et al. (2002), however, did not support those conclusions. In their experiment, broilers 28 days of age were fed diets containing corn, milo, or wheat and then slaughtered each day from 42 to 45 and 49 to 52 days of age. Although both type of diet and time of feed withdrawal affected color characteristics, CIE $L*$, $a*$, $b*$ values indicated no differences in color of fillets due to age.

Cooking processes change the color of both skin and muscle. This can be accredited to Maillard browning, a chemical reaction that involves amino acids, reducing sugars and moisture, all things present in raw meat. Heat is required for the reaction to take place. Unlike browning in other foods, such as apples or avocados, there are no enzymes that cause the color change. This reaction gives cooked meat a desirable color.

Flavor and Aroma Characteristics

Raw meat has a distinctive flavor very unlike its cooked form. Generally, raw meat has a bloody, metallic, salty taste, with an aroma resembling blood serum (Wasserman, 1972). The flavor is changed drastically once cooked. Flavor develops during cooking through complex reactions between components found in raw meat combining with heat. The primary components of flavor may include reducing and phosphorylated sugars, amino acids, thiamine, and lipids. Chemical compounds found in the meat also undergo thermal degradation, resulting in flavor formation.

Several of the compounds contributing to aroma and flavor have been isolated and identified. According to Aliani and Farmer (2005), ribose may be the most important compound in chicken aroma. Thiamine has also been shown to be an important precursor of a wide range of sulfur compounds. In a study by Aliani and Farmer (2005), isolated precursors were added to ground raw chicken

prior to cooking and the cooked products were then evaluated by trained sensory panelists. A series of sensory experiments were conducted to screen the flavor precursors to determine the most important one affecting the sensory attributes of the panelists. When the thiamine precursor was used, the panelists used "roasted" and "vegetable soup" to describe the flavor of the cooked product. In the same study, cysteine was combined with ribose. Panelists used "chicken" and "savory" to describe the flavors of this sample when evaluated.

Besides the natural flavor compounds within the meat contributing to flavor, the diet of the bird also contributes to the flavor of the meat. The diet source of the bird has a noticeable effect on the flavor of broiler breast meat. Three diets with different primary carbohydrate sources (corn, milo, and wheat) were fed to 28-day-old broilers in a study by Lyon et al. (2004). The birds were processed between 42 and 52 days of age, and the breasts were removed and frozen. Thawed breasts were cooked to an internal temperature of 80°C and evaluated for 18 characteristics by a sensory panel. Feed withdrawal did not affect flavor characteristics. Meat from birds fed corn, however, scored significantly higher for broth than meat from birds fed milo or wheat (Lyon et al., 2004).

Dehydrated alfalfa was incorporated in the regular diet of male broilers in a study by Ponte et al. (2004). At days 35 and 56, birds were slaughtered and a meat sample was collected. On the day of sensory evaluation, the meat samples were slightly salted and cooked for 40 minutes in a commercial oven at 200°C. The sensory panelists were given half a split breast piece served without the skin to evaluate the flavor of the meat. Equal numbers of the panel preferred meat from birds consuming moderate levels of dehydrated alfalfa to birds consuming a regular commercial diet. The portion of the panelists preferring meat from the broilers that consumed dehydrated alfalfa claimed that the taste was the primary attribute influencing their decision (Ponte et al., 2004).

Some processors are beginning to use alternatives to corn-based additives as the price of corn increases. They are turning to lower-cost additives but first have to evaluate what the result on the meat will be. In a study by Poste (1990), poultry diets were supplemented with fish meal at three different levels (0, 4, 8, and 12%). It was determined that even small amounts of feed additives affected the flavor of the meat. Birds fed a diet consisting of 8% herring meal resulted in fishy, unpleasant, rancid, or stale flavors in the raw meat. After cooking, the off-flavor was less apparent but increased when the samples were held overnight at 4°C and reevaluated 24 h later.

Feed supplements including a dietary fat source and *dl*-α-tocopheryl acetate and ascorbic acid were incorporated into the feed regimen of chickens by Bou et al. (2001). The flavor of the dark meat from the birds that consumed supplements was reported to have an influence from the dietary fat source and α-tocopheryl acetate. Sensory panelists noted these flavor variations in rancid flavor and aroma and acceptability scores. The ascorbic acid supplement had no influence on these scores.

Just as the Maillard reaction affects color, it also influences the flavor and aroma. This reaction is important in the development of key flavors associated

with cooked chicken. Different compounds are formed when the condensation of the carbonyl group of the reducing sugar combines with an amino group. The products then combine with other reactive components, leading to many classes of flavor compounds. The Maillard reaction generates many possible compounds that are dependent on the components present in the meat. Since there are so many possible products, an extremely large assortment of volatile products can be formed. Some aroma compounds that are formed during meat preparation include oxazoles and oxazolines, which are also found in coffee and cocoa; thiazoles and thiazolines, which are closely related to oxazoles and oxazolines but are more commonly associated with fried foods; polysulfur heterocyclics; furans; thipphene thiols; sulfides; disulfides; and thiophenes (Mottram, 1994).

Irradiation affects flavor and aroma as well as color. As irradiation affects color by changing the heme pigments, an off-flavor may be generated. The heme pigments in irradiated meat can act as a catalyst in lipid oxidation and release iron, resulting in an off-flavor. Irradiation affects meat quality primarily through the production of free radicals. The radiation received by the meat affects lipid and protein molecules, and as a result, volatile compounds are formed. It is the volatile compounds formed that are responsible for the off-odor associated with irradiated meat. The compound dimethyltrisulfide is the strongest off-odor found in irradiated raw chicken meat (Patterson and Stevenson, 1995; Ahn et al., 1998). Irradiation dose, along with other conditions, greatly influences the microbial and nutritional quality of meat (Thayer et al., 1993). Oxidative chemical changes in meat are irradiation dose dependent, and the presence of oxygen affects the rate of oxidation considerably (Katusin-Razem et al., 1992). It has been reported that raw irradiated chicken meat produced a bloody and sweet aroma (Heath et al., 1990). The effect of irradiation on refrigerated and frozen chicken skinless boneless breasts and leg quarters was evaluated by sensory panelists in a study by Hashim et al. (1995). They reported that raw irradiated chicken had higher “fresh chickeny,” bloody, and sweet aromatic intensities than those of nonirradiated samples. They also determined that cooked irradiated frozen dark meat had a more intense chicken flavor than did nonirradiated samples (Hashim et al., 1995).

Texture Properties

Acceptance of meat is driven by several factors, texture, particularly tenderness, being one of the most important. Diet, age, feed withdrawal, transport, and processing conditions are all major contributors affecting the texture of meat.

As meat ages, it tends to become tough, which results in its economic value decreasing by limiting its use as a whole muscle food. Tenderness decreases with age, due to the nonenzymatic glycosylation of tissue protein. During glycosylation, saccharides are added to proteins present in the muscle. This contributes to the formation of cross-links leading to the deterioration of collagen. Over time there is an accumulation of these cross-links, which contributes to the toughness of meat from aged animals.

Inhibition of cross-link formation may be achieved by diet restriction. The cross-linking inhibitor aminoguanidine was added to the daily feed regime to evaluate its effectiveness in reducing the accumulation of cross-links in broiler breeder hens (Iqbal et al., 1999). Increasing age was associated with linear increases in shear values and pentosidine content in the skin. Both diet restriction and supplementation with aminoguanidine were associated with increased tenderness even as age increased.

Most producers feed a regimen of corn and/or soy diets. With the cost of corn rising, producers are looking for low-cost feed replacements. In a study by Lyon et al. (2004), it was determined that meat samples from birds fed a corn diet and a milo diet were significantly less springy, less chewy, and had smaller particle size and bolus size than did fillets from wheat-fed birds. The birds on a strict wheat diet also produced meat that was tough and more cohesive.

The effect of outdoor access (free range) and conventional methods on poultry meat tenderness has been noted by many researchers. Some argue that birds with outdoor access will produce tougher meat as a result of the increased mobility, and others believe that there is no difference in texture compared to conventional birds. Fanatico et al. (2006) assessed the effects of indoor versus outdoor access in chickens with genetically different growth rates. Although breast meat from medium-growing genotypes was determined to be more tender than other genotypes held indoors, breast meat from all treatments was judged to be slightly to moderately tender.

The defect PSE affects not only color negatively, but also meat texture and integrity. Slow, inadequate chilling decreases the pH of the meat from lactic acid buildup and begins to denature proteins within the muscle. Meat quality as well as water-holding capacity begins to decline, which can make meat tough. To minimize the occurrence of PSE, the temperature of the carcass should be less than 25°C by 60 min postmortem (Alvarado and Sams, 2002).

Preslaughter stresses can also cause PSE. In a study conducted by Zhang and Barbut (2005), boneless, skinless chicken breasts with PSE meat were collected at 10 different times from a deboning line of a commercial processing plant. Breasts with PSE lost 30 and 66% more moisture when cooked than did meat not having PSE. All texture profile values were lower for PSE meat than for dark, firm, and dry (DFD) meat and the rigidity of elastic (G') values indicated that PSE meat formed softer gels when cooked. Freezing enhanced the structural differences between the two types of meat, and analysis results indicated that PSE meat was more severely affected by freezing than was DFD meat (Zhang and Barbut, 2005).

Processing methods affect the whole bird both pre- and postmortem. Broken bones, meat toughness, discoloration, and loss of protein functionality are some of the negative effects associated with processing. Factors in which processing affects texture and overall quality of meat include temperature of processing conditions, handling, and stunning method.

Electrical stunning comprises an electric current from a saline bath being passed into the bird's head, through the body, and out the feet. The electric

current abolishes all brain responsiveness and induces cardiac arrest in over 95% of birds (Gregory and Wotton, 1990). An alternative to electrical stunning is the stun/kill (ASK) method, which is said to be more humane. This method involves using a pair of handheld tongs, from which an electric current is passed into a bird's body. Raj et al. (2001) found that birds stunned using the ASK method had fewer broken bones and less hemorrhaging in the breast muscled than did those stunned electrically.

Northcutt et al. (1998) investigated the effect of the stunning method on the quality of turkey breast muscle. Cook loss and shear force characteristics were evaluated on pectoralis muscles taken from 18-week-old tom turkeys that had undergone electrical stun, carbon dioxide stun, or no-stun methods. Although results from previous studies (Lee et al., 1979; Murphy et al., 1988) indicated electrical stunning under optimal conditions was associated with delayed glycolysis and increased muscle tenderness, Northcutt et al. (1998) found no statistical differences in cook loss or shear values among the three stunning methods. Shear values for the no-stun treatment (8.04 ± 3.6 kg), however, were about $1\frac{1}{2}$ times greater than values for the electrical stun treatment (5.22 ± 1.34 kg).

Postmortem handling can have significant effects on the quality characteristics of poultry meat. Deboning is one such handling procedure that is often used with poultry products, particularly the breast portion of chickens and turkeys. Conditions used during and after deboning can influence a variety of textural properties.

A study by Liu et al. (2004) evaluated shear force and organoleptic properties of chicken breasts deboned 2, 4, 6, and 24 h postmortem. Shear force decreased as deboning time increased. Sensory data indicated that springiness, cohesiveness, hardness, moisture release, and chewiness also decreased as deboning time increased. Strong correlations were detected between Warner–Bratzler shear values and the sensory texture properties of cohesiveness, hardness, and chewiness.

Hot-boning poultry products has gained favor over traditional cold-boning processes, due to savings in time, labor, and energy. Lesiak et al. (1997) held hot-boned prerigor turkey breast slices at either 0 or 12°C for 3 h and then stored the slices at 2°C before evaluating the sarcomere length and drip loss of the uncooked turkey breast slices and the shear force and water-holding capacity of the turkey breast slices after cooking. The effect of holding turkey breast for 15, 30, 45, 60, 90, and 120 min postmortem before chilling at 0°C on drip loss and water-holding capacity was also studied. Drip loss increased as time before chilling increased and was less in breast meat stored at 0°C than in that stored at 12°C. Cooking yield decreased in breasts chilled after 60 min but was not affected by chilling temperature. Shear force of breast slices chilled at 0°C (2.58 kg) was not different from that of breast meat stored at 12°C (2.42 kg).

Early deboning is typically associated with toughness in poultry products. Meek et al. (2000) used hydrodynamic shock waves to tenderize early deboned broiler breast meat. Breasts were subjected to one of four Hydrodyne treatments (200 g at 20 cm, 350 g at 23 cm, 275 g at 20 cm, or 350 g at 20 cm) and then

water-cooked to an internal temperature of 78°C. Warner–Bratzler shear values indicated that the 350 g at 23 cm treatment was the only one that improved tenderness of the early deboned breast meat (4.3 kg) to a level equal to the aged controls (3.1 kg). Sensory data, however, indicated that aged controls were more tender and juicy than were untreated early deboned breast meat and early deboned meat subjected to Hydrodyne treatment of 350 g at 23 cm.

High-pressure processing has been investigated in recent years as an alternative to high-temperature processing methods for destruction of microorganisms. Application of high pressure to meat may have significant effects on muscle structure and texture properties. Zamri et al. (2006) applied various combinations of heat (ambient temperature to 70°C) and pressure (0.1 to 800 MPa) to commercially processed chicken breasts and then used texture profile analysis to evaluate changes in the meat. Muscle hardness increased as heat and pressure acted synergistically through 50°C. Hardness decreased, however, at 60 and 70°C when pressure exceeded 200 MPa. At pressures >200 MPa, denaturation of actin and myosin occurred at 20°C, as compared to 60°C for myosin and >70°C for actin at ambient pressures.

The effect of heat on muscle texture is particularly important in poultry products since the USDA (2006a, 2006b) recommends that such products be thoroughly cooked to an endpoint temperature of 165°F before consumption. Wattanachant et al. (2005) investigated the effects of different endpoint cooking temperatures on the texture and structure of broiler muscle as well as meat from indigenous Thai birds. Both sarcomere length and collagen solubility were correlated with cooking loss and texture of meat from indigenous chickens with internal temperatures of 80 to 100°C associated with the greatest sarcomere shrinkage and cooking losses in those samples. Shear values for both types of chicken meat increased as internal temperature increased from 50 to 80°C, but remained unchanged at internal temperatures from 80 to 100°C.

Barbanti and Pasquini (2005) evaluated the tenderness and cooking losses of raw and marinated chicken breast meat prepared using hot air and hot air–steam mixtures at 130, 150, and 170°C for 4, 8, and 12 min. Marinated samples were tumbled in a mixture of water, sodium chloride, sugars, wheat flour, and milk proteins. Results indicated that air–steam cooking of marinated breasts produced the most tender product. Short cooking times (4 min) and lower temperatures (130 to 150°C) were associated with lower cooking losses and greater tenderness in both raw and marinated products. Meat tenderness was more highly correlated with cooking temperature, while cooking loss was more highly correlated with cooking time.

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CHEMICAL COMPOSITION AND NUTRITIONAL CONTENT OF RAW POULTRY MEAT

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INTRODUCTION

Consumers worldwide demand a protein supply that is safe, wholesome, nutritious, abundant, and affordable. Poultry meat is supplied chiefly by chicken (*Gallus gallus*) and turkey (*Meleagris gallopavo*), although ducks, geese, guinea fowl, quail, and other fowl also contribute. Poultry meat is economical and quick and easy to prepare and serve. It also has a number of desirable nutritional

Handbook of Poultry Science and Technology, *Volume 1: Primary Processing*, Edited by Isabel Guerrero-Legarreta and Y.H. Hui

properties. Globally, production of poultry meat approached 70 million metric tons in 2000, with an average annual growth rate of 5.3% during the last four decades. Currently, the United States, China, the European Union, and Brazil are the primary poultry producers, with a combined output of 65% of total poultry meat production in 2000. Worldwide, chicken (primarily broilers, but also spent breeder hens and males, and spent table egg layers) continues to be the most popular poultry meat, representing about 85% of total poultry meat output (FAS, 2001).

Poultry meat and eggs continue to be the most efficient and economical way to convert feed grains to animal protein. Broiler supply and demand is expected to grow more internationally, especially for frozen whole birds, parts, paws, bone-in-leg quarters, and boneless dark meat, driven primarily by large fast-food chains (Aylward, 2000). The demand for animal protein tends to be income-elastic and to follow the gross domestic product. Poultry products are in demand in all parts of the world. When there are no religious or cultural barriers, poultry meat usually leads in consumer preference (Van der Sluis, 2001). Poultry meat also enjoys popularity in developed markets, due to its price and perceived safety health advantages compared to other meat sources (FAS, 2001). However, annual per capita consumption of poultry meat varies substantially around the globe, ranging from 0.7 kg in India to 44 kg in the United States.

Development of new and efficient processing systems, adoption of advanced technologies, and introduction of novel products that meet market chain requirements and end-consumer needs have contributed significantly to the increase in global poultry meat consumption (Roenigk, 1998). Processing and marketing of poultry ranges from live bird markets or very primitive on-site slaughter and sale, to highly sophisticated, fully automated, and International Standards Organization (ISO)–certified facilities and ready-to-eat convenience products in many parts of the world.

Historically, introduction into the market of many novel poultry products was an attempt to find outlets for trimmings, low-value cuts, and parts from fabrication of whole birds. Later, expansion of food service and fast-food chains, increasing demand for finger foods, availability of mechanically deboned poultry meat for frankfurters and luncheon meats, and development of marination/injection technologies have all contributed to product diversification at the retail level. Most of these value-added products, formulated primarily to suit the local palate, not only target the changing needs of consumers (i.e., convenience, nutrition, health, quality, variety, shelf life), but also allow a marketing edge over imports. Many exotic recipes and ready-to-cook marinated stock products from Asia, developed primarily for domestic markets, are now in demand by poultry-importing countries elsewhere (i.e., Europe, Japan, Australia, New Zealand, etc.).

DIETARY RECOMMENDATIONS FOR A HEALTHFUL DIET

Dietary reference intakes (DRIs) are the current U.S. dietary standards, which are sets of recommended intake values for nutrients. The DRIs are reference

values for nutrient intakes to be used in assessing and planning diets for healthy people. They include four basic elements: estimated average requirement (EAR), recommended dietary allowances (RDAs), adequate intake (AI), and tolerable upper intake level (UL). Each of these values states the definition of foods that should be taken in on a regular basis to remain healthy. Two other concepts should be taken into account: the estimated energy requirement (EER) and the acceptable macronutrient distribution ranges (AMDRs) (Institute of Medicine, Food and Nutrition Board, 2005). The EER is defined as the energy intake that is estimated to maintain energy balance in healthy, normal-weight persons, while AMDRs indicate the recommended balance of energy sources in a healthful diet. These values consider the amounts of macronutrients needed to provide adequate intake of essential nutrients while reducing the risk of chronic disease (Table 1).

Nutrition Facts panels contain the most important label information for the health-conscious consumer. They state the content of selected nutrients in a food in a standard prescribed by the U.S. Food and Drug Administration (FDA). By law, Nutrition Facts must appear on nearly all processed food products in the United States. The nutrient information is given both in quantity (grams or milligrams per serving) and as a percentage of the daily value (DV). The DVs, which were established in 1993 specifically for food labels, are a set of dietary standards used to compare the amount of a nutrient (or other component) in a serving of food to the amount recommended for daily consumption (Table 2). Keep in mind that the DVs may not exactly match the more recent DRI values, but in most cases, the differences are small (FDA, 2004).

The Nutrition Facts panels must appear on all processed poultry products, while their use is voluntary on raw poultry. The FDA's jurisdiction does not include meat, meat products, poultry, or poultry products. The U.S. Department of Agriculture (USDA) regulates these foods. In 1980 the USDA and the U.S. Department of Health and Human Services (DHHS) jointly released the first edition of the Dietary Guidelines for Americans (DGA). Revised guidelines have been released every five years as scientific information about links between diet and chronic disease is updated. The purpose of the DGA is to provide science-based advice to promote health and to reduce risk for chronic diseases through diet and physical activity (USDA–DHHS, 2005). The most recent edition of the DGA offers key recommendations grouped under nine interrelated focus areas: (1) adequate nutrients, (2) weight management, (3) physical activity, (4) food

TABLE 1 Acceptable Macronutrient Distribution Ranges for Adults

Macronutrient	% Energy Intake
Fat	20–35
Carbohydrate	45–65
Protein	10–35
n-6 Polyunsaturated fatty acids	5–10
α-Linolenic acid	0.6–1.2

Source: Institute of Medicine, Food and Nutrition Board (2005).

TABLE 2 Daily Values for Food Labels

Nutrient	Daily Value
Energy	2000 kcal
Protein[a]	50 g
Fat	65 g
Saturated fat	20 g
Monounsaturated fat	20 g
Carbohydrate	300 g
Dietary fiber	25 g
Sugar	50 g
Cholesterol	300 mg
Calcium	1000 mg
Iron	18 mg
Magnesium	400 mg
Phosphorus	1000 mg
Potassium	3500 mg
Sodium	2400 mg
Zinc	15 mg
Copper	2 mg
Vitamin C	60 mg
Thiamine	1.5 mg
Riboflavin	1.7 mg
Niacin	20 mg
Vitamin B_6	2 mg
Folate	400 μg
Vitamin B_{12}	6 μg
Vitamin A[b]	5000 IU
Vitamin E	20 mg
Pantothenic acid	10 mg
Vitamin D[b]	400 IU

Source: FDA (2004).
[a]The daily values for protein vary for different groups of people: pregnant women, 60 g; nursing mothers, 65 g; infants under 1 year, 14 g; children 1 to 4 years, 16 g.
[b]The daily values for fat-soluble vitamins are expressed in international units (IU), an old system of measurement.

groups to encourage, (5) fats, (6) carbohydrates, (7) sodium and potassium, (8) alcoholic beverages, and (9) food safety. Taken together, these recommendations encourage Americans to eat fewer calories, be more active, and make wiser food choices. The American Dietetic Association strives to communicate healthful eating messages to the public that emphasize the total diet, or overall pattern of food eaten, rather than any one food or meal. If consumed in moderation with appropriate portion size and combined with regular physical activity, all foods can fit into a healthful diet (Freeland-Graves and Nitzke, 2002).

In 1992 the USDA introduced the Food Guide Pyramid to represent visually the variety, moderation, and proportionality needed for a healthful diet. The

pyramid was designed to illustrate the Dietary Guidelines for Americans in terms of food groups and recommended numbers of daily servings. The design of the pyramid illustrated that plant foods (grains, fruits, and vegetables) were to make up the majority of daily food servings, and meat and meat alternatives and dairy foods were to be consumed in smaller quantities. Fats, oils, and sweets at the tip of the pyramid were recommended to be used sparingly.

As with any form of dietary guidance, advances in science drive the need for change. So, in 2005, the USDA unveiled its new food guidance system: MyPyramid. The MyPyramid system is more than just a graphic. The system provides many options to help Americans make healthy food choices and be active every day. MyPyramid is based on both the DGA and the DRIs, translating these into a total diet that meets nutrient needs from food sources and that aims to moderate or limit dietary components often consumed in excess.

CONTRIBUTIONS OF POULTRY TO THE HUMAN DIET

Animal source foods can provide a variety of micronutrients that are difficult to obtain in adequate quantities from plant source foods alone. In the 1980s, the Nutrition Collaborative Research Support Program identified six micronutrients that were particularly low in the primarily vegetarian diets of schoolchildren in rural Egypt, Kenya, and Mexico: vitamin A, vitamin B_{12}, riboflavin, calcium, iron, and zinc. Negative health outcomes associated with inadequate intake of these nutrients include anemia, poor growth, rickets, impaired cognitive performance, blindness, neuromuscular deficits, and eventually, death. Animal meat is a particularly rich source of all of these nutrients, and relatively small amounts of these foods added to vegetarian diets can substantially increase nutrient adequacy. Food guides usually recommend several daily servings from animal source food groups (dairy products and meat or meat alternatives). An index that estimates nutrient adequacy based on adherence to such food guide recommendations may provide a useful method to evaluate dietary quality quickly in both developing and developed countries (Murphy and Allen, 2003).

Nutritionally, people eat poultry meat for its high content of high-quality protein. Various types of poultry meat have similar approximate chemical compositions, as shown on Table 3. Chicken and turkey meat are slightly higher in protein and slightly lower in fat than beef and other red meats. Chicken is a very popular and healthy food, as it can be prepared in a multitude of ways. From fried chicken to barbecued chicken to tandoori chicken to homemade chicken soup, chicken is appreciated by people of all ages as well as by diverse cultural culinary traditions. On the other hand, turkey is increasing its popularity beyond its association with the holidays of Thanksgiving (in the United States) and Christmas. Like its supermarket chicken predecessor, turkey parts such as breast, tenderloins, cutlets, and ground turkey are now widely available. Since some parts are quicker to prepare, it is now more practical for many people to enjoy turkey more regularly.

TABLE 3 Approximate Composition of Poultry Meat (g/100 g)

Component	Broiler	Turkey	Duck	Quail
Water	74.6	72.5	70.8	74.3
Ash	1.0	0.8	1.2	1.1
Protein	12.1	13.7	12.8	13.1
Lipid	11.1	11.9	13.8	11.1
Fiber	0.0	0.0	0.0	0.0
Carbohydrates	1.2	1.1	1.4	1.4

Source: USDA (2006).

Chicken is a source of protein, low in fat, which is less saturated than beef fat. Additionally, protein is a rich source of all the essential amino acids. However, eating chicken with the skin on doubles the amount of fat and saturated fat in the dish. For this reason, chicken should best be skinned before cooking. Chicken consumption is increasing as people look for alternative ways to reduce fat such as cholesterol in their diets. To reduce fat in cooked poultry, cooking methods such as broiling, roasting, baking, simmering, or microwaving have been suggested. Chicken also provides vitamins B_6 and B_{12}, iron, zinc, and phosphorus.

Turkey is a very good source of proteins, providing 65% of the daily value in one 113-g portion. It is also a very good source of selenium, zinc, niacin, and vitamins B_6 and B_{12}. Similarly, turkey contains almost all of the fat in the skin, and the dark meat is higher in fat than the light meat. The skinless white meat is an excellent high-protein, low-fat food (Demby and Cunningham, 1980). MyPyramid suggests two to three servings each day of food from the meat group, the equivalent of 142 to 198 g of cooked lean meat, poultry, or fish. Count as a serving 57 to 85 g of cooked poultry, roughly the amount of poultry meat on a medium chicken breast half.

Protein

The nutritional value of proteins is determined first by their content of essential amino acids and their digestibility. In the past, the nutritional value was commonly determined by means of growth trials with rats. Currently, the amino acid composition of a protein as determined by chemical analysis compared with that of a reference amino acid pattern. The score obtained from this comparison is corrected for protein digestibility. The value thus obtained serves as an alternative to the typical trials with experimental animals. Animal foods in general are considered to be foods with high protein qualities.

Red meats, poultry, fish, eggs, milk, and milk products contain complete protein. More than 20% of these foods' energy content is protein. Americans, on average, obtain about 63% of their protein intake from animal foods (14% of protein from poultry). In other parts of the world, animal proteins play a smaller role. In Africa and East Asia, for example, animal foods provide only 20% of protein intake (Young and Pellet, 1994).

Protein Quality The human body needs 20 different amino acids, nine of which are called *indispensable* because the body cannot make them and must get them in the diet. Indispensable amino acids for adults are histidine, isoleucine, leucine, lysine, methionine, phenylalanine, threonine, tryptophan, and valine. Additionally, children need arginine. Food proteins that supply all the indispensable amino acids in the proportions needed by the body are called *complete*. Animal foods are considered to have high protein qualities, although their qualities are not always similar because of differences in essential amino acids. The higher quality of animal protein is due to the high lysine and methionine content (Edmonson and Graham, 1975; Jenkins and Mitchell, 1989).

In 1985, an FAO/WHO (Food and Agriculture Organization/World Health Organization) working group (FAO/WHO/UNU Expert Consultation) issued the first age-specific amino acid reference patterns based on data on human requirements for essential amino acids expressed in mg/day per kilogram of body weight or mg/g crude protein. Table 4 shows the amino acid requirements recommended by FAO/WHO (1991). These reference patterns show that the amount of essential amino acids per gram of protein decreases with age from 434 mg in infants to 111 mg in adults (histidine excluded).

Hamm (1981) studied the amino acid content of the principal meat tissues of broilers (i.e., breast and thigh meats) and determined the differences in the amino acid profiles between broiler breast and thigh meats produced in several regions of the United States. On a percent protein basis, amounts of valine, leucine, isoleucine, and histidine were found to be significantly greater in breast meat, and glycine, hydroxyproline, hydroxylysine, threonine, and serine were greater in thigh meat. It was found that the area of production and/or related management practices appeared to influence the concentration of about half the amino acids. The results of this study were compared with other data found previously by other authors (Table 5).

The amino acid composition of breast and thigh muscles from pheasant chickens aged 42 days has been compared with that of broiler chicken of the same

TABLE 4 Suggested Human Essential Amino Acid Requirements (mg/g of Protein)

Amino Acid	1 yr old	2–5 yr old	10–12 yr old	Adult
Thr	43	34	28	9
Cys + Met	42	25	22	17
Val	55	35	25	13
Ile	46	28	28	13
Leu	93	66	44	19
Tyr + Phe	72	63	22	19
His	26	19	19	16
Lys	66	58	44	16
Trp	17	11	9	5

Source: FAO–WHO (1991).

TABLE 5 Amino Acid Profile (mg/g Protein, Kjeldahl N × 6.25) of Chicken Meat

Amino Acid	Hamm (1981)[a]	Vervack et al. (1977)[b]	FAO (1968)[c]	Tajima et al. (1978)[c]	Millares and Fellers (1948)[a]	Gruhn and Jahreis (1977)[d]	CFEI (1979)[e]
Alanine	57.4	57.5	34.0	60.6	—	56.0	54.6
Valine	45.5	47.1	50.0	43.2	46.5	38.0	49.6
Glycine	48.1	64.7	53.0	70.1	38.8	54.0	49.1
Leucine	80.7	71.6	74.0	63.7	70.4	71.0	75.6
Isoleucine	42.6	44.7	53.0	33.0	55.0	42.0	52.8
Proline	41.8	41.4	41.0	48.5	—	53.0	41.1
Threonine	48.8	46.1	39.0	31.5	38.3	36.0	42.2
Serine	51.4	32.8	39.0	33.1	—	34.0	34.4
Aspartic acid	97.2	86.7	92.0	76.8	—	72.0	89.1
Methionine	32.5	15.1	25.0	14.7	24.3	21.0	27.7
Cysteine	7.3	—	—	—	—	—	—
Phenylalanine	40.2	36.4	40.0	30.7	38.9	40.0	39.7
Glutamic acid	150.7	136.6	150.0	124.3	—	113.0	149.8
Histidine	38.9	20.2	26.0	14.6	33.3	40.0	31.1
Tyrosine	39.8	27.0	33.0	23.0	—	31.0	33.7
Lysine	82.4	71.7	79.0	63.2	80.7	76.0	85.0
Arginine	64.4	68.3	56.0	61.1	60.1	57.0	60.3
HO proline	7.1	—	—	—	—	—	—
Cystine	—	9.2	13.0	—	—	10.0	12.8
Tryptophan	—	11.0	11.0	—	10.7	—	11.7

Source: Adapted from Hamm (1981).
[a]Values are weighed (55% breast/45% thigh meat) means.
[b]Identified as poultry meat.
[c]Identified as chicken meat.
[d]Identified as male broilers.
[e]Calculated from raw broiler meat values.

age. The results show that the levels of individual amino acids in breast muscles (related to 100% of dry matter content) ranged from 8 to 127 mg/g in pheasant chickens and from 19 to 110 mg/g in broiler chickens, while the corresponding average values in thigh muscles ranged from 14 to 132 mg/g in pheasant chickens and from 14 to 93 mg/g in broiler chickens (Table 6). The results of studies of the amino acid composition of pheasant and broiler meat have proven the high nutritive value of pheasant meat with regard to human nutrition (Straková et al., 2006).

The protein efficiency ratio (PER) is still used frequently as the biologically determined measure of protein quality. PER values are determined in rat experiments in which the animals are fed a diet containing a marginal proportion of the test protein (10% w/w). The PER value is the growth in grams per gram of protein ingested. The PER value found in experiments is commonly standardized for a reference protein, usually casein. Table 7 shows both protein content and PER values for a variety of chicken retail cuts (Hernández et al., 1996).

TABLE 6 Amino Acid Composition of Breast and Thigh Muscles from Broiler and Pheasant Chickens Aged 42 Days (mg/g of Protein)[a]

	Breast Muscle		Thigh Muscle	
Amino Acid	Broiler	Pheasant	Broiler	Pheasant
Thr	36	31	27	40
Val	45	47	33	42
Met	20	23	14	14
Ile	42	44	30	41
Leu	68	79	51	73
Tyr	35	43	19	26
Phe	24	24	23	21
His	44	51	24	18
Lys	77	77	58	69

Source: Stratová et al. (2006).
[a]The results are related to 100% of dry matter.

TABLE 7 Protein and PER Value of Chicken Meat

Chicken	Protein (g/100 g)	PER	Digestibility (%)
Breast	20.6	3.07	88.3
Leg	16.8	3.01	89.1
Liver	20.5	2.99	83.8

Protein digestibility can be determined both in vitro and in vivo. In vivo experiments distinguish primarily between true and apparent digestibility. *True digestibility* refers to the amount of dietary nitrogen absorbed divided by the amount ingested. *Apparent digestibility* is calculated by subtracting the amount of nitrogen secreted in feces from the amount ingested. The difference between true and apparent digestibility is highly relevant if a food is rich in crude fiber or if other factors increase endogenous fecal nitrogen losses. Protein digestibility can be expressed as a fraction or as a percentage.

In 1989, the FAO/WHO/UNU Expert Consultation proposed using the protein digestibility corrected amino acid score (PDCAAS), defined as the ratio between the content of the first limiting amino acid in the protein under study (mg/g) and the content of that amino acid in a reference protein (mg/g), multiplied by true digestibility (Henley and Kuster, 1994). The PDCAAS has been adopted by FAO/WHO as the preferred method for measurement of the protein value in human nutrition. The reference pattern is derived from the essential amino acid requirements of a preschool-age child. The chemical score obtained is then corrected for true fecal digestibility of the test protein. The PDCAAS value assessed for poultry meat is 0.94 (Suárez-López et al., 2006), and no limiting amino acid has been reported.

Fat

The DGA suggests choosing a diet containing 20 to 35% of calories from fat and less than 10% of calories from saturated fatty acids. It also suggests that dietary cholesterol be limited to an average of 300 mg/day. Consumers should choose a diet low in fat, saturated fat, and cholesterol to help reduce the risk of getting certain diseases and to help maintain a healthy weight. For this purpose, poultry meat is a very good choice.

Fatty Acids The lipid contents of fowl show that both poultry and game birds contain greater amounts of unsaturated [oleic acid (C18:1) is a dominant fatty acid in all tissues] than saturated fatty acids. The dark meat and skin of fowl contain as much as or even more oleic acid (C18:1) than the total of the saturated fatty acids. The three acids—palmitic (C16:0), oleic (C18:1), and linoleic (C18:2 *n*-6)—account for at least 68% of the total fatty acids in fowl tissues. The total lipid content of chicken tissues increases with age. Young chicken meat (light plus dark meat) has 2.5% of total fat of the edible portion, which is less fat than that of stewing hens, turkeys, and other fowl. All of them have an approximately equal total fat content (7 to 8% of the edible meat). The fatty acid composition of both chicken and turkey tissues reflects the fatty acid composition of the dietary fat. Breed, sex, and environmental temperature do not have any effects on tissue fatty acid compositions. The skin of all birds contains more fat than the meat and is the major contributor of fat to the edible portions.

The skin of duck and goose is particularly high in fat content. The total fat level in duck meat is 8% of the edible portion, and in the meat plus skin, the total fat content is 28% of the edible portion. The total lipid content of goose meat is 7% of the edible portion, but in goose meat plus skin, the fat content rises to 34% of the edible portion. The flesh plus skin of ducks and geese contains the highest fat content of fowl. The breast meat of young turkeys and broiler-fryer chickens has a very low fat content, 1% of the edible portion. In stewing hens, although the fat content of breast tissue is 3% of the edible portion, this is less than the fat content of the dark meat of all kinds of chicken (Fristrom and Weihrauch, 1976).

Kishowar et al. (2004) have studied the fatty acid composition in chicken breast from different production regimes and have found that the dominant saturated fatty acids were palmitic acid (C16:0; 21 to 24%) and stearic acid (C18:0; 15 to 17%). Myristic acid (C14:0) contents ranged from 0.40 to 1.02%. Among the monounsaturated fatty acids, the dominant fatty acid was oleic acid (C18:1), then palmitoleic acid (C16:1) and gadoleic acid (C20:1). With regard to polyunsaturated fatty acids (PUFAs), linoleic acid (C18:2 *n*-6) was dominant, at 16.1%. Arachidonic acid (C20:4 *n*-6) was found over the range 1.5 to 5.6%. The dominant *n*-3 fatty acid was found to be α-linolenic (C18:3 *n*-3), with a range of 1.15 to 2.51%. The least abundant *n*-3 fatty acid was eicosapentaenoic acid (EPA) (C20:5 *n*-3), comprising 0.24 to 0.96%. The contents of docosahexanoic acid (DHA) (C22:6 *n*-3) varied from 0.67 to 3.35%. The *n*-6/*n*-3 ratios varied from 3.37 to 11.35. The consumption of chicken breast contributes to a healthy diet

through its low fat content (1.15%), cholesterol (245 to 627 mg/kg), the atherogenic myristic acid (C14:0), and greater contents of total PUFAs, particularly the beneficial *n*-3 PUFAs, notably EPA and DHA.

Chicken breast muscle is an important component of a modern healthy diet, and consumers demand both wholesomeness and a desirable flavor. Consumers demand for food products of superior health quality has renewed interest in modifying the lipid composition of poultry meat. The importance of a relatively high intake of (PUFAs) in human nutrition is now generally accepted; PUFA should constitute 7% of total energy consumed (Ralph, 2000). The dietary fatty acid modification has proved to be a feasible method of adding value to poultry products for the health-conscious consumer (Hargis et al., 1993). Those fatty acids that are deemed to be essential for human consumption can be found in PUFA. They are linoleic acid (C18:2*n*-6; LA) and α-linolenic acid (C18:3*n*-3; LNA), the precursors of the PUFA *n*-6 and *n*-3 series, respectively. Because of the association with a decreased risk of coronary heart disease, recent dietary fat studies have centered on the manipulation of specific PUFA. The quantitatively and qualitatively most important metabolites of LA and LNA are arachidonic acid (C20:4*n*-6; AA), eicosapentaenoic acid (C20:5*n*-3; EPA), and docosahexanoic acid (C22:6*n*-3; DHA), respectively. DHA and AA are the major PUFAs in the membranes of brain and retinal cells and have an impact on neuronal functions (Alessandri et al., 2004). As a dietary staple, chicken muscle should ideally provide the essential fatty acids (Table 8; Kishowar et al., 2004).

Eicosanoids (prostaglandins, thromboxanes, and leucotrienes) derived from AA, on the other hand, have different physiological effects on humans (Von Sacky, 2001). Pro-inflammatory and pro-aggregatory AA-derived eicosanoids increase the risk of cardiovascular and autoimmune diseases (Adam, 2003; Balyn

TABLE 8 Fatty Acid Composition of Chicken Tissue (g/100 g)

Fatty Acid	Light Meat	Dark Meat	Skin
Saturated			
C14:0	0.6	0.9	1.1
C16:0	20.1	19.5	22.3
C18:0	8.3	7.1	5.6
Monounsaturated			
C14:1	1.1	1.1	0.0
C16:1 undifferentiated	2.6	4.3	5.9
C18:1 undifferentiated	22.0	27.9	33.1
Polyunsaturated			
C18:2 undifferentiated	15.8	19.5	23.8
C18:3	0.6	0.9	1.6
C20:4 undifferentiated	4.5	2.9	0.6
C20:6	3.0	0.9	0.0
Other	2.0	1.5	0.0

Source: Fristrom and Weihrauch (1976).

and Campos, 2004). On the other hand, the anti-inflammatory, antithrombotic, antiarrhythmic, and immunomodulating properties of EPA and DHA can be helpful in the prevention of atherosclerosis (Moreno and Mitjavila, 2003), coronary heart diseases (Yaqoob, 2004), hypertension, inflammatory (Calder, 2001) and autoimmune disorders (Zamaria, 2004), cancers (Terry et al., 2004), and diabetes (Nettleton and Katz, 2005).

Both *n*-3 and *n*-6 fatty acids make powerful substances in the body that play key roles in the structure and function of every cell and, ultimately, in health and well-being (Harbige, 2003). Epidemiological data suggest that increasing the *n*-6/*n*-3 PUFA ratio led to a rapid increase in mortalities from "Western-type" cancers and allergies in Japan. Therefore, the recommended *n*-6/*n*-3 PUFA ratio is ≤ 2 (Okuyama et al., 1997). With regard to inflammatory diseases, AA intake should be <90 mg/day, but it has also been estimated to be 100 to 500 mg/day as an optimal consumption (Taber et al., 1998; Adam et al., 2003). Fat from poultry meat could be a significant contribution to the dietary intake of AA (Li and Sinclair, 1998). Information on how much AA is actually consumed is sometimes conflicting; according to Mann et al. (1995), actual AA intake is lower than sometimes estimated.

Increasing the consumption of fish can decrease the *n*-6/*n*-3 PUFA ratio, which is currently 10 or more in many population groups with Western-type consumption. On the other hand, due to the current limited availability and high cost of fish and the low acceptance of fish meat to many consumers, meat, dairy products, and eggs enriched by *n*-3 PUFA seem to be a feasible alternative. The addition of flaxseed oil to diets fed to hens allowed the production of eggs with higher EPA and DHA content and a lower *n*-6/*n*3 PUFA ratio (Milinsk et al., 2003). Fish oil or linseed oil and rapeseed oil are used most commonly in diets with an aim to manipulate the *n*-3 PUFA composition of poultry meat (Komprda et al., 2005). Similarly, the fatty acid profile of ostrich meat was altered as a result of the consumption of fish oil (Leskanich and Noble, 1997; López-Ferrer et al., 1999; Hoffman et al., 2005). However, a higher PUFA content of poultry meat increases the degree of unsaturation and, as a result, also increases the susceptibility to oxidation. This may then lead to off-flavors and off-odors associated with carcass and egg samples enriched with fish oil and, consequently, lower consumer acceptability (Bou et al., 2004). Therefore, this issue has prompted investigation into the use of alternative sources of *n*-3 fatty acids such as those found in some seeds. Although effective in enriching meat and egg products with LNA, plant sources result in only minor changes in the content of *n*-3 fatty acids. On the other hand, various methods of oil refinement and extraction, as well as alterations in production practices and the use of dietary antioxidants, have been examined as a way to improve flavor quality and storage stability or *n*-3 fatty acid–enriched products (Hargis et al., 1993).

Cholesterol Cholesterol is an indispensable constituent of the cell membranes and brain tissue. However, opinions regarding relationships of dietary cholesterol intake and the process of atherosclerosis are ambiguous. There is a correlation

between serum cholesterol level and mortality rate on human cardiovascular diseases, and a lower consumption of foods with high cholesterol content has been the consequence (Griffin, 1999). On the other hand, the endogenous cholesterol synthesis in liver is three times higher than amounts usually consumed, which led to weakening of the importance of dietary cholesterol and increasing interest in total dietary energy intake, saturates, monounsaturated and polyunsaturated fatty acid intake, and the PUFA *n*-6/*n*-3 ratio in foods (Okuyama et al., 1997). However, changes in plasmatic cholesterol level depend significantly on dietary cholesterol. It is possible to induce hypercholesterolemia in experiments on primates, using only diets containing cholesterol (Ruddel et al., 1998). Knowledge of cholesterol content is important, especially in poultry, because the consumption of poultry is currently increasing based on recommendations regarding healthy nutrition. Chicken or turkey breast meat content is 53 mg/100 g; turkey thigh meat (61.5 mg/100 g) and chicken thigh meat is 82.9 mg/100 g. Hence, a serving of 100 g of poultry meat contributes 18 to 28% of the dietary cholesterol limit per day (Komprda et al., 2003).

Mineral Salts

Minerals are the inorganic elements, other than carbon, hydrogen, oxygen, and nitrogen, that remain behind in the ash when food is incinerated. They are usually divided into two groups: macrominerals and microminerals (or trace elements). Minerals are classified as either essential or nonessential, depending on whether or not they are required for human nutrition and have metabolic roles in the body. Nonessential elements are also categorized as either toxic or nontoxic.

Minerals function in the body in primarily three ways:

1. As structural components (e.g., calcium, phosphate, and magnesium in bones and teeth)
2. In organic combinations as physiologically important compounds (e.g., phosphorus in nucleotides, zinc in enzymes such as carbonic anhydrase, iodine in thyroid hormone)
3. In solution in body fluids to maintain pH, helping to conduct nerve impulses and control muscle contraction (e.g., sodium and potassium in blood and intracellular fluids)

The macrominerals are involved primarily in functions 1 and 3, and the microminerals in function 2.

Iron Iron insufficiency is probably the most common nutritional deficiency in the world. Even among the inhabitants of well-fed developed countries, it continues to be common, especially in women (Looker et al., 1997). Iron has two major roles in human physiology. As a component of hemoglobin, the pigment of blood and myoglobin in muscle, iron atoms combine reversibly with oxygen

to act as its carrier from the lungs to the tissues. In a variety of enzymes (e.g., the cytochromes), iron atoms, present in the ferrous and ferric states, interchange with gain or loss of an electron, as part of the electron chain responsible for the redox reactions necessary for release of energy in cellular catabolism and the synthesis of large molecules (Brock et al., 1994).

In addition to its major functions in oxygen transport and as a cofactor in many enzymes, iron also plays an important role in the immune system. Although the mechanisms involved are complex, there is good evidence that an abnormal iron nutritional status can lead to impaired immune function, with serious consequences for health (Walter et al., 1997). One of the richest sources of dietary iron is animal offal, especially liver. Other animal products, in particular red meat, are also rich in iron. This iron is organically bound heme iron, which is easily absorbed. The U.S. iron recommendation (National Research Council, 1989) is 1.7 to 8.7 mg/day, which is lower than those of WHO. It is also lower than that suggested in many developing countries. According to the FAO, a diet typical of most segments of the population in industrialized countries includes generous amounts of meat, poultry, fish, and/or foods containing high amounts of ascorbic acid (FAO, 1988). Iron absorption from such diets can be assumed to be 15%. Iron content in mixed dark and white chicken meat has been found over the range 4.9 to 5.0 mg/kg of the edible portion (Bou et al., 2005), of which 100 g provides, roughly 3% of the daily value. In contrast, the less varied high-cereal diet of developing countries with a similar diet may have a lower iron content, with an absorption level of 5% or less.

Muscle tissue and ascorbic acid are the major enhancers of dietary iron absorption (Hurrell, 1997). Ascorbic acid is thought to exert its effect primarily by reducing ferric iron to the ferrous state, thus preventing its reaction with inhibitors such as phytic acid and/or its precipitation as ferric hydroxide. The nature of the enhancing effect of muscle tissue is uncertain, and the mechanism of meat effects has been subject to much debate (Zhang et al., 1990). Meat, fish, and poultry have often been demonstrated to enhance nonheme iron absorption, especially form cereal- and legume-based meals. Cook and Monsen (1976) performed human absorption studies using semisynthetic liquid meals containing glucose, corn oil, minerals, and a protein component. They demonstrated a two-fold-higher nonheme iron absorption from meals containing beef, pork, chicken, and fish than the same meal containing egg albumin used as a control. Freeze-dried chicken muscle increased iron absorption 100% over that of egg albumin. In another study, Rasmussen and Hallberg (1979) found that the addition of chicken, beef, or fish to a maize meal increased nonheme iron absorption two- to threefold compared with no influence with the same quantity of protein added as egg albumin. When Hurrell et al. (2006) added a semisynthetic liquid formula at an equivalent protein level (30 g), isolated chicken muscle protein (94% protein) increased iron absorption in a manner similar to native chicken muscle. Their outcomes supported the hypothesis that the enhancing effect of muscle tissue on iron absorption is mainly protein related, but they also point to other factors that may play a role.

Zinc Zinc is an essential component of more than 200 enzymes in the living world, of which as many as 50 play important metabolic roles in animals. It occurs in all six classes of enzymes. In addition, the metal provides structural integrity in many proteins. Zinc ligands help maintain the structure of cell membranes and of some ion channels. Zinc finger protein is involved in processes of transcription factors that link with the double helix of DNA to initiate gene expression (Berg and Shi, 1996). The expression of certain genes is known to be regulated by the quantity of zinc absorbed from the diet. It is also believed that zinc has an intracellular role that includes regulation of cell growth and differentiation. Clinical signs seen in persons suffering from marginal zinc deficiency include depressed immunity, impaired taste and smell, night blindness, impaired memory, and decreased spermatogenesis in men (Walsh et al., 1994). Severe zinc deficiency is characterized by severely depressed immune function, frequent infections, bulbous dermatitis, diarrhea, alopecia, and mental disturbances. An inadequate intake of zinc retards growth and can result in stunting, dwarfism, and failure to mature sexuality.

A number of problems have been encountered in trying to establish dietary zinc requirements. This is due largely to the difficulty of assessing zinc status and optimal zinc with regard to human nutrition. Measurements of plasma levels may not give a true measure of a body's available zinc. Other biomarkers of zinc status, such as the activity of zinc-dependent enzymes, are not sufficiently specific to be of more than supportive value (Hambidge and Krebs, 1995). The U.S. recommendation for zinc is 15 mg/day for adult males and 12 mg/day for women up to the age of 50 years, with an extra 16 to 19 mg/day for lactating women, on top of an additional 15 mg/day all through pregnancy.

In Western societies, more than 70% of zinc consumed is provided by animal products, especially meat (Welsh and Marston, 1982). Liver and other organ meats are particularly rich in the element, as are most seafoods. Zinc content in mixed dark and white chicken meat, reported by Bou et al. (2004, 2005), falls within a range of 8.5 to 9.0 mg/kg of the edible portion, and 100 g provides, roughly 6% of the daily value. Other foods that contain high levels are seeds and nuts, as well as whole-grain cereals. However, these and other plant foods also contain phytate, which can decrease the bioavailability of the element. In many countries zinc intakes are particularly low because of the absence of appreciable amounts of animal products and the presence of phytate-rich plant foods in the customary diet. There is evidence that zinc deficiency is widespread, especially in children, in several countries (Osendarp et al., 2001). Efforts are currently being made by health authorities in such areas to improve zinc intake through poultry product consumption, provision of zinc supplements, and by other methods, including fortification (Gibson and Ferguson, 1998). Turkey thigh muscle has a higher zinc content than does turkey breast muscle (Oleane and Bowers, 1977).

Selenium Selenium is an essential trace nutrient for humans and all animals. Its essentiality was not recognized until the 1970s, when the enzyme glutathione peroxidase was shown to be a selenoprotein (Rotruck et al., 1973). Selenium, in the

form of the unique amino acid selenocysteine, is the cofactor in several important functional metalloproteins. At physiological pH, the selenium in the selenocysteine is almost totally ionized and is an extremely efficient redox catalyst. One group, the glutathione peroxidases, plays a role in intracellular antioxidant systems. Selenium is also an essential cofactor in the iodothyronine deiodinases, which are enzymes involved in thyroid hormone metabolism. Another important selenoenzyme is thioredoxin reductase, which helps control cell growth and division. Several other selenoproteins, including selenoprotein P and selenoprotein W, also occur in human tissues, where they appear to have antioxidant and redox roles (Arthur and Beckett, 1994).

In humans, chronic low intake of dietary selenium is responsible for Keshan disease, a sometimes fatal cardiomyopathy which occurs especially in children and young women, and for Kashin–Beck disease, a chronic osteoarthropathy, which also affects mainly children. Several other selenium-responsive conditions occur in humans, including cardiomypathies and muscular problems in patients on total parenteral nutrition if there is inadequate selenium in the fluid. Normal functioning of the thyroid gland is also dependent on an adequate supply of the element (Arthur et al., 1999). There is evidence that selenium deficiency can cause a wide range of other problems, including immunodeficiency and increased susceptibility to various forms of cancer and to coronary arterial disease (Beck, 1999).

Selenium is widely distributed, but normally at levels of less than 1 mg/kg, in most foods. The richest sources are organ meat, such as liver (0.05 to 1.33 mg/kg), muscle meat (0.06 to 0.42 mg/kg), and fish (0.05 to 0.54 mg/kg) (Reilly, 1999). When total and soluble selenium were compared from four species (chicken, duck, turkey, and ostrich), it was observed that the total selenium content was higher in duck muscles (0.149 mg/kg) than in chicken (0.117 mg/kg), ostrich (0.106 mg/kg), and turkey muscles (0.110 mg/kg). The selenium content was higher in the oxidative muscles of turkey than in the corresponding glycolytic muscles. There is a considerable variation among species of total and soluble selenium content in muscle, which may be important for the oxidative stability and nutritional value of various meat products (Daun and Björn, 2003).

Vitamins

Vitamins, a heterogeneous group of substances, are vital nutrients that must be obtained from the diet. With the exception of vitamin D, they cannot be produced by the body. Thirteen substances, divided into two categories, are recognized as vitamins: the fat-soluble vitamins, of which there are four (vitamins A, D, E, and K) and the water-soluble vitamins, of which there are nine (vitamins C, B_1, B_2, B_6, B_{12}, niacin, pantothenic acid, and biotin). The water-soluble vitamin group contains eight vitamins collectively known as the B-complex vitamins, plus vitamin C. Poultry provides vitamins B_2, B_6, and niacin (Borenstein, 1981). When light and dark muscles are cooked, the cooking process decreases the thiamine content but not the riboflavin content (Al-Khalifa and Dawood, 1993).

Riboflavin (Vitamin B_2) Riboflavin is the most widely distributed of all the vitamins and is found in all plant and animal cells, although there are relatively few rich food sources. It is present naturally in foods in two bound forms as coenzymes: riboflavin mononucleotide and flavin adenine dinucleotide. These coenzymes participate in numerous metabolic pathways, including the citric acid cycle and the β-oxidation pathway, which breaks down fatty acids. For adults aged 19 and older, the RDA is 1.1 mg/day for women and 1.3 mg/day for men. Intake recommendations for riboflavin, like those for thiamine, reflect the higher energy needs of males. Pregnancy and lactation increase energy needs, so the RDA for women rises to 1.4 mg/day during pregnancy and 1.6 mg/day during lactation. Chicken meat is a moderately good source of riboflavin and thiamine. Thiamine and riboflavin contents in broiler light meat are 1660 μg/kg and 1.4 mg/kg, respectively, while the same vitamins in dark meat are 1920 μg/kg and 3.0 mg/kg, respectively. Differences have been found in the thiamine and riboflavin contents in breast and thigh from broiler meat according to age, sex, and the part being examined (Singh and Essary, 1971). Several researchers have studied the effects of cooking methods on vitamin content in chicken, and most of them have found that riboflavin is more heat stable than thiamine. Broiler light meat cooked by roasting, braising, deep-frying, and microwave methods resulted in thiamine retention ranging from 28 to 64%, while riboflavin was retained fairly well (46 to 94%). Cooking methods had no adverse effects on broiler dark meat's riboflavin content (Al-Khalifa and Dawood, 1993).

The most important factor influencing the stability of this vitamin is light, with the greatest effect being caused by light in the range 420 to 560 nm. Fluorescent light is less harmful than direct sunlight, but poultry products in transparent packaging can be affected by strip lighting in retail outlets. Riboflavin and riboflavin phosphate are both stable to heat and atmospheric oxygen, particularly in an acid medium. In this respect, riboflavin is regarded as being one of the more stable vitamins. It is degraded by reducing agents and becomes increasingly unstable with increasing pH. Vitamin B_2 is sensitive to light, particularly in a liquid medium such as milk. It remains stable in meat poultry wrapped in transparent packaging and kept in a lit retail area (Berry-Ottaway, 1993; Ryley and Kajda, 1994).

Pyridoxine (Vitamin B_6) Vitamin B_6 activity is shown by three compounds—pyridoxol, pyridoxal, and pyridoxamine—and these are often considered together as pyridoxine. Vitamin B_6 is found in red meat, liver, poultry, milk, and green vegetables. The vitamin B_6 coenzyme pyridoxal phosphate supports more than 100 different enzymes involved in reactions that include the transfer of amino groups (NH_2), carboxyl groups (COO^- or COOH), or water (as H and OH). These enzymes support protein metabolism, blood cell synthesis, carbohydrate metabolism, and neurotransmitter synthesis.

Pyridoxine is normally stable to atmospheric oxygen and heat. Decomposition is catalyzed by metal ions. Pyridoxine is sensitive to light, particularly in neutral and alkaline solutions. Average losses as a result of roasting or grilling of poultry

meat are 20%, with higher losses (30 to 60%) in stewed and boiled meat (Lenz and Lund, 1980; Berry-Ottaway, 1993).

The RDA for vitamin B_6 for men and women aged 19 to 50 is 1.3 mg/day. For men 51 years and older, the RDA is 1.7 mg/day; for women 51 years and older, the RDA is 1.5 mg/day. Pyridoxine content in breast meat ranging from 7.2 to 8.6 mg/kg has been reported for broilers aged 7 through 12 weeks old reared commercially (Hamm and Ang, 1984). Due to the role of vitamin B_6 in amino acid metabolism, people on very high protein diets may need higher intakes.

Niacin The term *niacin* is generic for both nicotinic acid and nicotinamide (niacinamide) in foods. The two forms have equal vitamin activity; moreover, they are present in a variety of foods and are also available as commercial isolates. Niacin occurs naturally in poultry, meat, and liver of hoofed animals. The niacin precursor tryptophan is found in protein-rich animal foods. To convert tryptophan to niacin in the body, it needs riboflavin, pyridoxine, and iron. A deficiency of any one of these nutrients decreases tryptophan to niacin; a deficiency of any one of these nutrients decreases tryptophan conversion. Tryptophan supplies about half of the average American's niacin intake. Both forms of niacin are normally very stable in foods because they are not affected by atmospheric oxygen, heat, and light in either aqueous or solid systems. The niacin coenzymes play key roles in oxidation–reduction reactions. Many metabolic pathways that promote the synthesis of new compounds, such as fatty acids, rely on reduced nicotinamide adenine dinucleotide phosphate (NADPH). NADPH is concentrated in cells (such as liver cells) that make up large amounts of fatty acids.

TABLE 9 Niacin Content of Various Poultry Products

Food Description	Niacin (mg/kg)
Chicken	
Breast meat	133.0
Fried meat only	
Dark meat	70.6
Light meat	134.1
Roasted meat only	
Breast with bone and skin	137.2
Drumstick with bone and skin	61.4
Thigh	65.4
Stewed, meat only, light and dark meat, chopped or diced	64.3
Duck, roasted, flesh only	51.1
Turkey	
Roasted meat only	
Dark meat	36.5
Light meat	68.2
Turkey neck, meat only, simmered	17.1

Source: Gebhardt and Thomas (2002).

Intake recommendations are expressed as niacin equivalents (NE). The RDA for adult men of all ages is 16 mg of NE/day, and RDA for adult women of all ages is 14 mg of NE/day. It increases to 18 mg of NE for pregnancy and 17 mg of NE for lactation. The light meat of broiler chicken contains more niacin than does the dark meat, and it is a better source of niacin than turkey or duck meat (Table 9). One hundred grams of fried chicken light meat provides 67% of the daily value.

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POULTRY MEAT TENDERNESS

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Handbook of Poultry Science and Technology, *Volume 1: Primary Processing*, Edited by Isabel Guerrero-Legarreta and Y.H. Hui

INTRODUCTION

In this chapter we explain the factors that affect poultry meat tenderness and provide a basis for developing instrumental methods adapted to the instrumental evaluation of poultry meat texture. It is important to understand the fundamental mechanisms responsible for poultry meat tenderness to assess tenderness by instrumental means. Our discussion in this chapter concentrates on the biological factors affecting tenderness and the correlation of instrumental measurements with sensory perception of texture. Since texture is a sensory property, it seems appropriate to obey this principle.

FACTORS AFFECTING POULTRY MEAT TENDERNESS

Tenderness is one of the most important meat quality characteristics as related to consumer acceptance. Deboning time, age, genetic strain, and cooking method are some of the major factors that can affect the tenderness of poultry (Lawrie, 1998; Northcutt et al., 2001; Cavitt et al., 2004). These factors can affect the fundamental mechanisms responsible for meat tenderness of poultry: the myofibrillar component, connective tissue component, and juiciness.

Rigor Mortis Development

Postmortem metabolism in muscle plays a significant role in the myofibrillar component that affects meat tenderness; therefore, it is important to understand rigor mortis development. The conversion of muscle to meat results in dramatic postmortem changes in the physical and biochemical aspects of muscle. This conversion, or rigor mortis development, is characterized by stiffening, loss of extensibility and elasticity, shortening of the muscle due to the formation of permanent actomyosin bonds, and decline in muscle pH and adenosine triphosphate concentration (Hedrick et al., 1989).

Adenosine triphosphate (ATP) is required for muscle contraction and relaxation; ATP stores deplete quickly and must be synthesized by the muscle. Aerobic metabolism is capable of producing relatively large amounts of ATP in order to keep the muscle functioning. However, loss of the circulatory system upon slaughter of an animal ceases oxygen delivery to the muscle. This results in a shift from aerobic metabolism to anaerobic metabolism, which depends solely on glycolysis; it is relatively inefficient in producing ATP. Adenosine triphosphate can also be formed from creatine phosphate and adenosine diphosphate (ADP); however, this supply of energy is short term. Continued use of ATP for relaxation, coupled with the reduced ability to produce ATP, results in insufficient ATP to prevent the formation of actomyosin bonds, and thus rigor mortis develops.

Not only is there a depletion of ATP, but the pH of the muscle also declines as rigor develops. The end product of glycolysis is lactic acid (Lehninger et al., 1993). In the live animal, the circulatory system removes lactic acid from the

muscle; however, with loss of the circulatory system after death, lactic acid accumulates in the muscle and lowers its pH (Khan and Nakamura, 1970). The pH decreases from 7.4 in living muscle to 5.5 to 5.7 after rigor development (Hedrick et al., 1989; Pearson and Young, 1989). The decline, and the rate of decline, in pH are important because these changes can affect many meat quality attributes, including color, water-holding capacity, and texture.

Myofibrillar Component of Meat Tenderness

The contractile state of the muscle is probably the most important factor affecting tenderness in market-aged poultry, due to their young age. Fennema (1996) reported that tenderness is influenced by the state of the sarcomere (basic contractile unit of muscle) when actomyosin cross-bridges form. During rigor mortis development, there is a natural shortening of the sarcomeres, due to the increased number of actomyosin bonds that are formed. This natural form of shortening does not affect tenderness a great deal. However, shortening that is induced can affect meat tenderness significantly. Prerigor excision, or early deboning prior to rigor completion, is a major cause of induced sarcomere shortening and meat toughening (Goodwin, 1984; Stewart et al., 1984) (Figure 1). In an early postmortem state, the cutting process can stimulate the muscle to contract, resulting in shorter sarcomeres. Furthermore, when deboning takes place prerigor, the lack of skeleton restraints limiting the shortening of boneless breast muscle results in more sarcomere shortening and tougher meat (Papa and Fletcher, 1988; Papa et al., 1989).

The relationship between deboning time and rigor development is important. Stewart et al. (1984) observed that meat that had a lower pH at deboning times of 0, 15, 30, 60, 120, and 240 min postmortem had lower shear values and was therefore considered "more tender." The lower pH at those times indicates muscle that is further along in rigor. The lower shear values can be expected because if muscle is an advanced state of rigor, less ATP will be present, so the

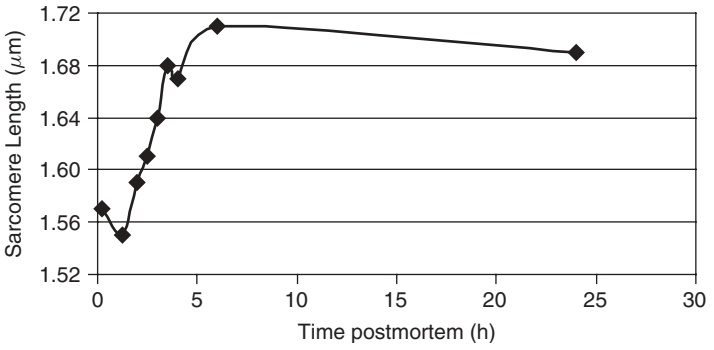


FIGURE 1 Length of sarcomeres in broiler breast fillets deboned at various times postmortem. (Adapted from Cavitt et al., 2004.)

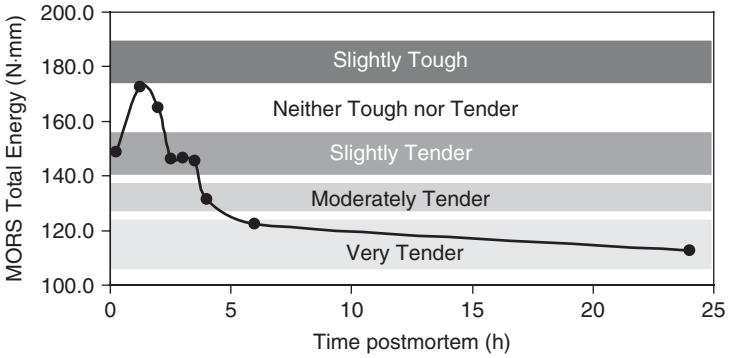


FIGURE 2 Meullenet–Owens razor shear values of cooked broiler breast fillets deboned at various times postmortem and their corresponding sensory equivalents. (Adapted from Cavitt et al., 2005.)

muscle is not as reactive to the deboning process. It is well documented that tenderness increases the longer the carcass is aged prior to deboning (Stewart et al., 1984; Dawson et al., 1987; Thompson et al., 1987; Cavitt et al., 2004, 2005) (Figure 2). Mehaffey et al. (2006) reported differences in tenderness of fillets deboned at 2 h postmortem among five commercial broiler strains and suggested that these differences were due to differences in muscle pH (i.e., rigor development) at the time of deboning, 2 h postmortem. Cavitt et al. (2005) reported that the percentages of consumers tested who considered broiler breast fillets as "just about right" for tenderness generally increased and the percentage judging "too tough" decreased as aging time increased. In fact, the percentage of consumers considering meat as to be too tough was approximately 60% when deboned $\geq$2 h postmortem, approximately 40% when deboned between 2.5 and 3.5 h postmortem, and approximately 20% when deboned $\leq$4 h postmortem. The interaction between deboning time and rigor development plays a significant role in the contractile state of muscle.

Age has also been reported to affect meat tenderness of young broilers. Northcutt et al. (2001) reported that when deboning early, younger broilers (42 to 44 days of age) were more tender than older broilers (49 to 51 days of age). Mehaffey et al. (2006) reported that fillets deboned 2 or 4 h postmortem from broilers raised to 7 weeks were significantly more tough than those raised to 6 weeks, indicating that age affects tenderness when deboning takes place soon after processing. Furthermore, meat deboned 4 h postmortem from 7-week-old broilers had instrumental shear energy values that correlated to consumer perceptions of "neither tough nor tender," whereas meat from 6-week-old broilers was considered "moderately tender," indicating slightly decreased tenderness in older birds. These differences due to age are probably due to differences in rates of rigor mortis and its interaction with deboning time. Northcutt et al. (2001) reported no differences in shear values among broilers of varying age when deboned at 4 h postchill (i.e., >4 h postmortem) or after. Rigor development

takes approximately 4 h in broilers, so the lack of differences in tenderness after this period in relatively young broilers is not surprising.

Connective Tissue Component of Meat Tenderness

Collagen is the most abundant protein in the body and makes up the majority of the connective tissue proteins (Hultin, 1985; Bechtel, 1986). Collagen has a unique structure, as it is designed to have high tensile strength. The collagen molecule is made up of three polypeptide chains that form into a triple helix known as *tropocollagen*, the structural unit of a collagen fibril. Collagen fibrils are assembled by the tropocollagen molecules aligning adjacently end to end. The molecules align in a quarter-stagger parallel pattern with an end overlap of 25 nm and are stabilized by ionic and hydrophobic interactions (Pearson and Young, 1989; Sims and Bailey, 1992). The fibrous structure of collagen has a high tensile strength due to its enzyme-induced intermolecular (between molecules) cross-links. As an animal ages, trivalent cross-links, also known as mature cross-links, form between the tropocollagen molecules. These cross-links increase the tensile strength of connective tissue and are heat stable. Therefore, they are the cause of toughness associated with mature animals because the collagen does not melt upon cooking and retains its tensile strength.

The connective tissue component of meat tenderness does not play a major role in young broilers. At young market ages (approximately 6 to 8 weeks), the mature cross-links have not yet formed and therefore the collagen will melt upon cooking. Connective tissue generally affects older animals, such as spent fowl, to a greater extent. For that reason, spent fowl meat is often used in soup products that have small meat portions and undergo high thermal treatments.

Water-Holding Capacity: Juiciness

Water-holding capacity is an important meat quality attribute because juiciness (a sensory attribute) and tenderness are partially dependent on the ability of the meat to retain moisture under normal storage conditions and during thermal processing (Jeffery, 1983; Lawrie, 1998). Juiciness, an indicator of water-holding capacity, is important in meat tenderness because it provides lubrication to consumers as they chew the meat. The cooking method can affect juiciness significantly. Cooking to high internal temperatures for long periods of time, in a dry, high-heat environment can lead to decreased juiciness, due to an increased loss of moisture. Lyon and Wilson (1986) evaluated various rigor conditions and cooking method effects on intact broiler breast fillets and reported that the cooking method had a significant impact on the moisture and tenderness of the finished product. Researchers have also reported significant differences in moisture content and tenderness utilizing various heating methodologies (Lyon and Lyon, 1990a; Roberts and Lawrie, 1974). Generally, moisture content and shear value are negatively correlated (Lee et al., 2008), so that as the moisture content decreases, shear values increase; thus, tenderness decreases.

INSTRUMENTAL ASSESSMENT OF POULTRY MEAT TEXTURE

Texture is related to the viscosity, elasticity, and other physical properties of foods (Amerine et al., 1965), but the relationship is very complex and sometimes difficult to explain. In past decades, researchers often instructed sensory panelists to evaluate texture as a single overall sensory attribute (Matz, 1962). With Szczesniak's pioneering work in the 1960s, researchers came to recognize that texture has many different attributes (Moskowitz, 1977). Szczesniak (1990) defined *texture* as "the sensory manifestation of the structure of the food and the manner in which this structure reacts to the applied forces; the specific senses involved being vision, kinesthetics, and hearing." From this it is quite clear that texture is a sensory property and that instrumental practices should yield results that can be related to the sensory perception of poultry meat texture.

There are many instruments and methods with which the texture of poultry meat can be evaluated mechanically. The techniques and methodologies that are used repeatedly in research and in industry are discussed first here and alternative methods are presented last. Prior to 1963, much of the work on meat texture focused on instrumental procedures to cut, compress, or manipulate food samples in some way (DeMan et al., 1979). Because texture at that time was not viewed as a multiparameter characteristic, research was geared toward finding the single measurement whereby texture could be measured. This early research helped develop devices such as the Warner–Bratzler shear blade and the Allo–Kramer shear cell, that are commonly used today in evaluating poultry meat texture. As texture research evolved and it became apparent that texture is a multiparameter characteristic, the need for an imitative instrumental test was felt so that multiple measurements that would relate to perception of sensory texture characteristics could be made. Development of the General Foods texturometer and the texture profile method eventually led to the development of the texture profile analysis (TPA) method.

Warner–Bratzler Shear Blade

The Warner–Bratzler (WB) shear blade, first described in 1928, has been used widely in texture evaluation laboratories and is still one of the most commonly used instruments for measuring meat texture. In the original WB device (Figure 3) a cylindrical meat core sample was placed in a triangular hole in a thin blade. The sample was then cut by pulling the blade manually through a slot, with the force indicated by a spring scale (DeMan et al., 1979). In its modern incarnation, WB attachments are fitted on motorized multitest instruments such as the TA-XT2i texture analyzer (Texture Technologies Corp., Scarsdale, New York/Stable Micro Systems, Godalming, Surrey, UK) or other universal testing machines, such as those available from Instron (Canton, Massachusetts). The blade dimensions have varied somewhat depending on the instrument manufacturer, but the blade used most commonly is stainless steel, the blade thickness is 1.4 mm, and the triangular opening is an isometric triangle with 40-mm sides.

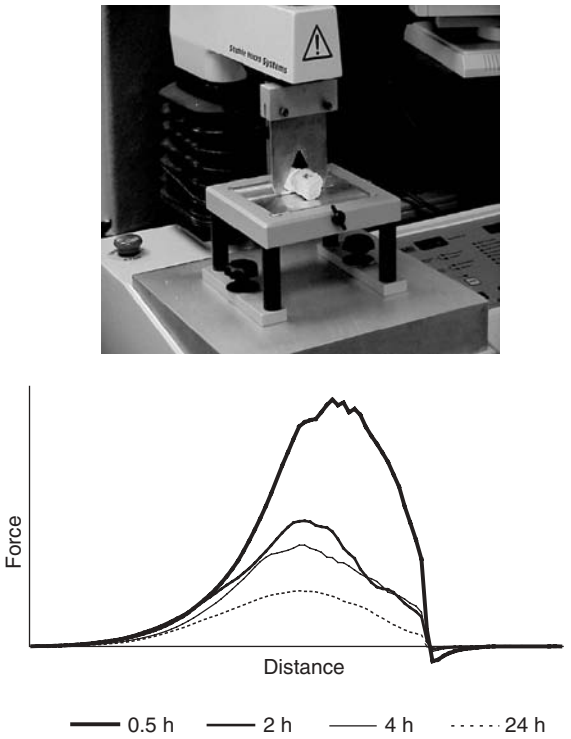


FIGURE 3 Warner–Bratzler device and sample force–deformation diagram.

Many studies in the late 1960s were performed on a variation of the WB device by testing the correlation between WB readings and sensory measurements, mainly for beef. Variation in test performance was attributable to poor control of experimental conditions and incorrect interpretation of test results (DeMan et al., 1979). Davey and Gilbert (DeMan et al., 1979) indicated that sample dimensions were very important to the accuracy of the WB shear blade since the cutting force depends on the test core diameter.

Poultry meat testing using WB equipment has been documented often during the past four decades (Palmer et al., 1964; Klose et al., 1970; Peterson, 1977; Lyon et al., 1985; Lyon and Wilson, 1986; Lyon and Hamm, 1986; Lyon and Lyon, 1990, 1991, 1993, 1997). Most of the published research has been for the WB tabletop apparatus, even though universal testing machines have also been employed (Lyon and Dickens, 1993; Dickens and Lyon, 1995; Lyon et al., 1997). Contrary to testing performed for beef muscles, testing of poultry muscles has been performed on strips rather than cores. Sample dimensions reported for this test have varied greatly over the decades, but it seems that most recent articles, published mainly by researchers from the U.S. Department of Agriculture's Russell Research Center (Athens, Georgia), have used a strip width of 19 mm (Table 1). In these studies, the strip length and thickness are being measured

TABLE 1 Test Conditions Described in the Literature for Warner–Bratzler, Allo–Kramer, Texture Profile Analysis, and Meullenet–Owens Razor Shear Tests

Test	Instrument	Sample Type	Sample Dimensions (cm)			Amount of Sample	Crosshead Speed	Number of Tests per Sample	Strain Level	Results Unit	Reference
			Height	Width or Diameter	Length						
Warner–Bratzler	WB apparatus	Strip	Variable	2.54	Variable	—	Stroke = 15 s	5	—	kg/g	Palmer et al. (1964)
	WB apparatus	Strips or whole muscle	—	Cross section measured	—	—	—	3–6	—	g/mm^2	Klose et al. (1970)
	WB apparatus	Strip	Variable	1.7	Variable	—	—	3	—	kg	Peterson (1977)
	WB apparatus	Strip	0.8–1.0	2.5	Variable	—	—	3	—	kg	Lyon and Wilson (1986), Lyon and Hamm (1986)
	WB apparatus	Strip	Variable	2.54	7.0	—	—	2	—	kg	Lyon et al. (1985)
	WB apparatus	Strip	Variable	1.9	Variable	—	—	2	—	kg/cm^2 or kg	Lyon and Lyon 1990a, 1991, 1993, 1997
	Instron	Strip	Variable	1.9	Variable	—	200 mm/min	2 shears per strip	—	kg/cm^2 or kg	Lyon and Dickens (1993), Dickens and Lyon (1995), Lyon et al. (1997)
Allo–Kramer	Kramer shear press	Strip	0.75–1.26	2.0	6.6	—	—	1	—	lb/inch^2-g	Dodge and Stadelman (1958)
	Kramer shear press	Strip	1	1	2–3	Recorded	7 mm/s	1	—	kg/g	Thompson et al. (1987)
	Kramer shear press	Strip	Measured	2.5	6.5	4.2–6.0 g	—	1	—	lb/g	Wise and Stadelman (1959), Simpson and Goodwin (1974)
	Instron	Cube	Variable	1	1	20 g	—	1	—	kg	Lyon and Lyon (1993)
	Instron	Cube	Variable	2	2	1 cube	500 mm/min.	1	—	kg	Smith et al. (1988)
	Instron	Cube	Variable	1.9	1.9	2 cubes (5g)	200 mm/min.	1	—	kg	Lyon and Lyon (1997)
	Instron	Strip	Variable	1.9	Variable	—	200 mm/min	1	—	kg	Lyon and Lyon (1990a)
	Instron	Strip	0.7	2.0	4.0	—	500 mm/min	1 on 2 strips	—	kg/g	Sams (1990), Owens and Sams (1997)
Texture profile analysis	Instron	Core	Variable	2.54	—	1 core	50 mm/min	1	70%	Variable depending on parameter	Lyon and Wilson (1986), Lyon and Lyon (1990b)
	Instron	Cube	Variable	2	2	1 cube	50–100 mm/min	1	70%		Smith et al. (1988)
Meullenet–Owens razor shear	Texture analyzer	Whole fillet	20-mm penetration	—	—	Whole fillet	5 mm/s	2–5		N·mm (total energy) N (force)	Cavitt et al. (2004), Xiong et al. (2006), Lee et al. (2007)

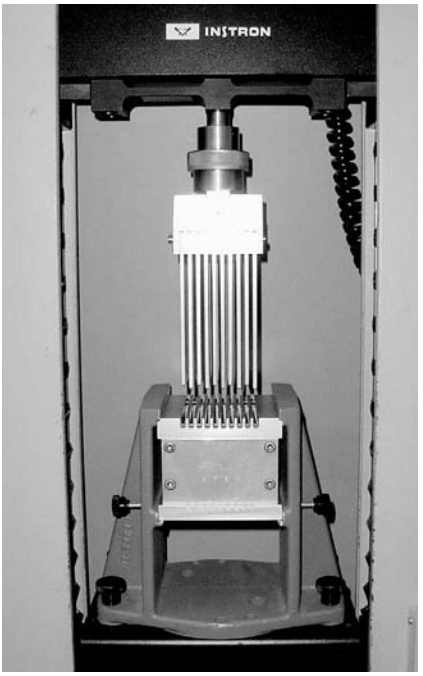
but not adjusted through trimming, and in many instances, two shear values are obtained for each strip. Peak load is recorded and expressed in kilograms or kg/cm^2 if the strip height is monitored. As for most instrumental tests performed on poultry and for that matter on many foods, the peak load is the instrumental parameter of choice. This approach neglects the fact that even though dominated by the attribute of toughness, texture in meats is a multidimensional quality. There have been few attempts at evaluating the use of additional parameters, such as the total energy expanded during the test, to describe the multidimensional aspect of meat texture (Davis, 2000). However, we believe that much research is needed in this area.

Allo–Kramer Compression-Shear Device

The pioneering work of Kramer at the University of Maryland led to the development of the first general-purpose test machine to measure the textural properties of foods by linear deformation. The Allo–Kramer (AK) shear instrument (Figure 4) was developed in the early 1950s. Like the WB device, it has been improved over the years and attachments are available to use on other machines, such as the Instron universal testing machine. The AK device has been used for a variety of foods, including vegetables, legumes, and meat, and has also been recommended by many researchers for use with poultry (Dodge and Stadelman, 1958; Wise and Stadelman, 1959; Simpson and Goodwin, 1974; Smith et al., 1988; Lyon and Lyon, 1990, 1993, 1997; Sams, 1990; Owens and Sams, 1997).

The AK instrument consists of a hydraulic press and ram (for the original press), a moving test cell, and the stationary cell component. The moving test cell consists of multiple blades (10 blades for poultry testing), 3 mm thick and 3 mm apart, that are connected to the ram, which moves the moving blades into the stationary cell (66 mm wide, 67 mm long, and 68 mm depth), at the bottom of which the meat sample is located. The AK device differs from the WB instrument in that it uses the multiple blades first to compress and then to shear the meat sample.

DeMan and Kamel (1981) reported that the sample dimensions had an effect on the resulting measurement for meat toughness using the AK shear instrument. Smith et al. (1988) also reported that sample orientation and condition could be important factors to consider when comparing results among studies where shear tests such as the WB and AK were conducted. The AK device is similar to the WB instrument in that a maximum shear value is also yielded, which cannot relate to the assessment or prediction of multiple sensory characteristics. Most of the studies performed on poultry meat have used sample strips, but a few have used cubes (Table 1). Over the years the size of the strips has been found to vary from 1.9 to 2.5 cm in width and from 3 to 7 cm in length. The height of the strip is rarely adjusted but often measured. It seems that in recent years two main sample geometries have become popular (Table 1). First, Sams (1990) described a test on a strip of 0.7 cm height, 2.0 cm width, and 4.0 cm long with a crosshead speed of 500 mm/min. Lyon and Lyon (1990) performed a



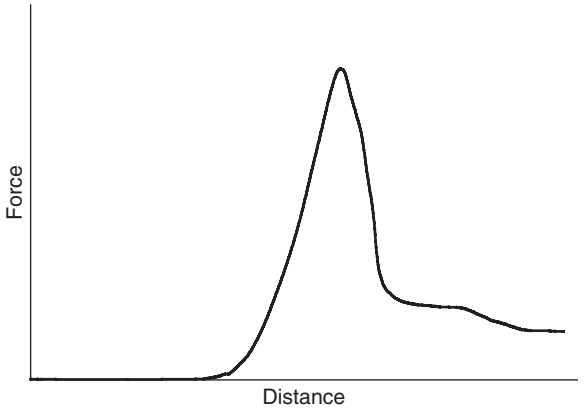


FIGURE 4 Allo–Kramer shear cell and sample force–deformation diagram.

similar test using 1.0-cm-wide strips of unspecified length at a crosshead speed of 200 mm/min. In other studies, Lyon and Lyon (1993, 1997) used cubes (either a specific number or a set weight) of 1- or 2-cm sides.

The results of the AK shear test are almost always expressed in kg/g of sample. This practice is interesting since it is assumed that the shear force is a linear function of the weight of the sample. This disregards, however, the fact that denser samples may also be significantly harder than less dense samples.

This questions the legitimacy of this correction if the sample dimensions are carefully controlled, as one may lessen or increase in some instance the level of difference found for various samples.

Texture Profile Analysis

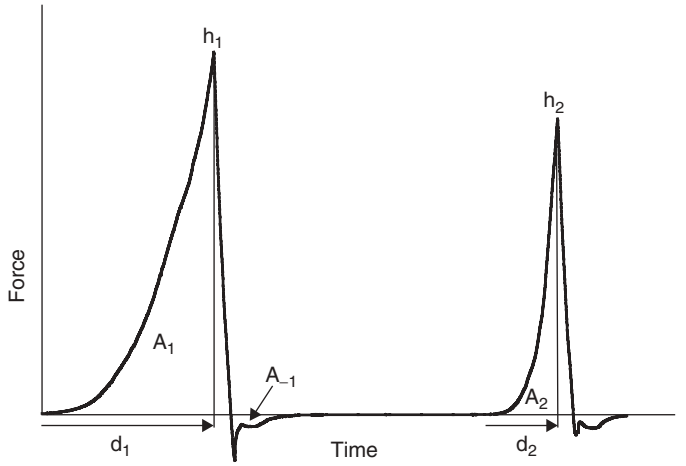
Texture profile analysis (TPA) is an instrumental method that imitates the conditions to which food is subjected in the mouth (Bourne, 1978). The first attempt to imitate mastication by instrumental means was with the MIT denture tenderometer (Szczesniak, 1962), in which a set of dentures was motorized and a force–time curve was obtained.

The major breakthrough in TPA was the development of the General Foods texturometer (Szczesniak, 1962), which used a small flat-faced cylinder to compress a bite-sized piece of food, usually a cube, to 25% of its original height two times in a reciprocating motion that imitated the action of the human jaw (Bourne, 1978). Similar to the way in which the sensory texture profile method provides a complete description of the textural characteristics of a food product, the instrumental TPA attempts to quantify several instrumental parameters (DeMan et al., 1979). Analysis of the force–time curve of the TPA instrument method led to the extraction of seven instrumental parameters (five measured and two calculated from the parameters measured) (Bourne, 1978). A sample force–deformation curve and the TPA parameters are shown in Figure 5. However, TPA is not a perfect method. TPA correlates a specific sensory attribute with several instrumental parameters. Selection of these instrumental parameters is for the most part intuitive. Furthermore, these individual parameters have shown in some cases to relate poorly to the corresponding sensory parameters (Meullenet et al., 1997). TPA has been used by a few people to evaluate poultry muscle texture (Lyon and Wilson, 1986; Smith et al., 1988; Lyon and Lyon, 1989; Meullenet, 1996). Measurements have been made on cores of 2 to 2.54 cm in diameter at a strain level of 70% and a crosshead speed between 50 and 100 mm/min.

Meullenet–Owens Razor Shear

Recently, researchers have investigated use of a razor blade shearing method, known as Meullenet–Owens razor shear (MORS), for determining poultry meat tenderness (Cavitt et al., 2001, 2004, 2005; Xiong et al., 2006). This method was developed in an effort to create a method equal or superior to existing methods that would also have a significant labor savings. By shearing an intact fillet, no sample cutting is required, which reduces labor and potentially decreases the variability of results due to cutting samples to exact dimensions.

The MORS method is conducted on cooked whole breast fillets and consists of shearing the sample perpendicularly to the longitudinal fiber orientation with a razor blade (flat-edge scalpel blade) in two to five predetermined locations (Cavitt et al., 2004; Xiong et al., 2006; Lee et al., 2007) (Figure 6). Shear force (N) and energy (N·mm) are determined using the TA-XT2i texture analyzer with a 5-kg



Parameter	Definition
Hardness	Peak force during the first compression cycle, $\mathbf{h_1}$
Cohesiveness	Ratio of the energy during the second compression (to peak force) to that during the first compression, $\mathbf{A_2/A_1}$
Adhesiveness	Negative force area for the first bite, representing the work necessary to pull the compression plate away from the sample, $\mathbf{A_{-1}}$
Springiness	Height that the food recovers during the time that elapses between the end of the first bite and the start of the second bite, $\mathbf{d_2/d_1}$
Gumminess	Product of hardness and cohesiveness, $\mathbf{h_1(A_2/A_1)}$
Chewiness	Product of gumminess and springiness, $\mathbf{h_1(A_2/A_1)(d_2/d_1)}$

FIGURE 5 Texture profile analysis sample force–deformation curve and instrumental parameter definitions. (Definitions modified from Bourne, 1978.)

load cell using a razor blade probe with a height of 24 mm and a width of 8.9 mm set to a penetration depth of 20 mm. For samples of less than 20 mm, total energy values should be converted to an equivalent energy value at a penetration depth of 20 mm, as the energy values are affected by penetration depth according to data by Xiong et al. (2005). The crosshead speed is 5 mm/s, the sample shear penetration depth is 20 mm, and the trigger force is 0.1 N. Using a texture analyzer, data points are collected with an acquisition rate of 200 points/s. The instrumental data

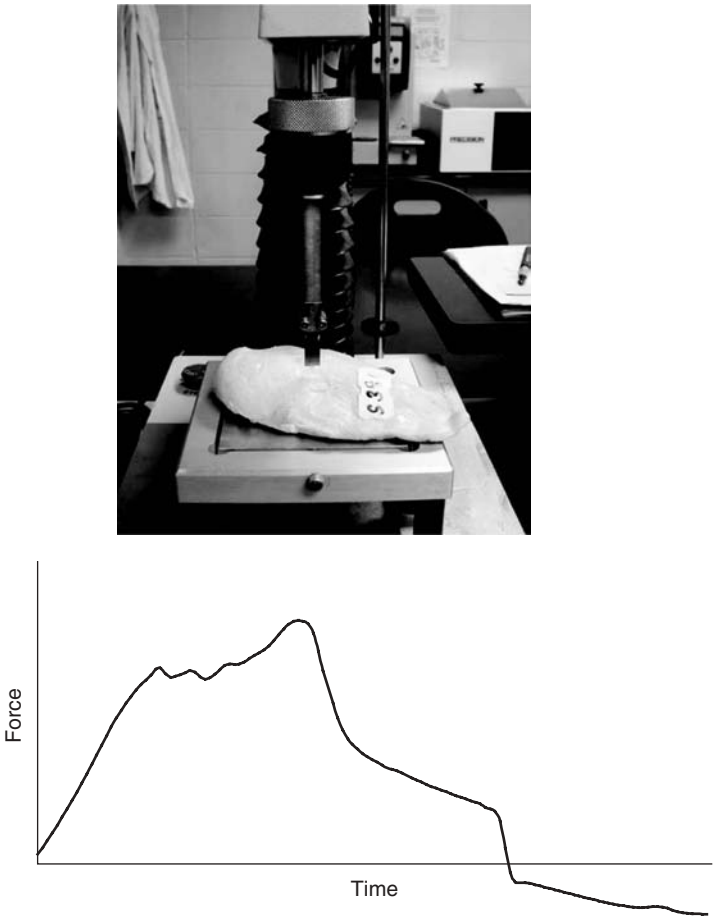


FIGURE 6 Meullenet–Owens razor shear and sample load–deformation diagram.

were collected using Texture Exponent 32 version 1.0.0.92. Total shear energy (MORSE, N·mm) is calculated from force–deformation curves using the macro options of Stable Micro Systems' texture exponent.

Cavitt et al. (2001) compared the use of a razor blade (i.e., MORS) and needle puncture to the AK shear press. Although no sensory data were acquired for this study, it was found that the razor blade shear test was equal to the AK shear press in discriminating between samples deboned after various aging durations.

Cavitt et al. (2004) evaluated MORS, Allo–Kramer, and the sarcomere length of broiler breast fillets. MORS force, energy, and sarcomere length were highly correlated to the AK device, but the MORS energy had the highest coefficient of determination ($R^2 = 0.87$). MORS energy and sarcomere length were highly correlated ($R^2 = 0.89$). Coefficients of determination were lower for the relationship of the AK press to sarcomere length ($R^2 = 0.82$) or MORS force to sarcomere

length ($R^2 = 0.72$). Xiong et al. (2006) compared multiple instrumental methods for assessing poultry meat tenderness and reported high correlations between the methods. MORS energy was highly correlated to both the WB ($r = 0.98$) and AK ($r = 0.92$) devices. MORS force was also highly correlated to the WB and AK devices ($r = 0.96$ and 0.88, respectively). In both studies, all methods detected differences in values as aging time increased. Shear forces or energies decreased as postmortem deboning time (aging) increased, and sarcomere length was larger in samples with longer aging times. In both studies the instrumental methods were compared to sensory methods, and these results are discussed in a later section.

Other Instrumental Tests

The methods described previously have been discussed by many others, and simply outlining the methods one more time would not set this description apart from many others. Although less well known than those discussed above, other devices have also been described. One of these is the Volodkewitz bite jaws, a method originating in Europe that has not enjoyed much success in the United States. The device consists of upper and lower blades, the upper blade being mobile. In addition, the sides of the lower blade are attached to a sample holder, allowing it to retain the sample in place during shearing (Figure 7). Although few data are available, the force–deformation curve for meat samples has a very interesting pattern (Figure 7). The curve is a two-peak curve thought to represent the characteristics of muscle fibers (peak 1, Figure 7) and connective tissues (peak 2, Figure 7). This is especially important since it seems to be the only instrumental test capable of differentiating between these two muscular structural components. In beef, peak 2 is very pronounced because of the importance of connective tissues in determining texture. However, in poultry meat, peak 2 would be expected to be much less pronounced. To our knowledge, no study on the correlation between sensory texture attributes of poultry meat and Volodkewitz parameters has ever been conducted.

Recently, Davis (2000) compared the WB shear test to two alternative tests: needle penetration (Figure 8) and Kraft Knife cutting. In these studies the author compared the performance of the three devices by correlating instrumental results to sensory measurements from a descriptive panel. In this study, multiple instrumental parameters were extracted and related to sensory data using multivariate regression analysis. The conclusions of the study were that both needle puncture and WB performed similarly, while the Kraft Knife showed significantly lower correlations. Although the data presented in this study are not sufficiently ample evidence, needle penetration may be an alternative to the WB, AK, or TPA tests. The main advantages of the needle test is that it does not require cutting the sample into a strip or core, that measurements are not dependent on sample dimensions, and that a multitude of measurements can be made on the same muscle (i.e., giving a distribution of texture within a muscle). Although these alternative methods have not been proven better than existing methods in

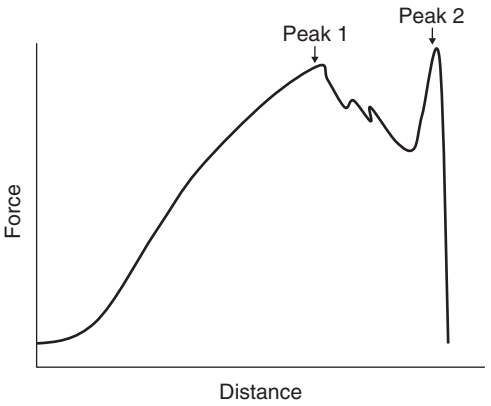


FIGURE 7 Volodkewitz bite jaws and sample load–deformation diagram.

describing the texture of poultry meat, their simplicity may be enough to promote their use in the poultry industry.

Correlating Sensory and Instrumental Texture Data

There is great interest in designing instrumental tests that could predict sensory data leading to the development of instrumentation that could complement descriptive panels. The fact that sensory evaluation is expensive and time consuming has been one of the main motivations for developing reliable instrumental tests capable of accurate prediction of the perception of texture characteristics. In the last 100 years, tremendous effort has been directed toward the development

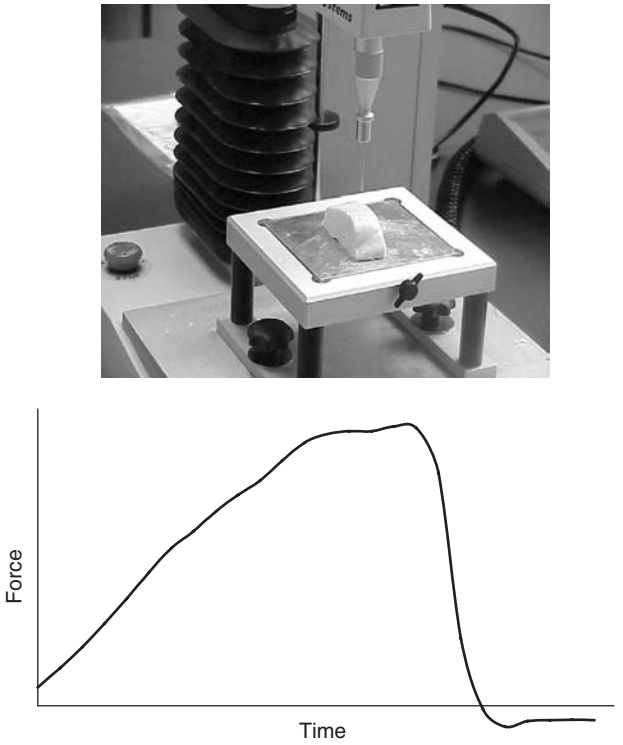


FIGURE 8 Needle puncture and sample load–deformation diagram.

of instrumental methods for evaluating texture (Szczesniak, 1987) and correlating these instruments with sensory data.

Many texture-measuring instruments are used by quality assurance departments in the food industry and have been successful in using these instruments to decide whether or not a product is within general specifications (Szczesniak, 1987). Texture instruments are calibrated to respond linearly to the intensity of the mechanical property tested (Szczesniak, 1987). This linear relationship is not true for human senses and often results in low correlation between sensory and instrumental data. Many factors affect the correlation between sensory and instrumental data, the principal ones being the testing conditions for both instrumental and sensory tests, the nature of the test sample, and the selection of sensory terms and scales (Szczesniak, 1987).

Generally, the closer the instrumental test conditions to the conditions for the sensory evaluation method, the higher the correlation is between the two tests (Szczesniak, 1987). The sample condition is also an important factor in obtaining a high correlation between sensory and instrumental data. For this correlation to increase, the sample must be as homogeneous as possible, which is a major problem with poultry muscles. Borderias et al. (1983) showed that

the correlation between sensory texture and instrumental analysis of fish was increased from nonsignificant to significant by mincing the fish meat instead of analyzing the fillets. However, it could be argued that mincing eliminated some textural characteristics, so that this practice is probably not to be recommended to solve problems of nonhomogeneity.

Sensory terms and scales can also affect the correlation between instruments and sensory scores. Karl and Schreiber (1985) studied the texture of canned fish utilizing the texture profile method along with the instrumental texture profile analysis. In their study they found that the panel's evaluation of "consistency" could not be correlated to instrumental measures. But when consistency was separated into "response on the first bite," "structure after prolonged chewing," and "juiciness," higher correlations were obtained for "response on the first bite" and "structure after prolonged chewing."

When sensory and instrumental data are regressed together, it is also suggested that the two factors (x and y) that are being correlated be related in some way (Szczesniak, 1968). A researcher may find a good correlation between an instrumental measurement of texture (i.e., maximum force) and a sensory attribute (i.e., sweetness). But a high correlation does not automatically mean that the two factors have anything to do with one another. Obviously, maximum force and sweetness do not explain one another very well. Factor x simply varied consistently with factor y and really does not explain anything about factor y. That is, when a correlation is found between sensory perception and instrumental measurements, causality needs to be established. When these and other factors are controlled, a researcher can expect better correlation between sensory and instrumental data.

Several researchers have evaluated correlations between instrumental and sensory texture data for poultry breast meat (Simpson and Goodwin, 1974; Lyon and Lyon, 1990a,b, 1997; Davis, 2000). Simpson and Goodwin (1974) reported on the correlation between Allo–Kramer shear and taste panel evaluation of the tenderness for 24 samples subjected to four processing conditions. The correlations reported were between 0.71 and 0.76 (i.e., marginal correlation). There were serious limitations to this study, including an untrained panel, use of a five-point category scale not broad enough to allow fine discrimination between samples, and a limited number of treatments. Lyon and Lyon (1990b) reported on the correlation of poultry breast meat tenderness evaluated by AK instrumentation, WB instrumentation, and an untrained panel composed of 24 people. The panel evaluated juiciness, tenderness, and texture acceptability of 24 samples submitted to eight different treatments (i.e., four deboning times and two cooking treatments). Correlations were found to be poor for juiciness ($r = 0.40$ to 0.53), but acceptable for tenderness ($r = 0.82$ to 0.84) and texture acceptability ($r = 0.81$ to 0.83). The authors also indicated that instrumental values of 3.5 to 6.5 kg for the WB and 6.0 to 8.8 g/g for the AK were in the slight to moderate range of tenderness. In the same year, Lyon and Lyon (1990a) evaluated the potential for instrumental TPA to predict the sensory profiles of poultry breast

meat. Treatments similar to those in the previous study were applied to the samples, but correlations were found to be much lower. Sensory hardness was poorly correlated to its instrumental corollary ($r = 0.53$ to 0.56); so was cohesiveness and cohesiveness of mass with instrumental cohesiveness ($r = 0.40$). Correlations were higher for springiness ($r = 0.70$) and chewiness ($r = 0.73$). Lyon and Lyon pointed out that the relationships of individual parameters did not show conclusive, singular corollaries between individual instrumental and sensory attributes. They concluded that instrumental TPA parameters may relate to some important muscle components that play a role in determining total texture (i.e., probably connective tissue) but that other tests, such as shearing tests, may need to be conducted to obtain a more complete description of poultry meat texture. Lyon and Lyon (1997) again published on the relationship between instrumental and sensory measurements of poultry breast meat. In this study, both WB and AK shear measurements were correlated with texture profiles determined using a trained descriptive panel. Correlations reported were high for all mechanical and chewdown attributes studied. In particular, initial hardness was highly correlated to both WB ($r = 0.91$) and AK ($r = 0.95$) data. Chewdown hardness was equally well predicted with both instrumental tests ($r = 0.91$ to 0.95). Low correlations were reported for attributes related to juiciness and residual attributes such as toothpack and mouth coating. This study seems to point out that WB and AK shear results are adequate to assess mechanical characteristics of poultry meat. In a study by Davis (2000), correlations for poultry breast meat deboned at various times postmortem were drawn between sensory evaluation and instrumental tests, including WB shear, needle puncture, and Kraft Knife cutting. In this study the author used multiple instrumental parameters in combination with multivariate regression to determine predictive models of eight sensory texture attributes of poultry breast meat. Results showed that both needle puncture and WB shear seemed to correlate equally well with sensory perception of poultry breast meat texture. Correlations in this study varied from 0.31 for springiness to 0.81 and 0.82 for initial and chewdown hardness, respectively.

Cavitt et al. (2004) evaluated instrumental (MORS, AK, sarcomere length) and descriptive sensory methods for assessing the meat tenderness of broilers deboned several times pre- and postrigor. In that study, both instrumental and sensory methods detected differences in "tenderness" as a function of deboning time. MORS total energy (MORSE), force (MORSF), and sarcomere length (an indirect measure of tenderness) were all better predictors ($R^2 = 0.84$, 0.75, and 0.86, respectively) of the sensory attribute, initial hardness, than was AK shear ($r^2 = 0.68$). Other sensory attributes, such as cohesiveness, cohesiveness of mass, and number of chews, followed similar trends. Overall, researchers stated that the MORSE and sarcomere length were better predictors of sensory attributes than was AK shear. This was the first study to show the relationship between the MORS method and sensory attributes. In other studies, Cavitt et al. (2005) compared MORS, AK, and WB and determined that all were similar predictors of descriptive and consumer sensory analysis (Cavitt et al., 2005; Xiong et al., 2006). However, using the MORS method, the labor involved can be reduced

TABLE 2 Classification of Acceptance and Intensity of Tenderness for Warner–Bratzler, Allo–Kramer, and Meullenet–Owens Razor Shear Tests[a]

Attribute	Hedonic Scale		WBF	AKSV	MORSE
Tenderness acceptance	Dislike extremely	1	≥17.84	≥17.37	≥220.72
	Dislike very much	2	15.57–17.83	15.27–17.36	204.07–220.71
	Dislike moderately	3	13.30–15.56	13.17–15.26	187.43–204.06
	Dislike slightly	4	11.02–13.29	11.07–13.16	170.78–187.42
	Neither dislike nor like	5	8.77–11.03	8.97–11.06	154.13–170.77
	Like slightly	6	6.51–8.76	6.87–8.96	137.48–154.12
	Like moderately	7	4.24–6.5	4.77–6.86	120.83–137.47
	Like very much	8	1.97–4.23	2.67–4.76	104.19–120.82
	Like extremely	9	≤1.96	≤2.66	≤104.18
Tenderness intensity	Extremely tough	1	≥16.83	≥16.55	≥212.77
	Very tough	2	14.69–16.82	14.53–16.54	197.16–212.76
	Moderately tough	3	12.54–14.68	12.52–14.52	181.55–197.15
	Slightly tough	4	10.40–12.53	10.51–12.51	165.94–181.54
	Neither touch nor tender	5	8.26–10.39	8.50–10.5	150.32–165.93
	Slightly tender	6	6.12–8.25	6.49–8.49	134.71–150.31
	Moderately tender	7	3.97–6.11	4.48–6.48	119.10–134.7
	Very tender	8	1.83–3.96	2.47–4.47	103.48–119.09
	Extremely tender	9	≤1.82	≤2.46	≤103.47

[a]WBF, Warner–Bratzler shear force (kgf); AKSV, Allo–Kramer shear value (kgf/g); MORSE, Meullenet–Owens razor shear energy (N·mm).

and the test can be performed faster, due to no sample cutting. One of the interesting features of MORS is the development of corresponding scales between specific sensory attributes or consumer acceptance of tenderness and ranges of instrumental measures (Table 2).

Modeling Techniques in Texture Evaluation

Food technologists involved in sensory science are developing novel approaches for increasing the correlation between sensory and instrumental assays of food material. Many researchers who are interested in instrumental texture measurements extract parameters such as maximum load, slope or modulus, and area under the curve or energy. These parameters are then used to correlate sensory attributes using simple regression techniques. These regression techniques attempt to fit a model to observed data, to quantify the relationship between two groups of variables. The model fitted may then be used either to describe the relationship between the sensory and instrumental variables or to predict sensory scores. In this instance, the researcher is assuming that the relationship between instrumental and sensory data is linear. However, human senses do not respond to intensities in a linear fashion (Stevens and Galanter, 1957; Meullenet et al.,

1997). Using this approach and failure to recognize the nonlinear relationship between sensory and instrumental measurements often results in poor statistical correlation (Szczesniak, 1987). Alternative approaches in correlating instrumental tests to sensory data are the topic of many research initiatives. Nonlinear models such as those described by Fechner (logarithmic law) and Stevens (power law) have been tested for the purpose of relating the perception of food texture to instrumental measurements (Meullenet et al., 1997). Although not done for whole-muscle meats, these models have been shown to improve significantly the correlation between sensory texture measurements and their instrumental corollaries (Meullenet et al., 1998; Meullenet and Gross, 1999). With many empirical tests, such as WB, AK, and TPA, the choice of instrumental parameters correlated to a given sensory attribute (e.g., the A_2/A_1 ratio in a TPA test is an instrumental measure of cohesiveness) is often based on intuition rather than scientific facts. As a result, there have been few attempts to rely on statistics to establish the relationship between sensory and instrumental measurements.

Spectral stress strain analysis (SSSA) is a novel approach to the prediction of texture attributes (Gross, 1999). SSSA was developed recently (Meullenet et al., 1998) but was inspired by techniques used in chemometrics (i.e., near-infrared spectroscopy) for several decades. In SSSA, the shape of the force–deformation curve from an instrumental assay of texture properties is used to predict sensory attributes instead of individual parameters that are chosen arbitrarily. The force–deformation curve is treated as a spectrum whereby the loads at various strain or deformation levels are subjected to multivariate analysis techniques (e.g., partial least-squares regression) to predict single sensory attributes. Because statistics are heavily involved in developing the models, the number of samples necessary to build a calibration model is much larger than for simpler approaches. However, multivariate techniques allow the validation of predictive models, so that these models become useful for prediction purposes.

Davis and Meullenet (2000a,b) showed the potential of these alternative data analysis techniques for predicting multiple sensory attributes of whole breast meat. Although these studies were preliminary and results should be confirmed by other studies, Davis and Meullenet (2000a) showed that several texture attributes could be predicted accurately using multiple instrumental parameters and SSSA.

CONCLUSIONS

The focus of this chapter was to provide a basic understanding of factors that affect meat tenderness and to demonstrate that when it comes to evaluating poultry meat texture, there is no standard methodology. Not only should a suitable test be selected, but the conditions of the test (e.g., sample size, crosshead speed) need to be determined. The experimenter should also realize that instrumental tests should not be used as a substitute for sensory evaluation when detailed information about the texture of a sample is needed, as instrumental tests described here have been shown not always to correlate more closely with the human perception of poultry meat texture.

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27

PALE, SOFT, AND EXUDATIVE POULTRY MEAT

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INTRODUCTION

PSE is an acronym for *pale, soft, and exudative* and refers to meat that is pale in color, forms soft gels, and has poor water-holding ability. Used most frequently in reference to pork, such defective meat is being seen with increasing frequency in

Handbook of Poultry Science and Technology, *Volume 1: Primary Processing*, Edited by Isabel Guerrero-Legarreta and Y.H. Hui

turkey- and broiler-processing plants. It has been estimated that PSE-type meat represents 5 to 47% of meat produced in the poultry industry (Barbut, 1996; Owens et al., 2000a; Woelfel et al., 2002). The high incidence of PSE meat in the poultry industry can result in significant economic losses to processors, due to the loss of water-holding capacity, change in color, and change in texture, especially in products processed further (Owens et al., 2000a).

PSE CHARACTERISTICS

Typical characteristics of PSE poultry meat have been reported by a number of researchers (Owens et al., 2000a; Van Laack et al., 2000; Woelfel et al., 2002; Zhang and Barbut, 2005a) (see Table 1). In PSE meat, the pH is generally low (pre- and postrigor), due to accelerated postmortem glycolysis. This low pH causes lower water-holding capacity in the form of higher drip losses, higher cooking losses, and higher expressible moisture, because more water is contained in the extracellular space than in the intracellular space (Swatland, 1993). Barbut et al. (2005) evaluated the microstructure of PSE meat and found more intercellular open space compared to that in fillets considered normal, or dark, firm, and dry (DFD) meat. These open spaces may contribute to the lower water-holding capacity that is typically observed with PSE meat, especially drip loss.

Furthermore, color is also affected because with more water in the extracellular space, light will be reflected rather than absorbed (Lawrie, 1998). Therefore, PSE meat is pale or has high L^* values (an indicator of lightness). Muscle pH is highly correlated ($r = -0.7$) with the L^* value, and the pH and L^* values are moderately to highly correlated with measurements of water-holding capacity (Barbut, 1993, 1997; McCurdy et al., 1996; Owens et al., 2000a; Van Laack et al., 2000; Woelfel et al., 2002). Because of its high correlation with pH and water-holding capacity and its relative ease of measurement, the L^* value, or color, has been recommended as a tool used to classify meat into PSE and normal categories.

TABLE 1 Characteristics of Pale and Normal Turkey and Chicken Breast Meat from a Commercial Plant*

	Turkey		Chicken	
Measurement	Normal	Pale	Normal	Pale
Lightness (prerigor†)	47.31^b	56.85^a	51.38^b	60.41^a
Lightness (24 h postmortem)	48.99^b	54.72^a	52.15^b	59.81^a
pH (prerigor†)	6.09^a	5.72^b	6.07^a	5.76^b
Expressible moisture (%)	23.41^b	32.31^a	25.18^b	30.61^a
Drip loss (%)	0.72^b	2.52^a	3.32^b	4.38^a
Cook loss (%)	15.17^b	17.56^a	21.08^b	26.39^a

Source: Data for turkey from Owens et al. (2000); data for chicken from Woelfel et al. (2002).
*Means within row–within species without common superscripts (a's or b's) differ significantly ($p < 0.05$).
†Prerigor sampling times: 1.5 h postmortem for turkey and 3 h postmortem for chicken.

PROTEIN DENATURATION IN PSE MEAT

PSE meat develops due to accelerated postmortem glycolysis, which leads to protein denaturation (Hedrick et al., 1989; Lawrie, 1998). Rapid glycolysis leads to a rapid decline in postmortem pH. Rapid postmortem glycolysis has been observed in swine and in turkeys, where postmortem pH is less than 5.8 at 45 min in swine and at 15 min in turkeys compared to "normal" muscle pH > 6 at either time (Enfalt et al., 1993; Rathgeber et al., 1999). The rapid glycolysis can be a result of premortem stress, which is discussed later. When this rapid decline in pH is combined with the high carcass temperatures typically observed within the first hour after death in turkeys and pigs, denaturation of proteins can occur (Penny, 1969). Myofibrillar and sarcoplasmic proteins can both be denatured as a result of the combined events and cause changes in color and water-holding capacity (Pietrzak et al. 1997; Rathgeber et al., 1999; Van Laack et al., 2000; Alvarado and Sams, 2004; Barbut et al., 2005). Denaturation of the myofibrillar proteins is generally more associated with decreased water-holding capacity, whereas denaturation of sarcoplasmic proteins is more associated with pale color (Offer, 1991).

Denaturation of myofibrillar proteins, specifically myosin, can cause a decrease in water-holding capacity (Penny, 1969; Offer, 1991). However, Offer (1991) stated that there was no reason to suppose that complete denaturation of myosin was required to produce PSE symptoms. There have been various reports on the mechanism of myosin insolubility. Bendall and Wismer-Pedersen (1962) suggested that sarcoplasmic proteins denatured and precipitated onto the myofibrils, resulting in poor extractability of myofibrillar proteins. Similarly, Pietrzak et al. (1997) observed that phosphorylase, the major sarcoplasmic protein, precipitated onto the myofibrils in turkey pectoralis but only at the Z line. Therefore, in contrast to previous reports, Pietrzak et al. (1997) suggested that myosin denaturation, rather than the sarcoplasmic proteins coating the myofibrils, was responsible for poor myosin extractability. Lower myosin extractability in PSE poultry has been reported by others as well (Rathgeber et al., 1999; Barbut et al., 2005). Offer (1991) suggested that denaturation of sarcoplasmic proteins contributed to high light scattering in meat but was probably not responsible for the softness or lower water-holding capacity of PSE meat. In addition, Offer (1991) reported that denaturation of myosin causes the myosin head to shrink, resulting in additional shrinkage of myofibrillar lattice and thereby increasing the expulsion of water into the extracellular space (decreasing WHC). The authors observed that the filament lattice in PSE meat had shrunk substantially compared to normal muscle. Offer (1991) also stated that myosin denaturation depended on the rate of pH decline, final pH, and chilling regime.

Denaturation of proteins, specifically the sarcoplasmic proteins, can cause increased scattering of light in the muscle, resulting in lighter (or paler) meat (Bendall, 1973). Additionally, the transmittance of individual muscle fibers is decreased at low pH, resulting in less light absorption and paler meat (Swatland, 1993). Furthermore, myofibrils are birefringent, or have two refractive indices,

which causes light to take two different paths as it travels through the myofibrils. Muscle pH strongly affects the difference between the two paths, with increased light scattering at low pH levels (Swatland, 1993). In addition, shrinkage of myofibrils at low muscle pH levels causes greater scattering of light at the myofibril surface (Offer et al., 1989; Swatland, 1993). Van Laack et al. (2000) reported a high correlation between the amount of sarcoplasmic protein extracted and the L^* value ($r = 0.71$).

The "S" in PSE refers to the soft gels that are formed in products processed further. PSE meat produces weaker gels, due to the protein denaturation that occurs. Alvarado and Sams (2004) reported that gel strength decreased as the chilling temperatures of carcasses increased. Carcasses held at 30°C had the lowest gel strength; carcasses held at 0°C had the highest gel strength. Zhang and Barbut (2005) reported decreased gel characteristics (e.g., facture force, hardness, springiness, chewiness, and gumminess) of PSE meat compared to normal or DFD meat, indicating weaker gel formation. Weaker gels can lead to the soft, mushy texture that can be experienced in products processed further, such as a whole-muscle deli loaf.

CAUSES OF PSE MEAT

The causes of the PSE conditions seem to be genetic, environmental, and a combination of both. In swine, a genetic mutation in the ryanodine receptor has been identified (Fujii et al., 1991) and has been associated with animals that are stress susceptible and prone to developing PSE meat. Although this genetic mutation is well understood in swine, to date there is no evidence to support or refute a genetic mutation in poultry related to PSE development. PSE meat is also associated with pre- and postmortem stressors, including heat stress, preslaughter handling practices, and carcass chilling regimes. At this time, the development of PSE meat in poultry is generally attributed to these environmental (pre- and postmortem) stressors, due to a lack of understanding of the genetic component in poultry. Because of the similarities between pork and poultry with respect to this condition, our discussion of the factors that influence the development of PSE meat includes both poultry and swine.

Genetic Causes

PSE meat is the result of an animal's inability to tolerate stress. In swine, this condition is also referred to as *stress susceptibility* or *porcine stress syndrome* (PSS). The cause of the condition seems to be an inability to regulate the flow of calcium ions in the various compartments of the muscle cell. Because calcium is a key regulator of muscle contraction and relaxation, calcium imbalances can drastically alter energy metabolism and muscle activity. In some affected swine, the cause is a clear genetic error. There is a single-point mutation in the calcium-channel gatekeeper protein (the ryanodine receptor, RyR)

that controls the flow of calcium from storage compartments to the fluid surrounding the contraction proteins, actin and myosin (Fujii et al., 1991). This mistake in the amino acid sequence causes the protein gate to leak, or in the extreme case, to get locked open. When this happens the contraction apparatus is flooded with calcium, metabolism is accelerated, and body temperature rises.

Elevated body temperature is the source of another name for this syndrome in other species, *malignant hyperthermia* (MH), a genetic disorder that is autosomal dominant in humans (Benumof, 1998). It has been linked to at least one gene, the ryanodine receptor gene in humans, with eight known point mutations on the gene involved (MacLennan et al., 1994; Lynch et al., 1997). Malignant hyperthermia is characterized by increased heat production, which increases body temperature, muscle rigidity, tachychardia, increased oxygen consumption and lactate production (metabolic acidosis), elevated end-tidal CO_2, hyperkalemia, cyanosis, mottling of the skin, and increased serum creatine kinase levels (Schulman and Gronert, 1994; Williams, 1988; Benumof, 1998).

This disorder has been observed in many other species, including canine, equine, and swine (Klein, 1975; Harrison, 1994; O'Brien, 1994). In swine, the malignant hyperthermia disorder is known as porcine stress syndrome (PSS). This syndrome is an inherited disorder that is linked to a single autosomal recessive gene, the ryanodine receptor (RyR) gene (Fujii et al., 1991). This single-point mutation, a cytosine-to-thymine conversion at nucleotide 1843 causing a substitution of cysteine for arginine in position 615, is also observed in humans. PSS is strongly associated with five major breeds, all of which are lean and heavily muscled (Fujii et al., 1991; Lister, 1993); however, other breeds can be affected by PSS as well. Unlike the MH observed in humans, PSS can be triggered by stress in swine. Additionally, it can be triggered by anesthetics and depolarizing agents such as halothane and succinlycholine (Hall et al., 1966; Webb and Jordan, 1978), which has led to screening tests used successfully in the swine industry to identify animals prone to developing PSE meat. The PSS syndrome is manifested by clinical signs similar to those observed in humans, including increased body temperature, blotchy cyanosis of the skin, and muscle rigidity. Meat from PSS animals is pale, soft, and exudative. This results from the accelerated postmortem glycolysis and a rapid decrease in muscle pH while carcass temperatures are high, causing protein denaturation (Mitchell and Heffron, 1982; Harrison, 1994; O'Brien, 1995).

To complicate the matter for poultry, there is more than one isoform of the RyR protein in skeletal muscle of the avian species, α and β (Percival et al., 1994), whereas there is only one isoform, α, in skeletal muscle of mammals. Little work has been conducted on the genetic component of PSE in poultry. Similar to swine, screening tests using halothane and succinlycholine have been studied for use in turkeys and broilers; however, unlike results with swine, the tests have shown little to no relationship to PSE meat (Wheeler et al., 1999; Owens et al., 2000b, Cavitt et al., 2004). More recently, researchers identified mutations in turkey RyR. Chiang and Strasburg (2003) reported three transcript variants in

the RyR, resulting in deletions in the amino acid sequence at different locations. These variants could lead to a nonfunctional ryanodine receptor protein, resulting in abnormal calcium regulation in the muscle which could then alter postmortem metabolism. Researchers studied commercial and random-bred turkeys and found that RyRs from these populations had variations in affinity for ryanodine (a measure of the RyR function), suggesting a heterogeneity of RyR channel activity among turkey strains, specifically in modern commercial strains (Wang et al., 1999; Chiang and Strasburg, 2003). Although mutations were identified in turkey, it is not the same single-point mutation that has been identified in swine, although it is in a similar region of the amino acid sequence. Therefore, the function of the defective RyR is not yet fully understood in turkey as it is in swine, and the relationship between these mutations in the turkey RyR and stress tolerance in poultry is not known. In the future it will be imperative to determine the function of the RyR forms in an animal and then to relate that information to the animals' tolerance of stress and meat quality.

At this time there is not enough information to address the genetic causes of this syndrome and allow selective breeding of poultry. It appears that the commercial incidence of PSE meat in broilers and turkeys ranges from 5 to 47% of the birds. However, there seems to be a small incidence that is present all the time, the "background." Above this background appear spikes that vary with the day, week, or season, even if the breed or strain is constant. It therefore appears that the background represents a rough estimate of the genetic component of the syndrome, while the spikes represent the "environmental" components. Thus, there are times when genetic factors cause the problem, while environmental factors are more important at other times. Lacking the ability to type poultry genetically, it is not possible to verify or separate the relative involvement of genetic or environmental causes. However, most processors can accommodate the background incidence and have problems only when the incidence increases.

Rapid Growth Genetic selection of swine for production qualities, including growth rate, leanness, muscularity, and feed efficiency, has also increased the incidence of PSS and PSE meat (Louis et al., 1993; Tarrant, 1993). In some breeds, such as the Pietran and Belgian Landrace pigs, which exhibit extremely developed hams, stress susceptibility is very high. The incidence of PSS in these breeds can be as high as 85 to 95% (Eikelenboom et al., 1978; Louis et al., 1993).

In recent years, intense genetic selection of turkeys and broilers has contributed to large, fast-growing birds. Additional contributing factors in the modern turkey and broiler industry are better feed efficiency and better management (Sante et al., 1995). Lilburn (1994) reported that over the past 20 to 30 years, body weights of broilers and turkeys have nearly doubled, with poultry achieving higher weights in the same amount of time. For example, in 1984, male turkeys weighed 23 lb at 18 weeks of age; in 1997, male turkeys reached 29.7 lb in 18 weeks (Ferket, 1998). Lilburn and Nestor (1991) evaluated body weight and breast percentages of turkeys from a growth-selected line, random-bred control population, and a

commercial sire line. The authors observed that although the growth-selected line had overall higher body weights, the commercial line had the greatest percentage of breast muscle, suggesting that breeders are selecting not only for rapid body growth, but also for maximal breast muscle yield. This is true in broilers as well.

Faster-growing, or heavier, birds have been shown to be more susceptible to heat stress. Mills et al. (1999) evaluated the effects of heat stress on fast- and slow-growing lines of turkeys; they observed that upon heat stress, the fast-growing line had higher body temperatures and greater metabolic heat production than those of the slow-growing lines. The authors concluded that the fast-growing line exhibited less efficient thermoregulation than did the slow-growing line, suggesting that fast-growing lines are more susceptible to thermal stress. Hunt et al. (1999) observed that heavier 6-week-old broilers died faster than lighter-weight 5-week-old broilers when subjected to heat stress (40°C, 70% relative humidity). They concluded that the differences could be attributed to body weight. Reece et al. (1972) observed increases in broiler mortality due to acute heat stress and reported that the heat stress effect was more pronounced in heavier birds. Similarly, Bohren et al. (1982) reviewed the effects of heat stress on selected and nonselected poultry and reported that researchers had observed that heavier breeds had higher mortality rates than those of lighter breeds. Lu et al. (2007) studied the effects of heat stress on fast- and slow-growing broilers and reported that a fast-growing commercial broiler was more susceptible to heat stress than was a slow-growing bird, as indicated by changes in L^* value and drip loss. These reports suggest that larger birds may be more stress susceptible.

In contrast, Duclos et al. (2007) observed no evidence of antagonism between growth rate of poultry and meat quality parameters. Additionally, they reported that slow-growing lines seem to be more reactive than fast-growing lines to preslaughter stressors. Berri et al. (2007) reported that broiler breast fillets with a larger cross-sectional area (CSA) of muscle fibers had a higher pH at 15 min postmortem, lower L^* values, and lower drip losses than did fillets with smaller CSAs, which is also in contrast to previous research, which suggests that rapidly growing birds are more prone to producing PSE meat characteristics. Berri et al. (2001) reported that broiler lines selected for rapid growth had higher L^* values than those of their unselected counterparts (controls); however, the authors suggest that this difference was due to a lower heme content in the lines selected because the redness (a^* value) was also lower in these lines. Additionally, no other negative attributes (e.g., decreased water-holding capacity) were reported, although birds processed in that study were under controlled conditions that minimized stress. Debut et al. (2003) reported higher L^* values in breast meat of fast-growing broilers than in slow-growing broilers; furthermore, they reported no differences in L^* value due to stress (heat stress for 2 h or transportation for 2 h). In all cases (genetic line or stress), drip loss and pH were not affected (Debut et al., 2003); it is likely that the stress conditions used in that study were not sufficient to produce change in meat quality characteristics. In another study, Le Bihan-Duval et al. (2001) found low correlations between body weight and

multiple meat quality attributes, suggesting that growth rate does not affect meat quality negatively.

Other research has suggested that rapid growth leads to more structural changes in the muscle. In a review by Mahon (1999), the author concluded that commercial lines of turkeys selected for enhanced growth exhibit a greater incidence of muscle abnormalities than do nonselected turkey lines. Sosnicki and Wilson (1991) have suggested that selection for rapid growth has led to muscles that outgrow both their life support systems (i.e., capillary beds) and their supportive connective tissue, resulting in a loss of muscle integrity.

From this research review it is apparent that more research is needed to better identify the relationship between PSE development and rapid growth of birds. It seems to be a complex situation where factors other than growth rate are involved.

Environmental Causes: Premortem Stress Factors

Various premortem stress factors, including environmental temperatures, preslaughter handling practices, and transportation, have been associated with PSS and PSE meat. Poultry are subjected to premortem environmental conditions similar to those of swine. Therefore, stressful conditions, along with rapid growth in poultry, may also influence the development of PSE in poultry meat.

Heat Stress Environmental temperatures can play a major role in premortem stress and, consequently, postmortem meat quality. Heat stress, chronic or acute, is one of the primary causes of stress during preslaughter activities because it can be associated with other physical stressors to birds, such as crowding during catching, transportation, and holding prior to slaughter, and result in additive stress effects. At high temperatures, evaporative cooling is the bird's primary mechanism for heat loss; however, at high relative humidity and high temperatures, evaporative cooling is impeded, thereby making it more difficult for birds to dissipate heat (Yahav et al., 1995), resulting in stress to the bird. McKee and Sams (1997) evaluated the effects of chronic heat stress applied during growout on rigor mortis development and meat quality of turkeys (Table 2). Turkeys

TABLE 2 Quality Attributes of Meat from Heat-Stressed or Control (Non-Heat-Stressed) Turkeys*

Attribute	Heat Stress Treatment	Control
pH 2 h postmortem†	5.85^b	6.07^a
L^*value†	53.00^a	49.75^b
Cooking loss (%)	24.56^a	19.08^b

Source: Adapted from McKee and Sams (1997).

*Means within a row without common superscripts (a's or b's) differ significantly ($p < 0.05$). $n = 61$ per mean.

†Values estimated from graphs.

subjected to elevated temperatures of 32/38°C (night/day) for 4 weeks exhibited lower muscle pH and higher L^* values, indicating paler color, higher drip loss, and higher cooking loss than in turkeys grown at ambient temperatures of 16/24°C (night/day). The incidence of PSE-like meat also increased in the heat-stressed turkeys. McCurdy et al. (1996) evaluated the effect of season on the incidence of PSE in turkeys and reported the highest L^* values in summer and the lowest in winter. There seems to be more PSE in summer, predominately in the early summer months, tapering off toward the later months. Birds growing rapidly in the spring would be larger at the same age when the heat of summer arrives than birds growing more slowly through the summer, being acclimated to the heat by the time they reach market size. The spring-growing bird would be less tolerant of the heat than the summer-grown bird. Bianchi et al. (2006) reported that holding broilers at temperatures above 18°C prior to slaughter (i.e., holding shed at plant) resulted in paler meat color than did holding broilers at 12°C, suggesting that elevated temperatures in the holding period prior to slaughter can also increase the incidence of PSE meat.

Transportation Stress Transportation is another potential stress associated with meat quality problems. Transportation stress is very complex because it not only includes the act of transporting (vibration and noise) but also thermal stress, relative humidity, airflow, and crowding. Turkeys and broilers are often transported to processing plants for 30 min to 3 h prior to processing. The transportation process can be stressful to the birds and thus may affect meat quality. However, research related to transportation stress and meat quality in poultry is not conclusive. Results have shown an improvement, no change, or a decrease in meat quality factors such as color and water-holding capacity (van Hoof, 1979; Kannan et al., 1998; Owens and Sams, 2000; Debut et al., 2003). These studies have varied under numerous conditions, including time, processing methods, environmental temperatures, and stocking density. However, based on research in swine and poultry, it can be concluded that there is potential for transportation to lead to increased postmortem metabolism, which can ultimately affect meat quality. Therefore, it is important to be aware of conditions that may lead to stressful situations for the birds, such as crowding, elevated temperatures, and transportation duration.

Environmental Causes: Processing Factors

Along with genetic and environmental conditions antemortem, PSE can develop in normal, nonstressed animals if they are processed improperly. Chilling conditions, especially, can have a great impact on the development of PSE in poultry meat. Improper chilling (slow rate of chilling) can cause carcass temperatures to remain high longer. PSE meat can develop in carcasses with normal pH declines if they are chilled inadequately or improperly (Offer, 1991). Previous research has shown that inadequate chilling results in meat with lower pH, lighter color, higher drip and cooking losses, lower gel strength, and fewer extractable

TABLE 3 Quality Attributes of Meat from Turkeys Chilled at 0°C or Held at 40°C for 4 h After Slaughter*

Attribute	Treatment	
	0°C	40°C
pH 2 h postmortem†	6.02[a]	5.87[b]
L^* value†	51[b]	57[a]
Cooking loss (%)	24.05[b]	28.86[a]

Source: Adapted from McKee and Sams (1998).
*Means within a row without common super scripts (a′s or b′s) differ significantly ($p < 0.05$). $n = 12$ per mean.
†Values estimated from graphs.

myofibrillar proteins (Table 3) (McKee and Sams, 1998; Rathgeber et al., 1999; Alvarado and Sams, 2002, 2004; Molette et al., 2006). McKee and Sams (1998) and Alvarado and Sams (2002) reported that holding carcasses at elevated temperatures (> 30°C) accelerated postmortem glycolysis and induced PSE meat characteristics (Table 3). Their results agreed with those of Khan (1971), who reported that muscles held at 30 to 37°C had increased rates of glycolysis. Rathgeber et al. (1999) reported that delayed chilling (by 90 min) increased L^* values in turkey breast fillets. Alvarado and Sams (2002) recommended that turkey carcasses reach 25°C or lower by 60 min postmortem to reduce the chance of developing PSE meat. The results of these studies suggest that carcasses should be chilled promptly and adequately to prevent and/or reduce the incidence of PSE meat.

STRATEGIES TO IMPROVE THE FUNCTIONAL QUALITY OF PSE MEAT

Regardless of how or why it occurs, processors are faced with defective meat and want to know what they can do to use it in their products without sacrificing yield or quality. Extreme cases produce up to a 20% purge loss in a cook-in bag and cook losses over 30% from a breast fillet. An additional defect is that the poor protein function in PSE meat causes poor binding of meat pieces in formed products, a condition called *cracking* (Figure 1). Furthermore, defective cook-in bag products need repackaging, which increases costs further.

There are limited strategies for dealing with defective meat. The reduced water-holding capacity of the meat is the result of protein damage from the low-pH condition of the muscle early after death. It is thought that this damage is at least partially reversible by adjustment of pH or ionic strength in the meat through the use of salts, phosphates, or other ingredients. Alvarado and Sams (2003) reported that marinating prerigor pale meat with pH 9 or 11 salt and phosphate marinades increased muscle pH and decreased the L^* value compared to premarinated fillets, although differences still existed between pale and normal groups.

FIGURE 1 Example of cracking condition in formed turkey deli loaves formulated with PSE meat.

Additionally, after marination of pale and normal fillets with these marinades, there was no difference in cooking loss between the groups, although differences still existed when measuring expressible moisture. The authors suggested that marinating pale fillets with a high-pH marinade can reduce the negative effects of PSE. Woelfel and Sams (2001) also evaluated high-pH marinade solutions and reported that pale meat characteristics were improved, but not to the level of the marinated normal-colored fillets. Therefore, adjusting the pH through marinades has the ability to improve PSE meat, but it does not necessarily totally reverse the negative attributes of PSE meat.

New marinade ingredients and formulations are currently being studied to provide processors with more options to utilize PSE in specific products. Ideally, the new marinades could be used on all meat and would correct PSE meat without adversely affecting normal meat. The use of modified food starch (MFS) in marinades for poultry meat reduced cooking losses successfully in PSE poultry meat, resulting in cooking losses similar to those in non-PSE meat marinated with MFS; also, both MFS treatments had reduced cooking losses compared to a control marinade consisting only of salt and phosphate (Cavitt and Owens, 2001). Zhang and Barbut (2005b) also reported that using MFS can significantly improve the water-holding capacity of PSE meat, suggesting that these starches can compensate for the lost protein functionality of PSE meat. They also reported that regular (nonmodified) starches can also improve cook losses. This could be beneficial to the industry, as the use of "natural" ingredients is a growing trend in the food industry.

The best strategy currently available is to sort meat so that the pale meat is directed to uses where PSE meat is not a major problem (e.g., comminuted, breaded patties) or into formulations containing ingredients or conditions

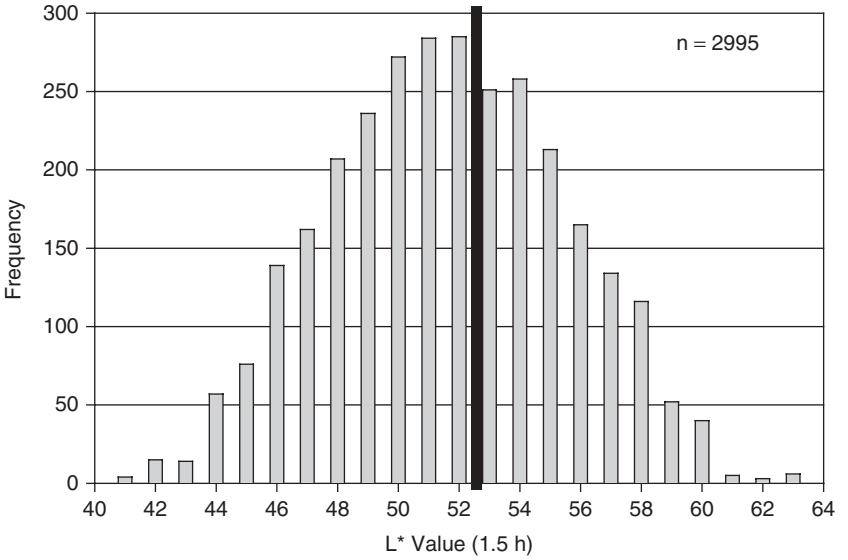

FIGURE 2 Frequency of $L*$ values (1.5 h postmortem) from turkey breast fillets in a commercial processing plant. The heavy black line indicates a threshold $L*$ value of 53. (Adapted from Owens et al., 2000a).

to restore protein function and water-holding capacity. Experience has indicated that PSE meat causes its greatest problem in whole-muscle products to which no or low amounts of salt and phosphates are added. These ingredients help hold the water in the meat and thereby reduce cook losses and purge. If PSE meat were directed away from these products and toward formulations containing these agents, the effect of the PSE meat would be reduced. This sorting process may seem initially like a difficult task, but fillets are already being sorted for other purposes, such as defects, size, and grade. Color is an easy and rapid characteristic to assess that could be accomplished easily using employees' eyes or optical scanning equipment currently available. The sorting equipment is already in place in many plants sorting fillets for size, and meat pH could be another sorting characteristic. Although pH measurement is more complicated, automated systems are already under development in the pork and beef industries for the very same purpose: to sort meat for optimum meat function.

A sorting system requires a threshold value for lightness (or pH) above which (or below which for pH) the meat is considered potentially to be PSE. Researchers have used threshold L^* values ranging from 49 to 54 to identify PSE meat (Barbut, 1997; McCurdy et al., 1996; Owens et al., 2000a; Quio et al., 2001; Woelfel et al., 2002). Using a threshold L^* value > 53, PSE incidence was estimated at approximately 40% in a commercial turkey plant (Figure 2) (Owens et al., 2000a). Even though the lightness of the meat in a slaughter plant can vary somewhat with flock and season, such a threshold can be a useful tool in

monitoring the PSE incidence in a commercial plant. However, the threshold L^* value should be determined by each processor depending on the product.

CONCLUSIONS

The future has both long- and short-term strategies for the problem of stress susceptibility and PSE poultry meat. Genetic typing, screening tests, and selective breeding are all possibilities but are many years away. The number of parameters needing to be addressed in this research is enormous and will require more research. Environmental stress is a set of issues that the industry can address now and should already be addressing for reasons of health, feed conversion, and growth. Finally, in the absence of a selective breeding program and in the inevitability of environmental extremes, the industry will continue to see PSE meat in processing plants. Better control of its flow/distribution among products will reduce the effect of this defective meat.

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PART VI

EGGS

28

NUTRITIONAL AND HEALTH ATTRIBUTES OF EGGS

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Handbook of Poultry Science and Technology, *Volume 1: Primary Processing*, Edited by Isabel Guerrero-Legarreta and Y.H. Hui

INTRODUCTION

Eggs contain everything that a bird needs to initiate and complete all of the processes of embryonic development. Birds invest in the reproductive process up front, transferring all the protein and energy needed to allow the embryo to reach the point of hatch. This is all packaged in a sturdy shell that is constructed in a way that allows for gas exchange while maintaining a defense that keeps pathogens out (Figure 1).

As an important part of the human diet, eggs are one of the few foods that are consumed throughout the world. It surely could be a timeless chicken-or-egg debate; however, without doubt, eggs are a perfect food, containing almost every nutrient essential to sustaining life—thus their role as total life support for the embryonic chick. The original jungle fowl were domesticated near modern-day India around 3200 B.C. Evidence of laying egg consumption from domesticated chickens is found in Chinese and Egyptian records dating back to 1400 B.C. Additionally, there is archaeological evidence of egg consumption going back to the Neolithic age. Romans first brought domestic fowl to northeastern Europe

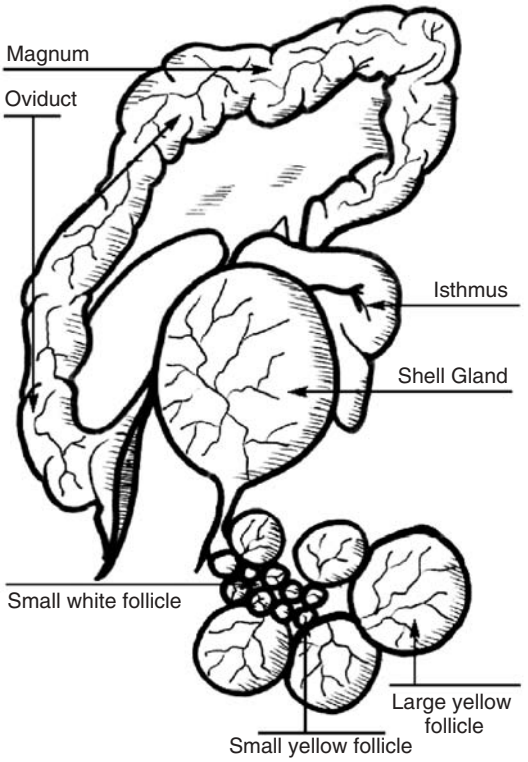

FIGURE 1 The oviduct. (From Robinson et al., 2003; reproduced with permission from the Spotted Cow Press.)

and England, and they first appeared in North America with Columbus's second voyage in 1493 (Katz, 2003). The protein in egg white is of such high quality that it has become the standard against which other proteins are judged. Egg yolk contains a great number of vitamins and minerals, including vitamins A, B_{12}, D, and E, plus riboflavin, folic acid, iron, zinc, phosphorus, selenium, and choline. It is one of the few sources of vitamin K.

However, shell egg consumption in the developed world has decreased or leveled off over the last three decades, due largely to consumer perceptions as to its cholesterol content. Other reasons for the decline include changing eating patterns [e.g., breakfast (when eggs have traditionally been eaten) is the meal most often skipped] and a demand for "heat and serve" grocery products that can be eaten on the move (Elkin, 2006). The shell egg market has turned around in recent years and slow growth is currently being experienced, with new emphasis on the egg's positive attributes. Specialty eggs, such as omega-3, brown eggs, free-run, and organic eggs, are in greater and greater demand by consumers. Consumers are increasingly interested in functional foods that can prevent or ameliorate chronic diseases. "Designed" egg concepts, such as eggs enriched with omega-3 fatty acids, which reduce the risk of cardiovascular diseases; with essential antioxidants such as lutein for eye health; and with vitamins such as folate for the prevention of neural tube defects in babies, represent an important milestone for the egg industry (Sim and Sunwoo, 2006).

TABLE EGG PRODUCTION

Producing an egg involves the conversion of genetic, environmental, and nutritional cues into a cascade of signals from the neuroendocrine system. These signals must be integrated and responded to by the organs and tissues primarily involved in reproduction, which will in turn produce more signals for both local and distant activities. The resulting eggs produced are the net result of a bird's attempt to coordinate the demands that its body and environment have placed on it.

Specific feed ingredients, hen age, and flock management decisions can directly affect the egg environment. Minor dietary ingredients are not always preferentially deposited in the yolk or egg. This opens the door to creating an "enriched" environment within the egg. An understanding of how some feed ingredients affect the egg environment directly can contribute to the improved success of table egg enrichment programs.

Control of Egg Production

The reproductive system of the laying hen is made up of the ovary, hormonal control centers, and support structures. The system includes the hypothalamus, the anterior pituitary, the ovary, the oviduct, the liver, and the skeletal system. The onset of sexual maturation begins when gonadotrophin-releasing hormone

(GnRH)–producing neurons acquire the ability to release GnRH, a small protein hormone. Increasing day lengths are perceived by the bird, and if its nutritional status is adequate to support a reproductive effort, maturation of the reproductive tract begins. The GnRH will travel a short distance to the anterior pituitary, where it stimulates the release of luteinizing hormone (LH) and follicle-stimulating hormone (FSH). These hormones trigger synthesis of estrogen and androgen hormones from the small follicles of the ovary. As follicular maturation progresses, the response to LH increases, whereas the response to FSH decreases (Calvo and Bahr, 1983).

On the ovary, steroidogenesis of the small follicles, particularly estrogen production, triggers the sexual maturation process. Increased concentrations of estrogen in the blood are associated with visible external changes, such as reddening and enlargement of the comb and wattles, a prenuptial feather molt (feather drop), and a widening of the pubic bones to permit egg passage. In the liver, estrogen stimulates production of egg yolk lipids. Yolk formation is stimulated by estrogen and modulated by some of the metabolic hormones. The oviduct also enlarges to its mature size and grows capable of secreting egg albumen.

Follicles destined to ovulate are recruited from a pool of immature follicles. The ovary contains thousands of these tiny follicles. More follicles than are needed are recruited for development. This ensures that a constant supply of good-quality follicles are available to enter the rapid growth phase, where yolk deposition occurs. Excess small follicles are reabsorbed by a hen through a process of follicular atresia. The rapid yolk deposition phase is the hen's greatest energetic investment in yolk formation. Follicles that reach this stage are highly likely to be ovulated. Continuous recruitment of replacement follicles from the immature follicle pool on the ovary creates continuity in yolk deposition requirements.

A hen will normally maintain five to eight large yellow follicles on the ovary. The growing follicle is transferred into the rapid growth phase weighing between 0.6 and 0.7 g and requires 7 to 11 days to pass from this point through to ovulation (Grau, 1976). In contrast, the process of egg formation in the laying hen takes between 24 and 27 h from the moment of ovulation to the moment that an egg is laid.

The ovulatory cycle of the hen is 24 h. Follicular maturation occurs independently, and if the most advanced follicle reaches the point of maturation (ability to secrete progesterone into the bloodstream rather than first having it converted to estrogen) during the 10-h portion of the day during which this can be detected, ovulation will be triggered.

Yolk Production and Egg Formation

The enrichment ingredients provided to hens to support the creation of enriched eggs must be transferred to an egg in either the yolk or the albumen. The egg is approximately 58.5% albumen, 31% yolk, and 10.5% shell. These values vary with age and bird strain. The proportion of yolk in the egg increases as the bird

ages, at the expense of albumen. A normal egg weight for a laying hen would be in the range 50 to 65 g. The egg contains a large amount of nutrients for the purpose of supporting the growth of the embryo. However, this concentration of easily digestible nutrients also makes it an ideal food source. The albumen contains primarily protein (and 88% water), whereas the yolk contains both lipids and proteins (2 : 1 ratio). The high fat content allows more energy to be packed into a smaller package without the concomitant association with water as happens with proteins (Speake and Thompson, 1999).

Most of the constituents of yolk are derived from the blood plasma. Key ingredients such as yolk lipids and vitellogenin are constructed in the liver and transported to the ovary, where they are transferred to the growing ovum. More than 90% of fatty acid synthesis occurs in the liver of poultry, for example (Leveille et al., 1975). The liver processes dietary fat, constructs other fat from carbohydrates, and packages them for release into the bloodstream. As such, the yolk production and transportation mechanisms are critical components in support of the reproductive effort of hens. Estrogen stimulates the range of structural adaptations which ensure that yolk–very low density hypoprotcin can be diverted to the growing ovarian follicles (Speake and Thompson, 1999). One of the roles of estrogen is to stimulate production of specific apoproteins for the creation of a unique very low density lipoprotein particle destined for yolk deposition. The yolk materials are deposited in the ovarian follicles in a circadian pattern, with distinct, successive layers of yolk deposited around the yolk core.

During ovulation, the mature ovarian follicle ruptures along the stigma, a linear avascular area on the follicle, and the ovum is released from the ovary. The yolk is protected by the yolk membrane, which is protein-based and forms as a meshlike structure. The infundibulum, which is the uppermost region of the oviduct, uses its thin, lightly muscularized tissue to engulf the ovum and funnel it into the oviduct (Figure 2). The yolk passes through in 15 to 30 min. The perivitelline membranes of the yolk and the chalazae layer of the albumen are applied in the infundibulum. The chalazae are the white coiled albumen structures that hold the egg yolk in the middle of the egg.

The ovum takes 3 to 4 h to pass through the magnum, where egg albumen is released, due in part to mechanical pressure from the moving ovum (Moran, 1987). The thick albumen from this region was formed previously and the walls of the magnum contain about a 2-day supply. Shell membranes are added to the forming egg during the 1.5 h it needs to pass through the isthmus. As the egg cools, the two shell membranes separate at the large end of the egg, forming the air cell (Figure 1), which will continue to grow due to moisture loss from the egg during storage. Final “plumping” occurs when fluid is added to the albumen in the shell gland. A crystalline calcium carbonate and glycoprotein matrix is formed on the shell membrane from glands in the surface of the shell gland secreting sodium bicarbonate, sodium chloride, potassium chloride, and calcium chloride in liquid form. Chicken eggs require roughly 20 h in the shell gland, followed by a period of a few seconds to pass through the vagina to complete the oviposition process (Burke, 1984).

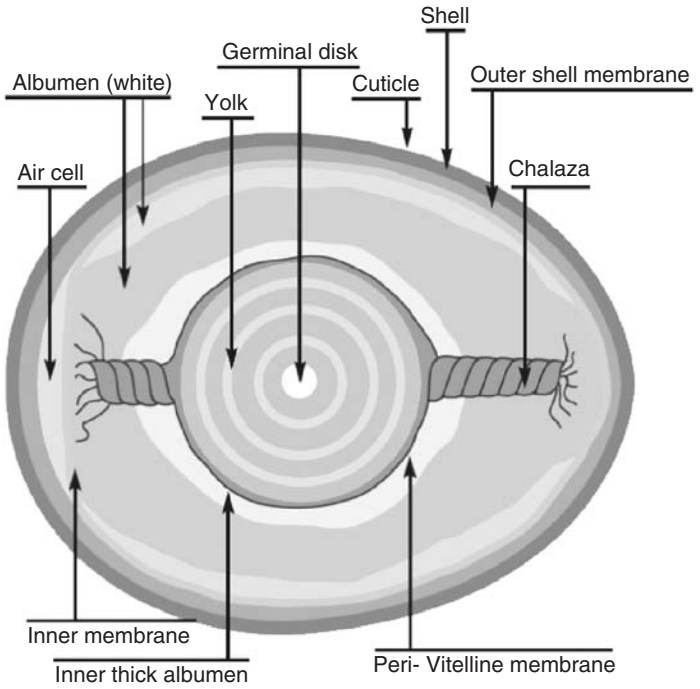

FIGURE 2 Structure of the egg. (From Robinson et al., 2003; reproduced with permission from the Spotted Cow Press.)

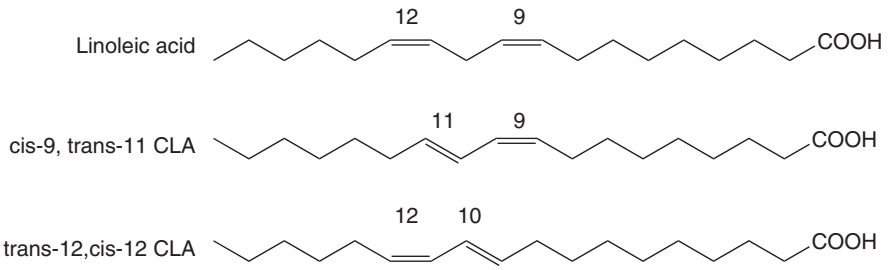

FIGURE 3 Structures of linoleic acid: *cis*-9,*trans*-11 CLA and *trans*-10,*cis*-12 CLA. (From Bhattacharya et al., 2006; by permission.)

Management of pullets and laying hens must often be strain-specific to optimize the frame size and body mass needed for adequate early egg size, long-term persistency, and prevention of skeletal disorders. Selection of layer strain, nutrient intake, and the rearing photoschedule can affect laying hen productivity. The goal is to create a bird large enough to begin to lay with a good egg size and to maintain a high rate of lay for the entire production year without burning out or suffering the effects of calcium depletion.

Table Egg Quality

The egg industry was built around the concept of marketing eggs into the consumer market while retaining their original quality. *Quality* is a broad term that captures aspects of physical characteristics, flavor, and odor. A high-quality egg can command a higher price for the producer and will maintain its quality longer during postmarketing. Egg grading is done commercially to classify egg quality using established standards. Quality is determined using external factors such as cleanliness, shell condition, color, and shape, as well as internal factors such as albumen thickness, yolk condition, air cell size, and the presence of defects such as meat or blood spots. Even poor-quality eggs deliver the same nutritional quality.

The storage of eggs is part of the commercial table egg marketing process. The maintenance of egg quality is strongly affected by storage conditions from point of lay to point of consumption. Moisture loss through the shell pores contributes to increased air cell size and reduced quality. This process can be modulated by the temperature, relative humidity, and ventilation of the egg environment. Incorrect temperature and humidity will increase CO_2 loss from the egg, which results in the breakdown of albumen structure.

Thin, runny albumen is a sign of poor egg quality. Young flocks lay eggs with high-viscosity albumen (Lapao et al., 1999). Albumen pH rises with storage and hen age. The albumen proteins are broken down by enzymes, degrading the structure and releasing the protein-bound water. The albumen gradually liquefies with storage, and in older hens, storage can cause more rapid deterioration of albumen quality (Lapao et al., 1999). The freed water and thin albumen can cross the yolk vitelline membrane, increase yolk mass, and put pressure on the yolk membrane (Moreng and Avens, 1985). This is an important issue in the egg-breaking industry, where adequate separation of yolk from albumen is required. Stabilizing the albumen or slowing the rate of deterioration during egg storage can optimize long-term egg quality.

Degradation of egg quality can be slowed with good antioxidant levels. The primary defense mechanisms within the embryo are a group of three enzymes (superoxide dismutase, glutathione peroxidase, and catalase) which convert free radicals produced by cellular respiration into less harmful alcohols (Ursiny et al., 1997). A second level of defense consists of the natural antioxidants: Vitamin E, the carotenoids, ascorbic acid, and glutathione protect the developing chick (Surai, 1999). The secondary level of defense is more important in the table egg because there are no growing tissues.

Several Brazilian studies examined the effects of an organic form of selenium on albumen quality and consistency and noted an improvement in albumen height with organic selenium (Rutz et al., 2005). Payne et al. (2005) reported the opposite effect, demonstrating that other factors may also influence the results obtained. Whereas Monsalve et al. (2004) did not report a difference in vitelline membrane strength due to either an inorganic or organic selenium source, they did report a positive effect of increased selenium concentration on membrane

strength. Results like this may indicate a protective effect on the cellular membranes of the magnum under certain conditions. Rutz et al. (2005) theorized that the indirect mode of action of organic selenium here may be through enhanced function of the selenium-dependent GSH-Px antioxidant system. If the secretory cells and tubular glands of the magnum are able to function more effectively, more protein will be secreted into the lumen of the magnum, resulting in a more viscous egg white (Butts and Cunningham, 1972).

Whereas egg-handling and storage conditions can influence how long an egg may stay fresh, there are also factors that can affect egg quality even before it is laid. Bird genetics, age, nutrition, environmental temperature, and disease status are some of major factors affecting egg quality.

Genetics Breed choice can be an important part of the fit of a company to its target market. Breed comparisons reveal strains with increased incidence of defective shells or poor early egg size. Hens can vary in their eggshell color, shape, yolk, and albumen quality attributes. Positive traits such as superior feed conversion or albumen quality can compensate for some negative traits, however. Some hen-based quality traits are difficult to reduce in time within a strain, such as blood or meat spots in brown eggs, because they are difficult to visualize with standard candling methods. Other breed-based traits, such as immune response, can be an integral part of a strategy to produce Ig-Y eggs.

Hen Age Hen age has the greatest influence on egg composition. The size of the pullet at photostimulation determines probable future egg size, with bigger eggs coming from bigger birds. Yolk size increases with age at a faster rate than albumen does, thereby increasing the proportion of yolk in eggs from older hens. Beginning egg production later through delayed photostimulation will result in larger eggs at the start of production (Robinson et al., 1996).

As hens age, egg size increases while shell quality goes down. Big eggs in older hens will tend to have a lower percentage of shell than in younger birds, resulting in poorer shell quality due to a thinner shell. Rate of egg production also has a big influence on egg size and composition. High-producing hens sometimes have both smaller eggs and poorer shell quality because they are not able to keep up with the magnitude of the demands of their rate of egg production. The time of day can affect shell quality, as chickens generally lay bigger eggs in the morning than in the afternoon. The specific gravity of the afternoon eggs will be greater, suggesting that these eggs have a better quality shell than those of the morning eggs.

A hen that is not laying as well will not have as many large yellow follicles on its ovary. These follicles are often larger and contribute to greater egg size. In general, the yolk/albumen ratio is fixed, meaning that yolk size directly influences how much albumen is laid down as it travels down the oviduct (Williams et al., 2001).

Nutrition Manipulating the dietary protein is one of the most effective ways to alter egg weight. As dietary methionine content is increased, for example,

there is an almost linear increase in egg weight (Leeson and Summers, 2001). Varying the dietary fat source and inclusion rate can also alter egg weight, with changes primarily in the albumen weight. These changes may relate to estrogen metabolism and its influence on oviduct function, as higher plasma estrogen concentrations were linked to higher egg weights (Whitehead et al., 1993).

In vitamin-enriched eggs, for example, factors affecting egg levels of specific vitamins include diet, breed and age of hen, level of egg production, and stage of the production cycle (Naber, 1979, 1993). According to Naber (1993), the most important factor influencing egg vitamin content was the dietary inclusion level of each vitamin.

Increased dietary energy content can increase the percentage of yolk in an egg (Spratt and Leeson, 1987). The adjustment of combinations of specific dietary ingredients (such as methionine, choline, folic acid, and vitamin B_{12}) has been used successfully to alter egg size without affecting the rate of lay (Keshavarz, 2003).

Feed additives are one of the best ways to modify egg composition (as with omega-3 polyan-saturated fatty acid (PUFA)–enriched eggs) and add value-added ingredients. Yolk color and shell quality are both easily modified through feeding. Some minerals and water-soluble vitamins can be altered by changing dietary inclusion rates, although many of them are limited to the capacity of the carrier molecules and binding proteins that aid in their transfer into the yolk. Off-flavors and factors contributing to reduced shelf life can also be introduced inadvertently through the diet.

Proper management of calcium metabolism is essential for laying hens to maintain high levels of production. Skeletal calcium deficiency and poor long-term shell quality are both management and animal welfare concerns in laying hens. Numerous products are on the market, from vitamin D metabolites to products enhancing calcium and phosphorus management by the hen. Simple changes such as using large-particle calcium sources contribute to improved shell quality and bone health by allowing the particles to be retained in the gizzard longer, thereby making it available for a longer portion of the day.

Environmental Temperature Egg size declines in the hot summer months. Declines in water consumption due to water being too warm or cold can also limit egg size. With heat stress, birds pant and shell quality can drop due to a reaction of calcium with carbon dioxide, resulting essentially in calcium being breathed out.

CHEMICAL COMPOSITION AND NUTRUTIONAL VALUE OF EGGS

General Chemical Composition of Eggs

The weight and composition of a table egg is dependent on heredity, age, season, diet, and other factors. A typical White Leghorn egg usually weighs from 53 to 63 g with an average of 55 g. Board (1969) has shown that in addition to water

(74%), the main chemical compositions of hen egg are 11.8% lipids, 12.8% proteins, and small amounts of carbohydrates and minerals. Most of the proteins are present in the egg white and the egg yolk, amounting to 50% and 44%, respectively; the eggshell contains the rest of the proteins. The yolk accounts for slightly over one-third of the edible portion, but it yields three-fourths of the calories and provides all or most of the fat in whole eggs. The yolk comprises 48% water, 16% protein, 32.6% fat, and some minerals and vitamins. The white consists of 88% water, 10% protein, and some minerals. The amount of lipid in the egg white is negligible (0.01%) compared with the amount present in the yolk. The shell makes up 11% of the weight of an egg, and approximately 98% of the shell consists of calcium.

Carbohydrates are a minor component of hen eggs. Their average content is about 0.5 g per egg, 40% of which is present in the yolk (Sugino et al., 1997). Carbohydrates are present as free and conjugated forms which are attached to proteins and lipids. Glucose accounts for about 98% of the total free carbohydrate in the white. The content of carbohydrate in egg yolk is about 1.0%; 0.7% of it consists of oligosaccharides bound to protein, composed of mannose and glucosamine; the remaining 0.3% is free carbohydrate in the form of glucose.

About 94% of the minerals are in the eggshell fraction; the rest are distributed in egg white and egg yolk. Most of the minerals are in conjugated form, and only a small portion is present as inorganic compounds or ions (Romanoff and Romanoff, 1949). Calcium represents over 98% of total mineral in the shell; other inorganic components include phosphorus, magnesium, and trace contents of iron and sulfur. Egg yolk contains 1.1% minerals (Board, 1969), phosphorus being the most abundant. More than 61% of the total phosphorus of egg yolk is contained in phospholipids. The major inorganic components of egg white are sulfur, potassium, sodium, and chlorine.

Nutritional Value of Eggs

Table 1 shows the nutrient content of various raw egg products. Egg contains four major nutritional components: protein, lipids, all necessary vitamins (except vitamin C), and minerals. Fat-soluble vitamins (A, D, E) are present in the yolk; water-soluble vitamins (B complex) are present in the white, the yolk, or both. Approximately equal amounts of trace minerals are present in the yolk and white, sometimes in combination with proteins and lipids. Lipids contained in the egg yolk provide most of the metabolic energy necessary for development of the embryo. The presence of lipids in egg yolk facilitates the absorption of fat-soluble vitamins. The high nutritional properties of eggs are indispensable for development of the embryo.

Proteins in Eggs Eggs are a good source of proteins. The quality of a protein is related primarily to its essential amino acid content and digestibility. High-quality proteins are those that contain all the essential amino acids at levels greater than the FAO/WHO/UNU reference levels (FAO/WHO/UNU, 1985) and digestibility

TABLE 1 Nutrient Composition of the Edible Portion of Fresh Raw Hen's Eggs and Egg Components [a]

Nutrient (Unit)	Whole Egg	Egg White	Egg Yolk
Proximate			
Water	37.66	29.33	8.1
Food energy (ca)	75	17	59
Protein (N × 6.25) (g)	6.25	3.52	2.78
Total lipid (g)	5.01	—	5.12
Total carbohydrate (g)	0.61	0.34	0.3
Ash (g)	0.47	0.21	0.29
Lipids			
Fatty acids as triglycerides (g)	4.327	—	4.428
Saturated (total)	1.55	—	1.586
8:0 Caprylic	0.002	—	0.002
10:0 Capric	0.002	—	0.002
12:0 Lauric	0.002	—	0.002
14:0 Myristic	0.017	—	0.017
16:0 Palmitic	1.113	—	1.139
18:0 Stearic	0.392	—	0.401
20:0 Arachidic [b]	0.02	—	0.02
Monounsaturated (total)	1.905	—	1.949
14:1 Myristoleic [b]	0.005	—	0.005
16:1 Palmitoleic	0.149	—	0.152
18:1 Oleic	1.736	—	1.776
20:1 Eicosenoic	0.014	—	0.014
22:1 Erucic	0.002	—	0.002
Polyunsaturated (total)	0.682	—	0.698
18:2 Linoleic	0.574	—	0.587
18:3 Linolenic	0.017	—	0.017
20:4 Arachidonic	0.071	—	0.073
20:5 Eicosapentaeonic	0.002	—	0.002
22:6 Docosahexaenoic	0.018	—	0.019
Cholesterol (mg)	213	—	213
Lecithin (g)[b]	1.15	—	1.11
Cephalin (g)[b]	0.23	—	0.219
Vitamins			
A (IU)	317	—	323
D (IU) [b]	24.5	—	24.5
E (mg)	0.7	—	0.7
B_{12} (μg)	0.5	0.07	0.52
Biotin (μg)[b]	9.98	2.34	7.58
Choline (mg)[b]	215.06	0.42	216
Folic acid (folacin) (μg)	23	1	24
Inositol (mg)[b]	5.39	1.38	3.95
Niacin (mg) (B_3)	0.037	0.031	0.002
Pantothenic acid (mg)	0.627	0.04	0.632

(*continued overleaf*)

TABLE 1 (*Continued*)

Nutrient (Unit)	Whole Egg	Egg White	Egg Yolk
Pyridoxine (B_6) (mg)	0.07	0.001	0.065
Riboflavin (B_2) (mg)	0.254	0.151	0.106
Thiamine (B_1) (mg)	0.031	0.002	0.028
Minerals (mg)			
Calcium	25	2	23
Chlorine[b]	87.1	60	27.1
Copper	0.007	0.002	0.004
lodine[b]	0.024	0.001	0.022
Iron	0.72	0.01	0.59
Magnesium	5	4	1
Manganese	0.012	0.001	0.012
Phosphorus	89	4	81
Potassium	60	48	16
Sodium	63	55	7
Sulfur[b]	82	56	25
Zinc	0.55	—	0.52
Amino acids (g)			
Alanine	0.348	0.203	0.143
Arginine	0.375	0.191	0.199
Aspartic acid	0.628	0.358	0.272
Cystine	0.145	0.091	0.05
Glutamic acid	0.816	0.467	0.353
Glycine	0.21	0.123	0.086
Histidine	0.148	0.079	0.072
Isoleucine	0.341	0.199	0.141
Leucine	0.534	0.296	0.244
Lysine	0.449	0.239	0.221
Methionine	0.195	0.121	0.069
Phenylalanine	0.332	0.205	0.119
Proline	0.249	0.137	0.116
Serine	0.465	0.242	0.238
Threonine	0.3	0.16	0.148
Tryptophan	0.076	0.043	0.033
Tyrosine	0.255	0.137	0.124
Valine	0.381	0.224	0.155

Source: USDA (1989).

[a] Assayed nutrient values for large raw eggs based on 59 g shell weight with 50 g total liquid whole egg, 33.4 g white, and 16.6 g yolk.

[b] Cotterill and Glauert (1979).

comparable to or better than that of egg white or milk proteins. As shown in Table 2, egg protein has the highest digestibility among major food proteins. Table eggs are considered to have the highest nutritional-quality protein of all food sources, providing all the essential amino acids in amounts that closely match human requirements for essential amino acids (FAO protein value = 100) (Table 3). Egg protein is therefore used as the nutritional standard against which all other proteins are compared.

Traditionally, dietary protein recommendations have been based on preventing deficiency and growth as opposed to promoting optimal health. However, research has indicated a link between high protein intake and incidence of diabetes, cardiovascular disease, and weight management (Layman, 2004). Although the optimum protein intake for weight-loss diets remains unknown, there is increasing evidence that protein intakes above the current recommended daily allowance may be beneficial for weight loss. It is thought that the increase in

TABLE 2 Digestibility of Various Food Proteins

Protein Source	Digestibility (%)	Protein Source	Digestibility (%)
Egg	97	Millet	79
Milk, cheese	95	Peas	88
Meat, fish	94	Peanut	94
Maize	85	Soy flour	86
Rice (polished)	88	Soy protein isolate	95
Wheat, whole	86	Beans	78
Wheat flour, white	96	Corn, cereal	70
Wheat, gluten	99	Wheat, cereal	77
Oatmeal	86	Rice, cereal	75

Source: FAO/WHO/UNU (1985).

TABLE 3 Recommended Essential Amino Acids for Food Proteins

	Recommended Pattern (mg/g protein)						
	Infant	Preschool Child(2–5 years)	School Child(10–12 years)	Adult	Egg Protein	Casein	Soybean Protein
Histidine	26	19	19	16	25	31	29
Isoleucine	46	28	28	13	55	57	53
Leucine	93	66	4	19	89	97	86
Lysine	66	58	44	16	72	82	67
Methionine + cystine	42	25	22	17	59	35	28
Phenyalanine + tyrosine	72	63	22	19	93	110	99
Threonine	43	34	28	9	46	43	38
Tryptophan	17	11	9	5	15	13	14
Valine	55	35	25	13	67	70	53
Total	460	339	241	127	521	538	467

Source: FAO/WHO/UNU (1985).

dietary protein, resulting in increased plasma levels of leucine, is consistent with molecular mechanisms for increased protein synthesis in skeletal muscle and stimulation of the glucose–alanine cycle (Parker et al., 2002; Layman, 2003). These changes appear to contribute a metabolic advantage during weight loss. These findings are consistent with other reports of a metabolic advantage for weight loss associated with a diet containing reduced levels of carbohydrates and increased levels of high-quality protein (Feinman and Fine, 2003). For example, in a randomized crossover study an egg breakfast was shown to have a greater satiating effect than a bagel breakfast (Vander Wal et al., 2005).

In the present U.S. diet, the percentage of total food energy derived from the three major macronutrients is as follows: carbohydrate (51.8%), fat (32.8%), and protein (15.4%). Current advice for reducing the risk of cardiovascular disease and other chronic diseases is to limit fat intake to 30% of total energy, to maintain protein at 15% of total energy, and to increase complex carbohydrates to 55 to 60% of total energy (Krauss et al., 2002). However, studies of hunter–gatherers showed an elevated dietary protein intake accounting for about 30% of total energy (Eaton and Konner, 1985; Eaton, 2006). A large egg provides 6 g of protein (3.6 g in white and 2.7 g in yolk); one serving of eggs provides 13.3 g of high-quality protein, which represents about 27% of the recommended daily intake (RDI) for adults. Egg proteins may be particularly useful in the diets of ovovegetarians, who could experience an insufficient intake of essential amino acids due to the low protein digestibility and poor biological protein value of many plant proteins (Millward, 2004). Egg proteins are also an ideal protein source for children and the elderly, due to their excellent essential amino acid profile, high digestibility, and ease in preparation. Further, many egg proteins are reported to have physiological benefits, which have been discussed extensively in the book *Bioactive Egg Compounds* (Huopalahti et al., 2007) and in several review articles (Kovacs-Nolan et al., 2005; Mine, 2007).

Lipid in Eggs Lipids, the main components of egg yolk, comprise about 60% of an egg yolk based on dry weight. In fresh eggs, the lipids are combined noncovalently with protein, largely in particles of lipoprotein, and to a very small extent with carbohydrate. The lipids include triglycerides, phospholipids, cholesterol, cerebroside, and some minor lipids.

The major fatty acids in egg yolk triglycerides are oleic acid (C18:1) and palmitic acid (C16:0). Linoleic acid (C18:2) and stearic acid (C18:0) are also significant (Romanoff and Romanoff, 1949). The composition of fatty acids in egg yolk can easily be altered through dietary intervention to increase the percentage of omega-3 content (discussed later in the chapter).

Phospholipids are lipids that contain phosphate and have a glycerol–phosphate backbone. They contain both hydrophilic headgroups and lipophilic fatty acid groups and therefore present good emulsifying properties. Egg yolk is an excellent natural emulsifier and is used widely in the food industry and in home cooking. The lipid fraction of the egg yolk consists of about 33% phospholipids. Nearly 80% of these are phosphatidylcholine, 11.7% phosphotidylethanolamine,

and about 2% each sphingomyelin and lysophosphotidylcholine (Juneja et al., 1994). Choline and choline derivatives are essential for normal cell function and brain development, synthesis of phospholipids in cell membranes, neurotransmission, transmembrane signaling, and lipid–cholesterol transport and metabolism (Zeisel, 2000). Eggs are a good source of bioavailable choline.

Almost all of the sterol found in egg yolk is cholesterol. Cholesterol contributes to about 1.6% of raw egg yolk and about 5% of lipids of egg yolk. Free cholesterol is about 84% of the total cholesterol, the remaining 16% being cholesterol ester (Okubo et al., 1996). Although most of the egg yolk cholesterol originates from the feed, some of it is synthesized when the egg yolk is formed inside a hen's body. It is noteworthy that cholesterol is an essential component of cell membranes and a precursor for hormones, vitamin D, and bile acids.

Cerebrosides are classified as glycolipids. They are composed of a sugar (galactose or sucrose), sphingosine, and a nitrogen-containing base. Two cerebrosides (ovophrenosin and ovokerasin), which differ in their fatty acid content, have been separated from egg yolk (Levene and West, 1917).

Vitamins and Minerals in Eggs Eggs contain most vitamins necessary for human nutrition, except vitamin C. The fat-soluble vitamins are contained exclusively in the egg yolk. One egg may supply almost 12% vitamin A, more than 6% vitamin D, 9% riboflavin, and 8% panthotenic acid of the recommended daily allowance in the United States. Vitamin A is found in two forms in the diet: performed vitamin A (retinol) and provitamin A (beta-carotene). The most predominant source of vitamin A in Western countries is from performed vitamins in animal products and egg yolk. Vitamin A is required to regulate growth, repair, and cell differentiation and healthy skin and eyes. The vitamin concentration is affected by genetics, rate of egg production, and the hen's diet (Naber, 1993; Lesson and Caston, 2003).

Eggs are an important source of minerals. Iron is present in eggs mainly in the ferric form bound to the proteins of ovotransferrin (in egg white) and phosphivitn (in egg yolk), which can reduce its bioavailability (Hallberg et al., 1997). Therefore, eggs are regarded as a food that has a low iron bioavailability (around 5%) compared to that of red met (15%) (Hurrell et al., 1988; Mann and Truswell, 2002). Adding enhancing factors to the egg diet, such as vitamin C, citric acid, cysteine-containing peptides, or ethanol, improves iron bioavailability in the diet (Mann and Truswell, 2002). Selenium is found in eggs as selenomethionine, with higher bioavailability than that of inorganic selenate or selenite (King, 2001). Selenium works with vitamin E as part of a key antioxidant enzyme (glutathione peroxidase); selenium-enriched eggs are available, with one egg delivering 50% of the RDI, as discussed elsewhere in the chapter.

ADDING DESIRED ATTRIBUTES TO EGGS

The possibility of manipulating the fatty acid composition of eggs by diet was recognized as long ago as 1934 (Cruickshank, 1934). However, the concept of

designer eggs, eggs enriched with omega-3 fatty acids, was not possible commercially until the 1990s, when Jeong Sim and his colleagues developed the Canadian designer egg during his time at the University of Alberta (Sim, 2009). This success contributed significantly to reestablishing the important role of eggs as a healthy and safe food item in human history. Other available designer egg products on the market include eggs enriched with vitamins (Michella and Slaugh, 2000), lutein (Leeson and Caston, 2004), and selenium; conjugated linoleic acid (CLA) enrichment (Van Elswyk, 1997); reduced yolk cholesterol; and more. The development of designer eggs not only fits well with today's health-conscious consumers but also contributes significantly to the egg industry in reversing the declining consumption of eggs over the past three decades. Sim presents the current state of research in this area in the book *The Amazing Egg* (Sim and Sunwoo, 2006).

Omega-3 Fatty Acid–Enriched Eggs

Omega-3 fatty acids (*n*-3 FA) are a family of polyunsaturated fatty acids which have the first carbon–carbon double bond at the third carbon position counting from the omega end of the carbon chain. Important omega-3 fatty acids are derived largely as eicosapentaenoic acid (EPA) and docosahexdenoic acid (DHA) from fish oils and as α-linolenic acid (LNA) from plant oils. A protective role of *n*-3 fatty acids against coronary heart disease (CHD) was firstly proposed by Dyerberg and Bang (1979), who observed a low incidence of CHD in Eskimos eating about 7 g/day of marine omega-3 fatty acids. The importance of omega-3 fatty acids in the prevention and management of CHD, inflammation diseases, and several cancers is well recognized.

The nutritional profile of the human diet changed rapidly with the introduction of agriculture and animal husbandry. The shift from a mobile, hunter–gatherer society to one that was able to remain in one place long enough to cultivate plants and maintain animals was very important. It allowed the provision of a much more stable and consistent food supply. With the advent of agriculture, novel foods were introduced as dietary staples. The nutrient characteristics of these foods began to change subtly at first, than much more rapidly once food-processing procedures were developed. The advancing technology of the industrial revolution allowed for quantitative and qualitative food and nutrient combinations that had not previously been encountered over the course of human evolution. For example, in the United States, during the 90-year period from 1909 to 1999, a striking increase in the use of processed vegetable oils occurred (Cordain et al., 2005). Specifically, per capita consumption of salad and cooking oils increased 130%, shortening consumption increased 136%, and margarine consumption increased 410%. These trends also occurred elsewhere in the world and were made possible by the industrialization and mechanization of the oilseed industry. The industrial advent of mechanically driven steel expellers and hexane extraction processes allow for greater worldwide vegetable oil productivity, whereas new manufacturing procedures allowed vegetable oils to take on

atypical structural characteristics. For example, margarine and shortening are produced by solidifying or partially solidifying vegetable oils via hydrogenation, a process leading to an increased content of saturated fat and trans fat. Consequently, the large-scale addition of refined vegetable oils to the world's food supply after the industrial revolution significantly altered both quantitative and qualitative aspects of fat intake. The modern human diet is characterized by a high intake of saturated fat and omega-6 fatty acids, and a low omega-3 fatty acid intake. An imbalance between omega-6 and omega-3 fatty acids is believed to have a wide range of health impacts for the development of "Western diseases." It is reported that an imbalance in the fatty acid ratio represents a risky factor for the onset and development of cancers and coronary heart diseases, especially the formation of blood clots (Enser, 2001). As an important part of the diet, the omega 6/omega 3 ratio in the chicken egg has increased dramatically, from 1.3 under absolutely natural conditions to 19.4 under a standard U.S. Department of Agriculture (USDA) diet (Simopoulos, 2000). Since the ratio between omega-6 and omega-3 in eggs can easily be manipulated through diet enrichment, development of omega-3–enriched eggs can contribute to an improved balance between omega-6 and omega-3 in the human diet.

It has been shown that the egg lipid profile is related to the concentration of lipids in a hen's diet. In this context, a bird's age and strain and nutritional changes in the diet are relevant factors in egg lipid composition (Nielsen, 1998). Moreover, dietary changes also affect the arrangement of triglycerides and phospholipids in the liver, in this way affecting yolk synthesis (Walzem, 1996). In this chapter the major *n*-3 FA ingredients used in egg enrichment and the effects of *n*-3 FA enrichment on egg quality, sensory quality, production, and oxidation are discussed.

Omega-3 Fatty Acid Dietary Sources Flaxseed oil is widely used in poultry egg and meat enrichment, due to its high content of LNA (50 to 60%) (Plourde and Cunnane, 2007). Other sources include fish oil (especially menhaden oil), marine algae, canola oil, and others (González-Esquerra and Leeson, 2000). A list of fats and oils used in poultry feeds and their fatty acid (FA) composition is shown in Table 4. In this chapter we discuss only the primary *n*-3 FA dietary sources. González-Esquerra and Leeson (2001) have discussed four omega-3 sources: flaxseed oil, menhaden oil, marine algae, and canola oil. Flaxseed oil and canola oil have higher percentages of LNA, $C_{18:3}$ (53.5% and 12%, respectively) than those of other omega-3 sources. Most long-chain PUFAs are higher in menhaden oil and marine algae.

Flaxseed Flaxseed is the most widely used ingredient in the production of omega-3 eggs. It is generally accepted that the amount of LNA in yolk increases linearly with the dietary level of omega-3 fatty acids up to 10%; however, the conversion of EPA and DHA from LNA does not increase equally with increasing LNA (Aymond and Van Elswyk, 1995). It is estimated that the conversion of LNA to EPA is only 15% efficient. Hens fed a flaxseed-enriched diet have

TABLE 4 Fatty Acid Composition of Oil Sources Used in Poultry Rations[a]

Fat Source	Saturated Fatty Acids	Polyunsaturated Fatty Acids		Monounsaturated Fatty Acids
		n-6	*n*-3	
Restaurant grease	21.4	23.3	2.6	52.4
Canola oil	7	22	10	61
Flaxseed oil	10	17	55	18
Safflower oil	10	76	Trace	14
Sunflower oil	12	71	1	16
Corn oil	13	57	1	29
Soybean oil	15	54	8	23
Cottonseed oil	27	54	Trace	19
Beef tallow	48	2	1	49
Palm oil	51	10	Trace	39
Fish oil	16.8	10.9	26.4	41.5
Menhaden fish oil	26.9	2.2	29.5	25

Source: Cherian (2007); reproduced with permission from *Poultry Science*. Copyright © 2007 by the Poultry Science Association.

[a]Values reported as percentages (weight of total fatty acids) and subject to change due to differences in batch, cultivars, or processing method used.

a relatively low conversion rate from LNA to DHA or EPA (Aymond and Van Elswyk, 1995). Furthermore, the use of flaxseed is limited, due to the presence of antinutritional factors such as mucilage, linatine, trypsin inhibitors, and phytic acid (Bhatty, 1995). Schumann et al. (2003) indicated that hens fed 100-g/kg flaxseed diets had lower body weight, liver weight, liver dry matter and fat content, and plasma triglyceride concentrations than did hens given control diets (without flaxseed). Flaxseed reduces the availability of minerals and also inhibits the activity of proteolytic enzymes (Ravidran et al., 1995).

Total fatty acid profile, on the other hand, is also affected by a hen's age and strain and by the form of flaxseed, ground or whole (Scheideler et al., 1998). In contrast, Aymond and Van Elswyk (1995) found that the flaxseed form does not affect the LNA deposition when the diet contains more than 10% flaxseed. The form of flaxseed can also affect oxidation. Aymond and Van Elswyk (1995) found that the flaxseed form had no effect on yolk thiobarbituric reactive substances when eggs were stored under refrigeration. Moreover, Schumann et al., (2003) demonstrated that the supplementation of flaxseed in hen diets consistently produced eggs with lower deformation or stronger shells, while the overall egg quality was not affected. LNA is one of the essential fatty acids that must be supplied from foods. However, LNA must be converted into EPA and DHA in humans for a potential biological benefit. It is thought that LNA is converted into EPA and DHA via desaturation and elongation reactions in the liver and other organs (González-Esquerra and Leeson, 2001). LNA is easily available from plant sources such as flaxseed and walnut; the use of LNA as a substitute for marine omega-3 fatty acids could be of interest where fish consumption is not a very popular dietary habit. It should be noted that elderly people, hypertensive

individuals, and some diabetics have a limited capacity to synthesize EPA and DHA (Emken et al., 1994).

Menhaden Oil Menhaden oil is the most popular fish oil to be used as a source of enriching eggs with long-chain *n*-3. Generally, a linear response to feeding levels of menhaden oil was observed (González-Esquerra and Leeson, 2000), although some scientists found that the amount of long-chain *n*-3 in eggs did not increase further by adding menhaden oil from 1.5 to 3%. However, Oh et al. (1991) reported that the *n*-3 FA in eggs (60 g) was 760 mg of DHA and EPA when feeding 10% fish oil. Hargis et al. (1991) observed that adding 3% menhaden oil in the diet could slightly increase EPA to about 30 mg compared to DHA at 180 mg/yolk; similar results were reported by Huang et al. (1990). Considering that the original menhaden oil contains more EPA than DHA (González-Esquerra and Leeson, 2001), the deposition of higher DHA than EPA in enriched egg yolk was due to hens' differing metabolic pathway for *n*-3 fatty acids (González-Esquerra and Leeson, 2000). Compared with flaxseed, eggs enriched with fish oil contain DHA and EPA, which are thought to have a higher bioavailability than LNA for humans Simopoulus, 2000). However, menhaden oil supplementation was reported to cause off-flavor in eggs and the development of hepatic lipidosis in hens in long-term use (Amini and Ruiz-Feria, 2007).

Marine Algae Marine algae are an efficient dietary alternative to current *n*-3 fatty acid sources. Yongmanitchai and Ward (1989) reported that some marine microorganisms synthesize significant amounts of long-chain fatty acids, particularly DHA and EPA. A *Schizocpytrum* sp. has been used commercially as an alternative source of omega-3 fatty acids (Barclay et al., 1998). Herber and Van Elswyk (1996) found that marine algae contain about 11.2% long-chain *n*-3 on a dry matter basis. They also reported that a similar amount of *n*-3 fatty acids was enriched in eggs on a 1.5% menhaden oil diet vs. a 2.4% marine algae diet after 4 weeks. Also, Herber and Van Elswyk (1996) concluded that further increase in a marine algae supplement, to a level of 4.8%, increased the yolk content of total *n*-3 FA only slightly compared with hens fed on a 2.4% diet. However, the egg production was decreased on a 4.8% diet. It was also found that the presence of marine algae carotenoids may enhance the oxidative stability of *n*-3 fatty acid–enriched eggs (Herber and Van Elswyk, 1998).

Canola Seeds Canola and rapeseed seeds contain about 42% oil, of which about 12% is LNA (National Research Council, 1993). Brettschneider et al. (1995) reported that total *n*-3 fatty acids in eggs were 127 and 159 mg supplemented by 15 and 30% canola seeds, respectively. However, the transferring efficiency of the LNA from the diet to the eggs was lower in a canola seed diet than in a flaxseed diet (8.76 vs. 2.37% of LNA of yolk lipids in flaxseed and canola diets, respectively). These results are in agreement with Cherian and Sim's (1991) findings that the inclusion of 10% flaxseed in the diet led to a higher LNA content in yolk than did 10% canola.

Effect of Omega-3 Fatty Acid Enrichment on Egg Quality, Production, and Sensory Quality Novak and Scheideler (2001) studied the long-term effects of 10% flaxseed on egg production and egg quality. They indicated that dietary supplemental flaxseed does not have a significant effect on egg production parameters and overall egg weight. However, flaxseed supplementation altered the weight of yolk solids and yolk significantly, increased albumen percentages, and lowered the wet shell percentage. In contrast, Basmacioglu et al. (2003) found that there was no effect on egg quality criteria such as egg weight, yolk weight, yolk ratio, albumen height, albumen ratio, shell weight, shell ratio, shell strength, and shell thickness by supplying 1.5% fish oil (FO), 4.32% flaxseed (FS), 1.5% FO + 4.32% FS, and 8.64% FS in hens' diets. A significantly higher egg production was observed in hens fed 4.32% flaxseed than that of the control.

Since the degree of unsaturation (number of double bonds) is associated with the susceptibility of food lipid oxidation, the presence of a large amount of long-chain *n*-3 fatty acids in eggs carries a potential risk of lipid oxidation. The stability of *n*-3 enriched eggs is primordial in maintaining the quality of the eggs; therefore, supplementation of *n*-3 FA for laying hens may affect egg sensory quality. Dietary flaxseed enrichment was reported to cause unpleasant flavors in eggs (Jiang et al., 1992). Leeson et al. (1998) found that panelists were able to distinguish between eggs from hens fed 10% flaxseed or a control diet. The fishy taste that was reported in fish oil–enriched products was also associated with product peroxidation of *n*-3 fatty acids but could be improved by using stabilized *n*-3 FA sources in poultry diets. Elswyk (1997) indicated that trained flavor panelists could accept eggs fed with 15 g/kg menhaden oil (MO) but not at a level of 30 g/kg MO. Omega-3 fatty acid–enriched eggs are an alternative food source for improving people's healthful daily fatty acid intake. However, egg sensory quality should be maintained to provide a better *n*-3 FA–enriched poultry product for the consumer.

The formation of cholesterol oxidized products (COPs) could also contribute to sensory attributes. Tai et al. (2000) have concluded that heating, storage time, and condition are the major factors for the formation of COPs in eggs and egg products. For example, although failing to detect 25-hydroxycholesterol (25-OH) in fresh egg yolk and yolk powder, Kou and Holmes (1985) found a significant amount of 25-OH in yolk powder after heating it at 110°C for 4 days. Similarly, Nourooz-Zadeh and Appelqvist (1987) found no COPs in fresh or freeze-dried egg yolks but after one year of storage detected a 36-ppm total COP concentration. One of the cholesterol oxidation products, 7-ketocholesterol, could inhibit the activity of 3-hydroxy-3-methylglutaryl-CoA reductase (HMG-CoA reductase), the rate-limiting enzyme for cholesterol biosynthesis in eggs. However, Vargas et al. (1986) found that 7-ketocholesterol did not lead to any significant change in yolk cholesterol level, although there was a reduction of 43% in the activity of HMG-CoA reductase.

Antioxidants in Omega-3–Enriched Egg Vitamin E and selenium are key components of the antioxidant system to reduce lipid peroxidation. Surai et al. (2006)

summarized the advantage of eggs enriched with antioxidants as follows: (1) decreased susceptibility to lipid peroxidation; (2) prevention of fishy taste formation; and (3) could be a good source of antioxidants in the human diet.

Vitamin E Enrichment in Omega-3 Eggs Vitamin E is the common biological chain-break antioxidant, found in food in the forms of tocopherols and tocotrienols, each containing four isomers. Thurman and Mooradian (1997) have indicated that the α-tocopherol isomer is the only form of vitamin E that the human body can use. While the body can absorb both natural and synthetic forms of α-tocopherol, natural forms, either from foods or from natural-source supplements, have higher bioavailability than do synthetic forms. Vitamin E cannot be synthesized in the human body and its adequate intake relies on adherence to a well-balanced diet (Thurman and Mooradian, 1997). Major vitamin E sources are vegetable oils and some other plant-derived foods. The daily average vitamin E intake is 11.7 mg in men and 8.6 mg in women, with margarines and mayonnaise contributing 23% of the total vitamin intake. These levels are in line with the recommended daily allowances (RDAs) of the USDA. Vitamin E deficiency is associated with the development of a range of specific diseases involving major tissues of the organism, including immune system incompetence, impairment of lipid metabolism, fertility problems, and increased susceptibility to common and specific diseases (Machlin, 1991). Vitamin E is one of the most important in vivo antioxidants; intake of vitamin E has been linked to the prevention of several cancers and coronary disease (Diplock, 1991).

In addition, vitamin E is used widely to improve oxidative stability. Lipid oxidation is the leading cause of quality deterioration in *n*-3-enriched eggs. Quality deterioration involves changes in flavor, color, texture, and nutritive value. In fresh shell eggs, lipids are not easy to oxidize; however, oxidation can easily be induced in processing egg products or under high-temperature treatments (Galobart et al., 2001a). It is thought that instances of off-flavor (fish taint) in *n*-3 FA–enriched eggs are due to the rancidity of *n*-3 fatty acids in either feeds or animal products. Vitamin E is more vulnerable than *n*-3 FA during food processing, so *n*-3 FA can be protected by vitamin E supplementation. Dietary supplementation of vitamin E is commonly used in commercial *n*-3 eggs to mitigate the oxidation of *n*-3 FA, thereby preventing the formation of undesirable off-flavors. It was reported that the addition of vitamin E to hen diets increased the content of vitamin E in the egg yolk in a dose-dependent manner up to doses of 20 mg of α-tocopherol/kg feed but leveled off at higher levels in the diet (Grobas et al., 2002). Similar to many different nutrients, the transfer efficiency of vitamin E decreases with increasing levels of vitamin E in the diet. Galobart et al. (2001b) showed that the α-tocopherol transfer efficiency from feed to egg ranged from 41.8 to 26% when vitamin E was added at levels ranging from 52 to 200 mg/kg feed. Grobas et al. (2002) reported that the transfer efficiency ranged from 26.2 to 16.2% when vitamin E was added at levels from 20 to 1280 mg/kg feed. As vitamin E supplementation is used simultaneously with omega-3 fatty acid enrichment, the amount of omega-3 also affects the transfer efficiency of vitamin

E. A higher omega-3 content results in a higher oxidative susceptibility in an animal body, which contributes to a greater utilization of vitamin E, leading to a reduction in the deposition of vitamin E in egg yolk (Galobart et al., 2001b).

The findings of studies of the impact of vitamin E on the rate of egg production and on egg quality have been inconsistent. Egg production, vitelline membrane strength, yolk and albumen height, and foam stability were improved significantly by adding dietary vitamin E (60 IU vitamin E/kg feed) in high-temperature treatment (Kirunda et al., 2001). Moreover, Kucuk et al. (2003) indicated that supplementing dietary vitamin E and/or vitamin C improved laying hen performance significantly in a cold environment, including egg production, feed conversion rate, and body weight. Additionally, egg quality was enhanced by supplementation of dietary vitamin E and/or vitamin C. In contrast, Galobart et al. (2001b) found that supplementation of dietary vitamin E does not have a significant effect on laying rate, egg weight, daily feed intake, and feed efficiency. Similarly, Engelmann et al., (2001) fed laying hens five different levels of dietary vitamin E and assessed the effect on laying hen performance and egg quality, and none of the treatments indicated a significant effect on egg quality. Leeson et al. (1998) reported a decline in egg yolk flavor and overall egg acceptability when a higher level of vitamin E (100 ppm vs. 10 ppm) was used in conjunction with 20% dietary flaxseed. The deterioration in egg sensory attributes was related to the preoxidation rather than the antioxidant action of high doses of vitamin addition. Other authors, using a diet containing up to 400 IU vitamin E per kilogram of feed (Jiang and Sim, 1994), did not observe any effect of the vitamin on the sensory properties of eggs. Leeson et al. (1998) recommended that the level of dietary vitamin E in feed should be 100 IU/kg in commercial *n*-3 fatty acid egg production.

Selenium Enrichment in Omega-3 Eggs Because selenium is an essential animal and human nutrient, selenium deficiency has been studied in many regions of the world (Surai, 2006). Several studies have indicated that adequate selenium consumption in humans could improve the function of immunoregulation, protect cells from the damage of oxidative stress, improve sperm quality, and reduce the risk of cardiovascular disease, several cancers, and inflammatory disease (Dvorska et al., 2006).

Since selenium content in plant-based food depends on its availability from soil, and in animal-based food depends on its availability from diet, the level of this element in human foods varies by geographic location. Selenium is an essential part of a variety of selenoproteins, such as glutathione peroxidase (GSH-Px), and at least six forms of GSH-Px were reported; GSH-Px is involved in cellular antioxidant protection (Arthur, 1997). Selenium is a necessary trace element in reducing the oxidative damage of cell membranes of animals and humans. Selenium supplementation is required for several animal species and for humans. As one of the most effective antioxidants, selenium can be obtained in either inorganic or organic form. Inorganic selenium (selenite and selanate) has a lower transfer efficiency to eggs than does organic selenium (selenomethionine).

Selenium has shown an effect on egg quality. For example, Rutz et al. (2004) found that supplementation of organic selenium to layer diets significant improved egg production, egg weight, feed conversion ratio, albumen height, and specific gravity. In addition, eggshell weight and shell thickness were increased by a combination of organic selenium, organic zinc, and organic manganese. Papazyan and Surai (2007) reported similar results. They indicated that dietary selenium supplementation for laying hens resulted in an improvement in egg production, internal egg quality, and eggshell quality. The results showed that Se concentrations were increased significantly in both treatments, but the Se concentration was higher in Se-enriched yeast (SY) treatment than in sodium selenite (SS) treatment. Egg weight was increased significantly by a supplement of SY. At 7.2°C, there was no significant difference of albumen height between those two treatments, but albumen height improved significantly when eggs stored at 22.2°C were fed dietary SS (Payne et al., 2005). Similarly, in a study of a supplement of dietary selenium yeast, the authors supplied laying hen with four levels of SY in a basal diet: 0, 0.30, 0.60, 0.90, and 1.20 ppm. Eggshell thickness was improved significantly in 0.60- and 1.20-ppm SY treatments, and egg production was increased in 0.30- and 0.90-ppm SY treatments. In contrast, yolk color, eggshell breaking strength; and the feed conversion ratio showed insignificant differences among treatments (Nae et al., 2006). Organic selenium is used widely because its absorption (selenomethionine) is higher than that of the inorganic form (Payne et al., 2005).

However, a high level of selenium is toxic (Attia et al., 2004). Feeding chickens at 0, 5, and 10 ppm Se in the basal diet, Attia et al. (2004) found that the body weight, egg production, egg weight, and feed conversion ratio decreased significantly at increased Se concentrations. Further, egg quality, such as eggshell weight, eggshell thickness, and egg breaking strength, was also significantly reduced by supplementing 5- and 10-ppm Se rather than the basal diet. A higher mortality rate was found in 10-ppm treatment than in 0- and 5-ppm treatments. Therefore, Attia et al. (2004) concluded that retain to retain laying hen performance and high egg quality, and avoid some side effects, the concentration of dietary Se for a laying hen should not exceed 5 ppm Se.

Lutein-Enriched Eggs

Macular degeneration is the leading cause of blindness in developed countries, resulting in progressive and irreversible loss of central region vision. It was estimated that about 0.2% of people aged 55 to 64 years in North America, Europe and Australia and 13% of those aged 85 years or older may be affected by age-related macular degeneration (Grando et al., 2003). It is recognized that a delay in cataract formation of about 10 years would reduce the prevalence of visually disabling cataract by about 45%, enhancing the quality of life for much of the world's older population and substantially reducing the economic burden ($5 to 6 billion) due to cataract-related disability and cataract surgery (Taylor and Hobbs, 2001). As one of only two carotenoids found in the human crystalline lens, it

TABLE 5 Lutein–Zeaxanthin Content of Food

Food	Content (mg/100 g wet wt)
Broccoli, cooked	2.1
Brussels sprouts, cooked	1.3
Cabbage, white, raw	0.3
Corn, sweet, cooked	1.8
Egg yolk, medium	0.3
Kale, cooked	15.8
Lettuce, raw	2.6
Peas, green, cooked	1.4
Spinach, cooked	7.1
Spinach, raw	11.9
Lutein-enriched egg yolk[a]	1.95

Source: Johnson (2002); used with permission.
[a]Lesson and Caston (2004).

was suggested that increasing the daily intake of lutein may help in prevention of the onset and development of age-related macular degeneration (Johnson, 2002). Lutein and zeaxanthin are able to absorb blue light striking the retina, which is thought to initiate degeneration of the delicate surface membrane (Landrum and Bone, 2001). Lutein may also play a role as an antioxidant in macular surface membranes to limit the oxidant stress of the tissue that results from metabolism and light (Rapp et al., 2000). Landrum et al. (1997) showed that the optical density of the macular pigment increased by 30% in humans supplemented with lutein, which equates to a 40% reduction in blue light reaching the retina. Moeller et al. (2000) suggested that xanthophyll intake might also influence the development of cataracts. Although lutein exists widely in a variety of food items, including fruits and green vegetables, especially dark green varieties such as spinach, broccoli, beet, and lettuce (Table 5), the daily intake of lutein and zeaxanthin in North Americans is less than 1 mg/day (Landrum and Bone, 2001), which is much less than the preventive levels being suggested (Grando et al., 2003).

Although not known as a rich source of pigments, eggs contain highly bioavailable and stable pigments that could be of importance in preventing cataract and macular degeneration. The presence of carotenoid pigments such as lutein and zeaxanthin has been known for years in the egg industry as a means of manipulating the color of egg yolk. Carotenoids are a highly colored (red, orange, and yellow) group of fat-soluble plant pigments. Carotenoids belong to a family of phytochemicals containing 40 carbon atoms. Structurally, they are in the form of a polyene chain, which is sometimes terminated by rings. It is accepted that the types and amounts of carotenoids in yolk are diet-dependent. The major xanthophylls in the yolk are lutein, zeaxanthin, and cryptoxanthin, all of which are derived from commonly used pigmented feed grain ingredients such as yellow corn, alfalfa meal, and corn gluten meal involving intestinal absorption and

biotranslocation (Brockman and Volker, 1934; Smith and Perdue, 1966). Eggs normally contain 0.3 to 0.5 mg of total xanthophylls, with just over half present as lutein (Steinberg et al., 2000). Matsuno et al. (1986) reported a total of 2.5 mg of carotenoids per 100 g of yolk, the major carotenoids being lutein A (40%), zeaxanthin (19.8), cantaxanthin (17.9%), and β-cryptoxanthin (17.3%). Over the last decade there has been increased awareness of the role of xanthophylls in human health, in particular the roles of lutein and zeaxanthin in the prevention of certain eye disorders (Lesson and Caston, 2004).

Lutein-enriched eggs are currently available on the market. Lesson and Caston (2004) reported that it is possible to increase egg yolk lutein five to eight times above regular concentrations, which would represent an additional 1.5 to 2 mg contribution to our daily intake. Although general egg quality was not affected, egg yolk color increased significantly but leveled off with increased lutein supplements over 250 ppm. It should be noted that the conversion efficiency of lutein from feed to eggs was around 10% with 125 ppm in the diet, declining to 2 to 3% for a supplement level of 500 ppm. However, a much higher transfer efficiency (40%) was reported for canthaxanthin (Grashorn and Steinberg, 2002). In the same study, the efficiency of lutein transfer was closer to 10% and seemed to decline with higher levels of supplements. This transfer efficiency decreased further when flaxseed was added to the diet.

The bioavailability of lutein is affected by many factors, including the matrix in which they are contained and the interactions they have with other dietary constituents. Also, the amount and type of food processing affects lutein bioavailability. For example, the processing of spinach does not affect the bioavailability of lutein but does positively affect β-carotene bioavailability (Castenmiller et al., 1999). The amount of fat consumed with the lutein source is another factor that affects bioavailability, because higher fat increases the bioavailability of lutein esters (Roodenburg et al., 2000). The egg yolk is a matrix of digestible lipids, which may improve bioavailability due to their association with the lipid matrix (Handelman et al., 1999; Chung et al., 2004). Although research supports a potential protective role of lutein and zeaxanthin in eye diseases and in some cancers, studies related to lutein in eggs and their potential benefits in egg diseases are very limited. In the Beaver Dam Eye Study, egg consumption was inversely associated with nuclear cataract risk among members of the cohort who were less than 65 years of age at baseline (Lyle et al., 1999). Consuming 6 eggs a week resulted in a significant increase in macular pigment optical density as well as serum zeaxanthin levels; however, serum lutein levels remained unchanged (Curran-Celentano et al., 2003). A randomized crossover design of 33 men and women in an 18-week study showed that in older adults, consuming 1 egg/day for 5 weeks significantly increased serum lutein and zeaxanthin concentrations without elevating serum lipids and lipoprotein cholesterol concentrations (Goodrow et al., 2006). Eggs are recognized as a highly bioavailable source of dietary carotenoids and are an effective vehicle for increased and site-specific antioxidant uptake. However, further studies are needed to establish the benefits of consuming lutein-enriched eggs.

Conjugated Linoleic Acid–Enriched Eggs

Conjugated linoleic acid (CLA) is the name given to a group of positional and geometrical isomers of 18-carbon unsaturated fatty acids with two conjugated double bonds (unlike linoleic acid, which has a nonconjugated diene) (Figure 3). By comparison, the two double bonds in CLA can occur in several positions along the carbon chain: at positions 7 and 9, 8 and 10, 9 and 11, 10 and 12, 11 and 13, or 12 and 14. Each double bond can be found in either the *cis* or *trans* (meaning on opposite sides) configuration.

CLA exists naturally in ruminant animals such as cattle, sheep, and goats and hence is a component of most North American diets. It is now known that many such conjugated mienes are formed in the rumen by bacterial hydrogenation or by delta-9 desaturation of the co-product vaccenic acid (*trans*-11–18:1). These bioconverted fatty acids are deposited in the tissues and can be available to consumers in such ruminant products as milk and beef. The most prominent CLA isomer in rumen fats is *cis*−9,*trans*−11-CLA (abbreviated c9,t11-CLA), with minor amounts of *trans*−7,*cis*−9-CLA, (t7,c9-CLA), *trans*−11,*cis*−13-CLA (t11,c13-CLA), and *trans*−10,*cis*−9-CLA (t10,c9-CLA) (Dhiman et al., 2005). However, the most commonly occurring CLA isomers in synthetic mixtures are c9,t11-CLA and t10,c12-CLA, with minor amounts of t8,c10-CLA and c11,t13-CLA, which are indicative of more severe heating conditions during the synthesis of CLA from linoleic acid.

Recognition of the health benefits of CLA was quite accidental. While Michael Pariza of the University of Wisconsin was investigating the carcinogenic properties of grilled beef, contrary to expectations, the fatty acids present in the beef exhibited anticarcinogenic rather than procarcinogenic properties. Since this surprising result, CLAs have been shown to have antiadipogenic, anticarcinogenic, antiatherogenic, antidiabetogenic, and anti-inflammatory properties (Wahle et al., 2004; Bhattacharya et al., 2006). Whether individual isomers of CLA have distinct effects on tumorigenesis and lipid metabolism and therefore could affect biological activity significantly is now under extensive investigation. CLA isomers have been studied extensively (especially t10c12 and c9t11 in different concentrations) because of their ability to modulate cancer, prevent arteriosclerosis, modulate diabetes, improve the immunological function, and modify body composition in animals, but few have been studied in human (Rasooly et al., 2007).

Although in some early studies, CLA intake was estimated to be 1 g/day, a recent report using food-duplicated methodology suggests that average intake in the U.S. population is less than 500 mg/day (Ritzenthaler et al., 2001). It is supposed that the effective daily consumption of CLA by an adult is approximately 1.5 to 3.0 g of CLA (Decker, 1995), which is significantly greater than the estimated daily intake level. In view of the potential benefits of CLA for human health, a number of researchers have begun looking at possible ways of increasing the concentration of CLA in bovine milk, beef, and even egg. There appear to be two practical approaches to achieving this goal. The first is to use dietary modification in an attempt to increase the natural production of CLA in

cows and beef. The second approach is to feed a synthetic mixture of CLA isomers. It is supposed that supplementing CLA in animal feed to increase the CLA content in animal products is superior to using CLA-enriched oils as capsule or fortified foods, although further evidence is needed to justify this rationale.

Previous studies have shown that concentrations of CLA in yolk lipids increased linearly as dietary CLA increased. The maximum concentrations of CLA in the yolk lipids of hens fed 0.5, 2.5, or 5.0% CLA occurred 11 days after the start of the experiment and were 0.82, 5.82, and 11.20% of the total fatty acids, respectively (Chamruspollert and Sell, 1999). Feeding 5.0% CLA decreased feed intake but did not affect the rate of egg production; the weight of eggs, albumens, or yolks, or body weight gain through 36 days. It was also reported that feeding 5% CLA could affect the overall egg yolk lipid composition. For example, the saturated fatty acids (SFAs) increased while the MUFAs decreased as dietary CLA concentration increased (Chamruspollert and Sell, 1999; Suksombat et al., 2006). Increasing SFA intake is a concern for the increased associated risk of cardiovascular diseases, whereas DHA is required for proper development of certain body tissue, especially the brain and the rest of the nervous system, and a dietary supply of this fatty acid is desirable for humans (Clandinin et al., 1989). Increased SFAs and decreased MUFAs such as arachidonic and docosahexaenoic acids may therefore be considered undesirable. The change in fatty acid composition may be due to a competitive interaction among CLA, linoleic acid, or linolenic acids for delta-9 desaturase enzyme and metabolism.

Increased dietary CLA can also affect egg quality negatively. Ahn et al. (1999) have shown that yolk color was not influenced by dietary CLA and storage, but feeding either 2.5 or 5.0% CLA to hens resulted in egg yolks that were very firm when the yolks were refrigerated for 7 days or longer and then hard-cooked. It is evident that feeding a high level of CLA could significantly reduce egg, yolk, and albumen weights ($p < 0.05$), while yolk color decreased significantly as dietary CLA increased ($p < 0.01$). Shell thickness and Haugh units were not influenced by the dietary CLA (Suksombat et al., 2006). The firmness of egg yolks increased significantly with increased storage time and increased dietary CLA (Shang et al., 2004). But some of these deleterious effects could be improved when CLA was combined with other fatty acids. Kim et al., (2007) reported that co-supplementation with other fatty acids reduced the degree of change in egg weight, strength and thickness of eggshell, albumen index, yolk index, yolk color, and yolk diameter. Therefore, fat supplementation should be designed carefully to minimize side effects that may affect the reproduction capacity of poultry.

Most experiments show that eggs produced by hens fed 5.0% CLA will contain 310 to 1000 mg of CLA per egg (Chamruspollert and Sell, 1999; Suksombat et al., 2006). Such eggs could provide a substantial amount of CLA in human foods to meet the proposed CLA requirement. It is understood that the negative effect on egg quality of feeding a high dose of CLA could be alleviated by co-supplementation of other fatty acids although further study to define an optimized fatty combination and ratio has to be undertaken. It is also interesting to note

that different breeds of layers could respond differently to CLA supplementation. Yin et al. (2008) reported that concentrations of stearic, arachidonic, and docosahexaenoic acids were higher in the yolks of Brown Dwarf hens than in those of White Leghorn hens. Enrichment of *cis*−11,*trans*-13 was higher in the yolks of White Leghorns, but *cis*−10,*cis*-12 was higher in the yolks of Brown Dwarf hens. Given the fact that individual isomers of CLA have distinct effects on tumorigenesis and lipid metabolism, the observation that CLA isomers could be altered by the different breeds of layers could have a significantly effect on ultimate health outcomes.

Eggs with Reduced Cholesterol Content

The American Heart Association (2005) showed that coronary heart disease (CHD) is the leading cause death in the United States and most developed countries. A 10-year study (Coronary Primary Prevention Trial) indicated that a 1% reduction in plasma cholesterol could lead to a 2% reduction in CHD risk (Lipid Research Clinics Program, 1984). Although a close relationship between dietary intake cholesterol and plasma cholesterol has not been established, a high dietary cholesterol level carries a potential risk of a high plasma cholesterol level. In this context, about 30% of the cholesterol level in the Western diet comes from chicken eggs (Kritchevsky and Kritchevsky, 2000). In the 1970s the American Heart Association (AHA) recommended that people limit their daily cholesterol consumption and egg intake to reduce the risk of CHD (Herron and Fernandez, 2004; Elkin, 2006). This recommendation led to the controversial public perception that egg is cholesterol enriched and contributes to the risk of CHD. However, many current studies do not support this hypothesis, since the cholesterol metabolism is complicated in the human system and the human diet is not the sole factor that decides the level of cholesterol in the blood (Naber 1990; Elkin and Yan, 1999). Concerns about high cholesterol and egg intake have been going through a gradual reevaluation process. A metaanalysis of 224 studies (covering more than 30 years of research) found a limited relationship between dietary cholesterol and plasma cholesterol (Howell et al., 1997). In the largest epidemiological study conducted to date on the relationship between egg consumption and coronary heart disease, consumption of up to one egg per day did not have a substantial overall impact on the risk of coronary heart disease and stroke (Hu et al., 2001).

In 2000, the AHA and National Cholesterol Education Program (NCEP) suggested a healthy daily cholesterol intake of less than 300 mg/day. The cholesterol content in a typical large egg is 213 mg of cholesterol per yolk (USDA, 1991); in this way, the daily consumption of one yolk should technically meet the AHA guideline (Elkin, 2006). The growing egg industry, on the other hand, is demanding an increase in total egg production. Egg products are becoming more popular since people are eating more in restaurants and demanding more convenient food. As a result, consumers are having more than one yolk per day. If the egg yolk cholesterol content could be reduced to 50%, the consumption of two eggs per

TABLE 6 Egg Yolk Cholesterol Response to Genetic Selection in White Leghorn Hens

Line (mg/g yolk; as is basis)			Difference			
Random-Bred Control (C)	Low Cholesterol (L)	High Cholesterol (H)	H—L (%)	C—L (%)	Generations (*n*)	Reference[a]
—	12.91	13.62	−5.2	—	1	1
17.15	17.56	18.94	−7.3	+2.4	3	2
16.39	16.30	16.19	+0.7	−0.5	2	3
13.87	12.79	13.73	−6.8	−7.8	5	4
14.70	13.90	—	—	−5.4	3	5

Source: Elkin (2006); reproduced with permission from *World's Poultry Science Journal*. Copyright © 2006 World's Poultry Science Association.

[a]1, Cunningham et al. (1974); 2, Marks and Washburn (1977); 3, Becker et al. (1977); 4, Hollands et al. (1980); 5, Ansah et al. (1985). Total cholesterol contents (mg/yolk) were not reported in references 1, 2, and 4.

day will meet the AHA and the NCEP guidelines (Elkin, 2006). Efforts such as genetic selection, nutritional alternative, and anticholesterol drug addition have been pursued extensively to reduce egg cholesterol levels (Hargis, 1988; Elkin, 2006).

Genetic Selection From a genetic point of view, egg cholesterol content is affected by several factors, such as species of bird, breed or strain and age of fowl (Simmons and Somes, 1985; Jiang and Sim, 1991; Shafey et al., 1992; Campo, 1995; Kovacs et al., 1998; Chowdhury et al., 2002). In the 1970s, several genetic selection studies aiming to decrease egg yolk cholesterol were carried out. Washburn and Nix (1974) suggested that genetic selection could possibly change yolk cholesterol level. Elkin (2006) compared five of the genetic selection studies (Table 6) but showed a slightly reduction in the egg yolk cholesterol (<8%) within five generations. In fact, the reduction in egg cholesterol by genetic selection is fairly small (9 to 10 mg) and is not significant if an average daily intake of cholesterol is about 250 mg (Hargis, 1988). These results clearly indicate the potential that exists in changing cholesterol levels in eggs by using genetic selection. However, there is a lower limit to egg yolk cholesterol, due to its role in developing the embryo (Hargis, 1988).

It was reported that the yolk/albumen ratio is changed through genetic selection. Hartmann et al. (2000) showed that in the high yolk cholesterol line, an increase in yolk size led to a decrease in egg weight. In the low yolk cholesterol line, a decrease in yolk size did not affect egg weight.

Egg yolk provides the nutrition needs of the embryo (Burley and Vadehra, 1989). Hargis (1988) concluded that limited changes in yolk cholesterol concentration (5 to 7% reduction) can be achieved by genetic selection. However, the decrease in cholesterol level will cause egg production to cease simply because the reduced cholesterol level cannot meet the embryo's requirement. Bartov et al.

(1971) found a significant negative correlation between the rate of egg production and the amount of cholesterol in egg yolk. If the egg production rate is higher, the level of egg yolk cholesterol is lower. In contrast, Elkin and Yan (1999) and Elkin et al. (2003a) reported that a reduction of 30% or more of yolk cholesterol content did not reduce egg production.

Effects on Cholesterol of Dietary Change

Effect of Fat Dietary cholesterol supplementation can increase the concentration of cholesterol in eggs (Harris and Wilcox, 1963; Sutton et al., 1984). Weiss et al. (1967) reported that the yolk cholesterol level increased a by feeding 30% safflower oil, 30% hydrogenated safflower oil, or 30% coconut oil in the hen's diet.

Dietary omega-3 fatty acid is another factor affecting yolk cholesterol content. Yolk cholesterol content in omega-3–enriched eggs obtained from laying hens fed 10% menhaden fish had 13.6% less yolk cholesterol than did the control eggs (Oh et al., 1991). Similarly, Scheideler and Froning (1996) fed birds with 1.5% menhaden fish oil or 5% ground or whole flaxseed–based diet, resulting in about a 9% yolk cholesterol reduction.

Effect of Natural Products Some natural products have been shown to have the ability to reduce plasma cholesterol level in humans and animals (Yeh and Liu, 2001). Several studies have been focused on the effect of yolk cholesterol concentration by supplementation of various dietary natural products, such as garlic (Reddy et al., 1991), Probiolac (Panda et al., 2003), Ecozyme, Raftilose P95 (Chen and Chen, 2003), and *Lactobacillus acidophilus* (Abdulrahim and others 1996; Haddadin et al., 1996). Elkin (2006) has compared various natural products' ability to reduce egg yolk cholesterol (Table 7).

Garlic has been reported to be the most effective agent in reducing the cholesterol level in yolk and plasma. Hens' performance was not affected by feeding 2, 4, 6, 8, and 10% dietary sun-dried garlic paste to six strains of hens (Hisex Brown, Isa Brown, Lohmann, Starcross, Babcock, and Starcross-579) (Chowdhury et al., 2002). However, both plasma cholesterol and yolk levels were decreased significantly by feeding dietary garlic paste, and the cholesterol concentrations were negatively correlated with garlic paste concentrations, except that the plasma cholesterol content was not affected at 8 and 10% dietary garlic paste. Similarly, in another study it was reported that egg and plasma cholesterol levels were reduced by 23 and 22%, respectively, through feeding dietary garlic powder (Mottaghitalab and Taraz, 2002).

For other natural products, including trichoderma viride (Qureshi et al., 1986), tumeric (Keshavarz, 1976), supplemental shark cartilage, and chitosan (Nogueira et al., 2003), no influence on reducing yolk and plasma cholesterol concentrations was detected.

Effect of Phytosterols Phytosterols (also called plant sterols), which are structurally and functionally similar to cholesterol in vertebrate animals, are a group

TABLE 7 Influence of Natural Products on Plasma Cholesterol Content and Yolk Cholesterol Content

Nutrient	Species	Supplemental Dietary Level(s) (ppm)	Change in Plasma Cholesterol (%)	Change in Yolk Cholesterol (%)	Duration of Experiment (weeks)	Reference[a]
Probiolac	White Leghorn	100 150	— —	−27 −23	— —	1
Lactobacillus acidophilus	Lohmann Lohmann	— —	−56 −55	−17 −18.8	16 40	2 3
Ecozyme	White Leghorn	—	−13.67	−11.31	—	4
Raftilose P95	White Leghorn	—	−14.46	−13.25	—	4
Probiolac	White Leghorn	100 200	−19 −20	−14 −13	— —	5

[a]1, Mohan et al. (1995); 2, Abdulrahim et al. (1996); 3, Haddadin et al. (1996); 4, Chen and Chen (2003); 5, Panda et al. (2003).

of steroid alcohols existing in plants (Weiss et al., 1967). Sim and Bragg (1977) investigated the effect of cholesterol metabolism by feeding plant sterols to hens and reported a decrease of 16 to 33% cholesterol concentration in either plasma and egg yolk by feeding a 2% dietary soysterols with either saturated or unsaturated oil, with or without cholesterol. It was reported that a supplement of dietary β-sitosterol (at 2 and 4% levels) causes a significant decrease in egg cholesterol levels (Clarenburg et al., 1971). Weiss et al. (1967), however, reported that feeding 1% β-sitosterol did not affect plasma and egg cholesterol levels. Ostlund et al., (1999) have indicated that purified phytosterols could form highly stable crystals, which are difficult to dissolve in bile salt solutions. Consequently, supplementation by dietary phytosterols could reduce egg cholesterol levels.

Effect of Minerals and Vitamins Several studies have indicated that supplementation by dietary microminerals (copper, zinc, vanadium, chromium, and iodine) and/or dietary vitamins (vitamin A, ascorbic acid, and niacin) may change the yolk cholesterol level (Elkin, 2006). However, as indicated in Table 8, supplementation by microminerals (except Cu), and vitamins does not significant affect yolk cholesterol levels. Moreover, results on the effects of dietary copper (Cu) on egg yolk cholesterol content are conflicting. Elkin (2006) concluded that Cu possibly reduces the biosynthesis of cholesterol and stimulates conversion from cholesterol to bile acids.

Effect of Fiber Dietary fiber is a group of indigestible portion of plant foods that can be resistant to the human or animal gastrointestinal system, absorbing

TABLE 8 Influence of Feeding Supranormal Levels of Select Minerals and Vitamins on Egg Cholesterol Content

Nutrient	Dietary Form (Mineral)	Supplemental Dietary Level(s)	Change in Yolk or Egg Cholesterol Content from Unsupplemented Control (%)	Duration of Experiment (weeks)	Reference[a]
Vanadium	Ammonium vanadate	100 ppm	−0.3	4	1
		300 ppm	+11.2		
Zinc	Zinc oxide	25 ppm	−16.2	12	2
		50 ppm	+1.0		
		100 ppm	−15.8		
		200 ppm	−6.7		
Chromium	Chromium picolinate	800 ppb	+11.4	4	3
		1,600 ppb	+11.8		
Iodine	Calcium iodate	3 ppm	−2.1	30	4
		6 ppm	−6.3		
		12 ppm	−4.2		
		24 ppm	−1.4		
Niacin		1,000 ppm	0.0	3	5
		522 ppm	+2.4	3	6
		1,022 ppm	+2.5		6
		10,000 ppm	−0.4 mg/g yolk[b]	3	7
		20,000 ppm	−1.8 mg/g yolk[b]		7
Vitamin A		9,091 IU/kg	0.0	3	6
		22,000 IU/kg	−7.9	2	8
		220,000 IU/kg	−9.0		8
		10,000 IU/kg	−7.4	12	2
Ascorbic acid		1,333 ppm	−2.8	38	9
		30 ppm	−0.9	24	10
		60 ppm	−3.7		10
		90 ppm	−2.9		10

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[a]1, Hafez and Kratzer (1976); 2, Kaya et al. (2001); 3, Lien et al. (2004); 4, Yalçin et al. (2004); 5, Weiss et al. (1967); 6, Leeson et al. (1991); 7, Singh (1972); 8, Dua et al. (1967); 9, Nockels (1973); 10, Al-Janabi et al. (1988).

[b]Control yolk cholesterol content not reported; percentage decrease could not be calculated.

water and easing defecation. Since 1973, several studies have been conducted to decrease the egg cholesterol level by feeding laying hens with a variety of fibers. In fact, McNaughton (1978) demonstrated that increasing dietary fiber from 2% to 4% decreased yolk cholesterol levels by 5 to 10%. It is thought that fibers could affect cholesterol metabolism through bile acid binding and stimulate fecal sterol excretion (Mokady, 1973; Wu et al., 2003).

Elkin (2007) has concluded that supplementation with fiber can slightly reduce egg yolk cholesterol (<10%) in general. Regardless of the dietary source, feeding fiber to laying hens dilutes the available energy content of a diet and, as a result, may limit energy intake and potentially reduce hepatic cholesterol production, especially if prior energy intake had been excessive.

Even though genetic selection, alternative nutrition, and pharmacological techniques are an effective strategy in modifying egg cholesterol content, there is a certain limit possible for the reduction of cholesterol levels. However, because of consumer trends, efforts to reduce the egg cholesterol content will probably continue in the near future. Research needs to be done in the avian transgenesis field, which seems to be the most effective way to reduce the cholesterol level in eggs. Furthermore, the commercial ability to produce low-cholesterol eggs will be constrained by environmental policies, biotechnology, and public acceptance.

CONCLUSIONS

Eggs are a good source of nutrients of proteins, lipids, vitamins, and minerals. The development of omega-3–enriched eggs greatly enriches the context of functional foods for human health. Furthermore, the inclusion of omega-3 fatty acids in the diet of birds may also be beneficial in reducing the risk of coronary disease and consequently, sudden death in birds (Walton et al., 1999). However, having a higher content of polyunsaturated fatty acids in omega-3–enriched eggs is more susceptible to lipid oxidation, a situation that can be corrected with adequate antioxidants. The supplementation of plant extracts or herbal additives may not only contribute to birds' gut health, antioxidation, and liver function but also improve the oxidative stability in omega-3–enriched products (Yonnakopoulos et al., 2004). An egg is viewed in many ways as a "bioreactor"; however, the transferring efficiency of many nutrients or functional ingredients from diet into eggs is relatively low. The egg has a long history as part of the human diet and continues to demonstrate its value for the promotion of health as we learn more about how to optimize its nutritive value.

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29

FUNCTIONAL PROPERTIES OF EGG COMPONENTS IN FOOD SYSTEMS

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INTRODUCTION

Due to their highly nutritive value (Watkins, 1995) and unique functional properties (Table 1), hen egg components remain one of the most commonly used

Handbook of Poultry Science and Technology, *Volume 1: Primary Processing*, Edited by Isabel Guerrero-Legarreta and Y.H. Hui

TABLE 1 Functional Properties Attributed to Egg Proteins in Food Systems

Function	Underlying Mechanisms	Examples
Water binding	Hydrogen bonding and ionic hydration	Cakes and bread
Gelation	Water entrapment and immobilization, network formation	Gels, cakes, bakeries
Cohesion and adhesion	Hydrophobic, ionic, and hydrogen bonds	Pasta, baked goods
Emulsification	Adsorption and film formation at interface	Cakes, dressings
Foaming	Adsorption and film formation at interface	Whipped toppings, ice cream, cakes, desserts
Aroma and flavor binding	Hydrophobic bonds, entrapment	Low-fat bakery products, doughnuts

Source: Stadelman (1999); American Egg Board (2006).

ingredients in the food industry. The chemical composition of eggs has been and continues to be the subject of intensive investigations, which can be traced back to the 1960s (Bolton, 1961; Parkinson, 1966) and even earlier (Burns and Ackerman, 1955). A number of past and recent references are available that describe in detail the chemical composition of eggs (Li-Chan and Nakai, 1989; Huopalahti et al., 2007; Li-Chan and Kim, 2008). Similarly, the molecular basis of egg functional properties has been the subject of multiple scientific reviews (Li-Chan and Nakai, 1989; Mine, 1995, 2002; Campbell et al., 2003; Lomakina and Mikova, 2006) and these publications are highly recommended for those seeking detailed information on some of the topics presented in this chapter.

After providing an overview of the structural and chemical composition of hen eggs, we have gathered in this chapter the most recently acquired knowledge on the functional properties of egg components, in particular those of egg white proteins (e.g., gelation, foam formation) and those of egg yolk lipoproteins (e.g., emulsification). We also explore the many efforts that have been implemented toward improvement of egg functional properties.

STRUCTURE AND CHEMICAL COMPOSITION OF THE EGG

A hen egg is composed of a complex mixture of proteins (12%), lipids (12%), carbohydrates, and minerals (1%) immersed in water, which makes up 75% of its total weight (Kovacs-Nolan et al., 2005). The three main components of an egg are the eggshell, including the shell membranes (9 to 11%), the egg white or albumen (60 to 63%), and the egg yolk (28 to 29%) (Table 2 and Figure 1).

TABLE 2 Approximate Composition of Whole Egg, Eggshell, Albumen, and Yolk

Egg Component (% of total)	Approximate Composition [% (w/w)]				
	Moisture	Protein	Lipid	Carbohydrate	Ash (Minerals)
Whole egg (100%)	66.1	12.8–13.4	10.5–11.8	0.3–1.0	0.8–1.0
Eggshell (9–11%)	1.6	6.2–6.4	0.03	Trace	91–92
Albumen (60–63%)	87.6	9.7–10.6	0.03	0.4–0.9	0.5–0.6
Yolk (28–29%)	48.7	15.7–16.6	31.8–35.5	0.2–1.0	1.1

Source: Adapted from Burley and Vadehra (1989); Li-Chan et al. (1995); Sugino et al. (1997).

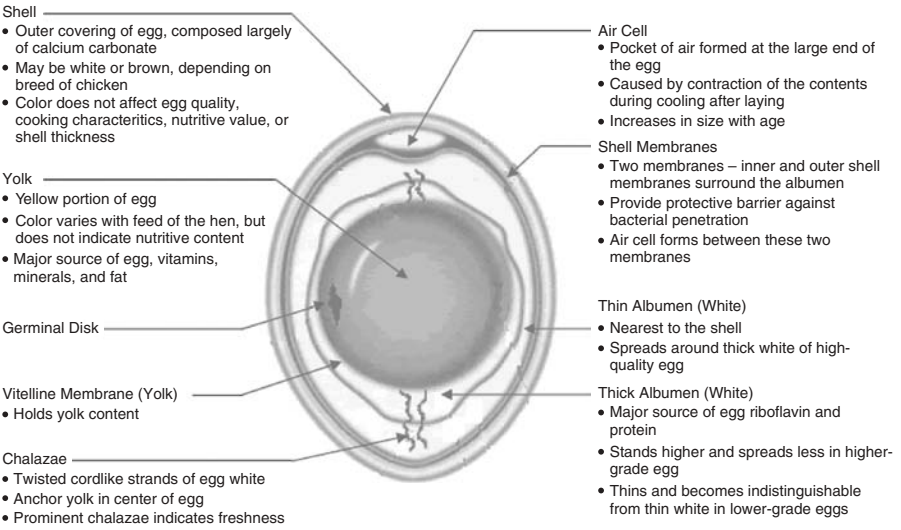

FIGURE 1 Structure of a hen's egg. (Adapted from the American Egg Board, 1981.)

Eggshell

Eggshell Structure The eggshell constitutes 9 to 11% of an egg's total weight and is designed 7000 to 17,000 pore canals per egg for gas exchange. It is comprised of two main structures: the external inorganic mineral matrix (eggshell per se) and the internal organic portion (shell membranes). A cross section of eggshell is presented in Figure 2 and shows the four main constituent layers: (1) the *cuticle*, a thin water-insoluble coat (10 μm thick) located on the external surface of the eggshell, which harbors the majority of its pigments (e.g., porphyrin and biliverdin); (2) the *palisade region* (200 μm thick), also known as the *spongy layer*, which is traversed by several thousands of funnel-shaped pore canals and features the presence of calcite crystal columns; (3) the *mammillary zone* (ca. 70 μm thick), which comprises the calcium reserve assembly and the crown region; and (4) the *eggshell membranes*, which reside at the interface between the shell and the albumen and consist of the inner (20 μm thick) and outer membranes

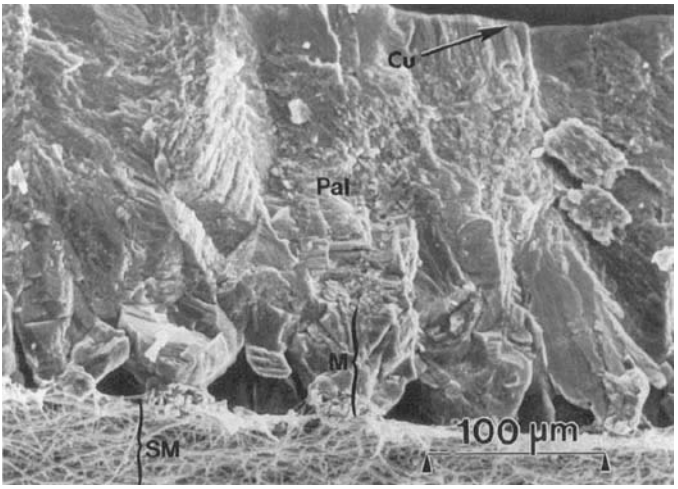

FIGURE 2 Scanning electron micrograph of a fractured eggshell showing a cross section of the mineralized and nonmineralized zones. The shell membranes (SM) constitute a nonmineralized, collagen-based matrix interposed between the egg white and the mineralized shell. The mammillary zone (M) or cone region is a mineralized zone on the outer surface of the outer shell membrane and forms the base for the palisade region (Pal), which extends to the outermost portion of the eggshell, the cuticle (Cu). (From Dennis et al., 1996.)

(50 μm thick) (Nys and Gautron, 2007; Li-Chan and Kim, 2008). Details on the ordered polycrystalline structure of the eggshell can be found in excellent reviews (Nys et al., 1991, 2001, 2004; Dennis et al. 1996).

Eggshell Chemical Composition The eggshell is commonly described as a natural porous bioceramic (Nys and Gautron, 2007). The solid matter found in the cuticle is made of approximately 3% ash, 5% carbohydrates, and 90% proteins (mostly insoluble) as well as a minority of glycoproteins (Li-Chan and Kim, 2008).

The eggshell matrix, including the palisade layer and the mammillary zone, is made primarily of calcium carbonate (ca. 97%) in the form of calcite crystals, combined with an organic matrix (ca. 2%) consisting of proteins (mostly insoluble) and polysaccharides rich in sulfated molecules (Nys et al., 1999; Li-Chan and Kim, 2008). More specifically, the palisade layer contains a variety of organic and inorganic compounds, including hyaluronic acic, ovoglycan (whose core protein is ovocleidin-116), and glycosaminoglycan chains with dermatan sulfate. In the mammilary zone, a keratin sulfate proteoglycan known as *mammillan* has been specifically identified in that region (Fernandez et al., 1997, 2001). Eggshell matrix proteins have triggered much interest for their contribution to the process of mineralization (Solomon, 1997). Hincke and others have studied the nature of these matrix proteins extensively, as well as their distribution in

the eggshell and their influence on the process of nucleation and crystal growth. Among them, ovocleidin-17 and 116 and ovocalyxin-32 have been investigated. (Hincke et al., 1995, 1999, 2003).

The inner and outer shell membranes both consist predominantly of highly cross-linked fibers of collagen types I, V, and X. The fibers are surrounded by a mantle of proteoglycan-like substance, identified as dermatan and keratan sulfate (Dennis et al., 1996). Their entangled thread structures represent a primary means of protection against microorganism contamination. Further details on the fine chemical composition of eggshell can be found in a recently published monograph (Li-Chan and Kim, 2008).

Egg yolk

Egg Yolk Structure Egg yolk consists of 52 to 53% dry matter, of which proteins represent about one-third (31%) and lipids about two-thirds (65%), the remaining being carbohydrates, vitamins, and minerals (Li-Chan et al., 1995). Egg yolk represents a natural oil-in-water emulsion made of lipid–protein particles in suspension in a clear yellow fluid (plasma). These particles have been designated as spheres (4 to 150 μm in diameter), profiles (12 to 48 μm), or granules (0.3 to 2 μm), depending on their respective sizes. Separation of egg yolk into two distinct fractions can be performed by dilution and centrifugation: a dark orange supernatant (plasma) and a pale pellet (granule) are then obtained (Figure 3). The granules comprise high-density lipoprotein (HDL, 60%) and phosvitin (16%), linked together by phosphocalcic bridges as well as low-density lipoprotein present in the granules (LDLg, 12%). On the other hand, the yolk plasma is extremely rich in low-density lipoprotein (LDL, 85%) but also contains livetins (15%) (Anton, 2007a).

The microstructure of egg yolk has been the object of a number of investigations. Earlier reports using transmission electron microscopy have in fact

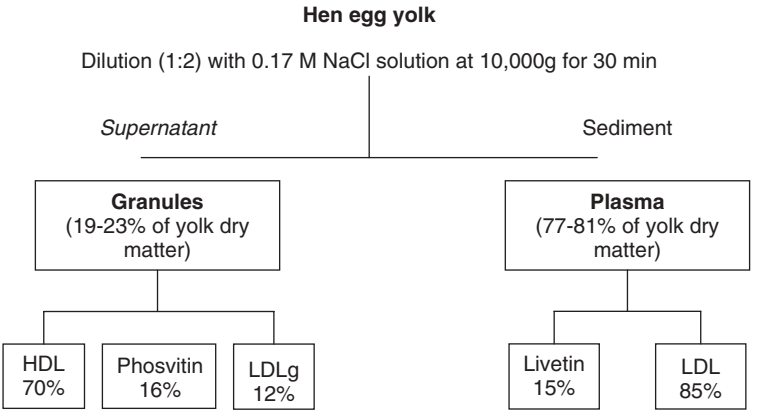

FIGURE 3 Fractionation of egg yolk into granules and plasma. (From Anton, 2007a.)

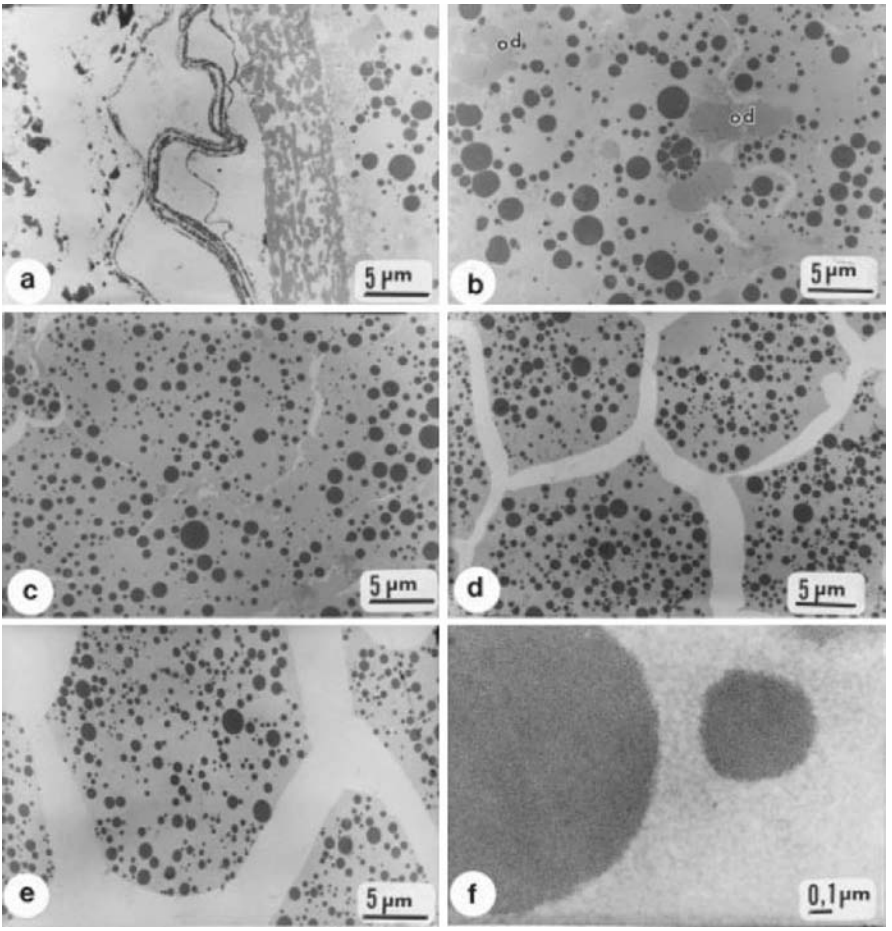

FIGURE 4 Transmission electron micrographs of fresh egg yolk: (a) vitelline membrane; (b) cortical layer of yolk (od: oil droplet); (c) yolk sphere bordering cortical layer; (d) yolk sphere in outer layer; (e) yolk sphere in inner layer; (f) protein granules in yolk sphere. (From Mineki and Kobayashi, 1997.)

reported the presence of globules of varying sizes, characterized by the presence of ultraparticles at the surface of micelles, possibly proteins, capable of being cleaved by pepsin treatment (Chang et al., 1977). Much more recently, Mineki and Kobayashi (1997) reported an improved method of deciphering the microstructure of fresh egg yolk. In the latter study, the approach, described as the frozen-section method, consisted of fixing the egg yolk specimen at extremely low temperatures, followed by a second fixation step using freeze-cutting fixation with liquid nitrogen (Figure 4). The authors were able to describe the cortical layer of the yolk (Figure 4b and c) as a distinct structure characterized by undeveloped yolk spheres with a shapeless membrane structure containing small granules consisting of

proteins and larger granules consisting of oil droplets (Figure 4b). Furthermore, the yolk spheres observed in the outer layer (Figure 4d) were described as round and smaller than the polyhedral spheres observed in the inner layer (Figure 4e). In the yolk spheres, protein granules with high electron density were shown to be highly dispersed (Figure 4f).

Egg Yolk Chemical Composition The main components of egg yolk are lipids (about 65% of dry matter) with a lipid/protein ratio of 2 : 1. The classification of egg yolk components is presented in Figure 5, and the proximate compositional analysis of fresh yolk components is detailed in Table 3.

Egg Yolk Proteins Proteins constitute 16% of liquid fresh egg yolk. The major protein components are listed in Table 4 and discussed below.

1. *Low-density lipoproteins*. Low-density lipoproteins (LDLs) are micellar structures found primarily in yolk plasma, with a small proportion present in the granules (LDLg, Figure 3), and are also known commonly as the *lipovitellenin fraction*. They represent globular structures made of a neutral lipid core (triglycerides and cholesterol esters) surrounded by proteins (apoproteins) and phospholipids (Speroni et al., 2005). Six apoproteins have been reported, apovitellelenins I to VI (Li-Chan and Kim, 2008), characterized by their high hydrophobicity and flexibility. They represent about two-thirds of the yolk solids and have been shown to be the main contributor to the emulsifying properties of yolk, by forming

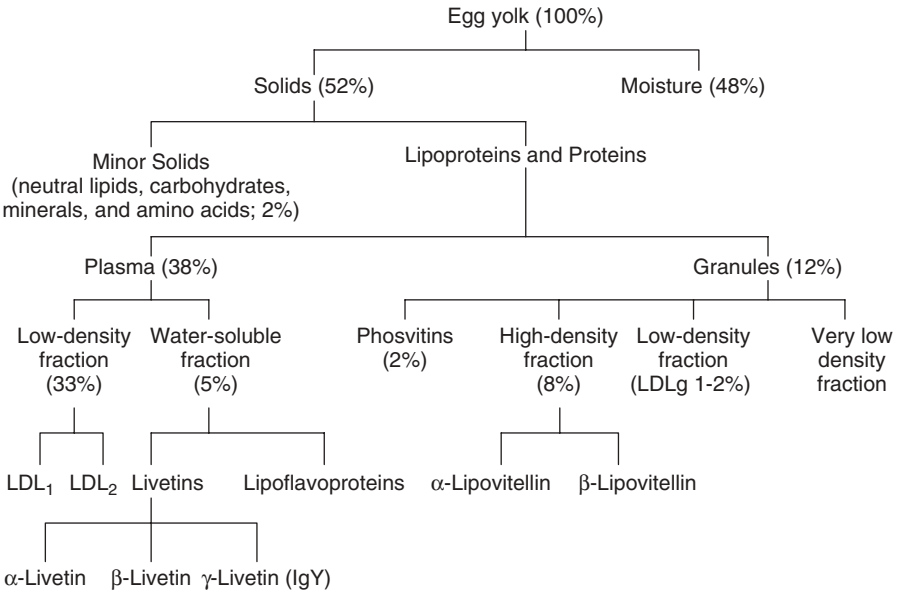

FIGURE 5 Composition of hen egg yolk. (From Li-Chan et al., 1995.)

TABLE 3 Compositional Analysis of Egg Yolk

	Fresh Yolk (%)	Dry Yolk (%)
Water	51.1	—
Lipids	30.6	62.6
Proteins	16.0	32.7
Carbohydrates	0.6	1.2
Minerals	1.7	3.5

Source: Powrie and Nakai (1985).

TABLE 4 Proteins and Lipids in Egg Yolk

Constituent	Major Components	Relative %
Proteins[a]	Apovitellenins I to VI	37.3
	Lipovitellin apoproteins	
	α-Lipovitellin	26.7
	β-Lipovitellin	13.3
	Livetins	
	α-Livetin (serum albumin)	2.7
	β-Livetin (α_2-glycoprotein)	4.0
	γ-Livetin (γ-globulin)	2.7
	Phosvitin	13.3
	Biotin-binding protein	trace
Lipids[b]	Triglyceride	65
	Phosphatidylcholine	26
	Phosphatidylethanolamine	3.8
	Lysophosphatidylcholine	0.6
	Cholesterol	4
	Sphingomyelin	0.6

[a] Modified from Burley and Vadehra (1989).
[b] Adapted from Juneja and Kim (1997).

a film at the interface between two phases. The adsorption mechanisms of LDL at the oil–water interface are further discussed later in the chapter. While apovitellin I, II, and III have their own specific characteristics, apovitellelenins III to VI were found to be derived from the proteolytic cleavage of the same apoprotein apo-B (Burley et al., 1993). The low density of apovitellenins (0.982) has been attributed to their much higher lipid/protein content ratio (Burley and Vadehra, 1989; Anton et al., 2003) and results in good solubility in aqueous solution (Anton, 2007c). The composition of LDL total lipids and fatty acids is provided in Table 5.

2. *High-density lipoproteins*. High-density lipoproteins (HDLs) consist of α- and β-lipovitellins, which differ in their amino acid composition as well as bound phosphorus and carbohydrate content (Li-Chan and Kim, 2008). Lipovitellins are made up of about 80% proteins and 20% lipids, divided into phospholipids

TABLE 5 Composition of Low-Density Lipoproteins in Egg Yolk

Component	g/100 g Dry Matter[a]
Proteins	12.0
Total lipids	86.7
Triglycerides	62.0 (71%)
Phospholipids	21.5 (25%)
Phosphatidylcholine	18.4 (21%)
Phosphatidylethanolamine	3.0 (3%)
Cholesterol	3.2 (4%)
Fatty acid	
Palmitic acid (16:0)	(24.7%)
Oleic acid (18:1)	(41.1%)
Linoleic acid (18:2)	(16.0%)
Saturated fatty acids	(34%)
Monounsaturated fatty acids	(45%)
Polyunsaturated fatty acids	(21%)

Source: Adapted from Anton et al. (2003).
[a]Numbers in parentheses represent the percentage of total lipid or fatty acid.

(60%, primarily lecithins) and triacylglycerols (40%), as well as small amounts of cholesterol, sphingomyelin, and other lipids (Burley and Vadehra, 1989). HDLs do not present the micellelike structure of LDL, but resemble that of globular proteins by forming a pseudomolecular complex of two monomers (Anton, 2007b). Both lipovitellins are glycoconjugates featuring mannose, galactose, glucosamine, and sialic acid, but α-lipovitellin has a much higher sialic acid content than does β-lipovitellin, explaining its relatively acidic nature. The apoprotein present in lipovitellins, sometimes referred to as *vitellin*, is present as a dimer and the delipidation of lipovitellin was reported to result in a loss of solubility (Juneja and Kim, 1997). A total of five distinct apoproteins have been accounted for in the structure of HDL. Five disulfide bridges as well as a number of ionic and hydrophobic interactions are responsible for the maintenance of HDL structure. Complexes formed between HDL and phosvitin via phosphocalcic bridges constitute the basic element of egg yolk granules (Anton, 2007b). At low ionic strength, HDL–phosvitin can form insoluble complexes rendering the granule structure very compact, weakly accessible to enzymatic digestion, and resistant to thermal denaturation or heat gelation (Anton, 2007b).

3. *Phosvitin*. Phosvitin represents about 11% of egg yolk total proteins (Anton et al., 2007). It is a glycoprotein that consists of two polypeptides (α- and β-phosvitins) and is made up of 10% phosphorus, making it one of the most highly phosphorylated proteins and strongest metal-binding biomolecules found in nature. In fact, 95% of the iron in egg yolk is bound to phosvitin. Close to 50% of its residues are serine, of which more than 90% are phosphorylated (Clark, 1985). The phosphoserine residues are arranged such that the protein presents a very large central hydrophilic area, framed by two hydrophobic areas at the N- and

C-termini. The carbohydrate content of phosvitin includes hexose, hexosamine, and sialic acid residues, and phosvitin is surprisingly void of any lipid components (Li-Chan and Kim, 2008). Its high water solubility, as well as its resistance to heat denaturation and proteolytic cleavage, have been attributed to its rich content of phosphoserine residues (Juneja and Kim, 1997; Anton et al., 2000b).

4. *Livetins*. The livetin fraction of egg yolk, which contains water-soluble proteins that account for 30% of the plasma proteins, is composed of α-livetin (serum albumin), β-livetin (α_2-glycoprotein), and γ-livetins occurring in the ratio 2 : 5 : 3, respectively (Schade and Chacana, 2007; Li-Chan and Kim, 2008). Egg yolk α-livetin and chicken serum albumin were reported to be identical (Schade and Chacana, 2007). Furthermore, α-livetin has been implicated as a causitive agent in the bird-egg syndrome, a form of type I hypersensitivity that occurs upon sensitization via inhalation of egg proteins (Quirce et al., 2001). Information on β-livetin remains scarce. The γ-livetins or γ-globulins in yolk are referred to as *immunoglobulin Y* (IgY) to distinguish them from mammalian IgG. Immunoglobulins Y have been the object of intensive investigations for the production of polyclonal antibodies (Behn et al., 2001) and as a means of passive immunization (Kovacs-Nolan and Mine, 2004).

5. *Other egg yolk proteins*. A number of enzymes, including cholinesterase, acid phosphatase, acid proteases, amylase, cathepsin-D, and peptidase, as well as sialylglycopeptides, have also been reported in egg yolk (Li-Chan and Kim, 2008).

Egg Yolk Lipids Lipids are the main components of the egg yolk (62.5% of dry egg yolk) (Li-Chan and Kim, 2008). They are found almost exclusively as lipoprotein conjugates, commonly known as high- and low-density lipoproteins, in the form of triglycerides (62%), phospholipids (33%), and less than 5% cholesterol (Anton, 2007a). Their fatty acid compositional analysis is presented in Table 6. One-third of the triglycerides are represented by saturated palmitic acids and stearic acids, with polyunsaturated (mostly linoleic and arachidonic acid) and monounsaturated (mainly oleic acid) fatty acids accounting for another third. The major phospholipids found in egg yolk are phosphatidylcholine (PC) and phosphatidylethanolamine (PE), accounting for 81% and 12% of egg yolk lecithins. Sphingomyelins (e.g., palmitosylsphingosines) are also present as minor components (2%) of egg yolk phospholipids (Li-Chan and Kim, 2008).

A large egg may contain between 200 and 220 mg of cholesterol (Sim, 1998). Free cholesterol represents more than 80% of total cholesterol content, and the remainder is present in the form of cholesterol ester (Mine and Yang, 2006). The majority of the egg yolk cholesterol originates from the hen diet, and the rest is synthesized during egg yolk formation (Sugino et al., 1997). As a result, many attempts have been made to reduce the content of cholesterol in hen eggs, (Li-Chan and Kim, 2008). The production of designer eggs enriched in ω-3 polyunsaturated fatty acids (PUFAs) such as eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA) has been widely documented, and such products are now commercially available.

TABLE 6 Fatty Acid Composition of Egg Albumen, Yolk Plasma, and Yolk Granules (g/100 g total lipids)

Fatty Acid[a]	Egg Albumen	Yolk Plasma	Yolk Granules
16:0	18.30	22.49	24.24
16:1 *n*-7	0.81	1.32	1.18
17:0	0.27	0.22	0.16
18:0	7.76	11.22	12.40
18:1 *n*-9	16.66	31.28	28.48
18:2 *n*-6	20.92	27.60	26.81
18:3 *n*-6	0.23	0.18	ND[b]
18:3 *n*-3	0.15	0.43	0.26
20:1 *n*-9	0.06	0.18	ND
20:2 *n*-6	0.23	0.31	0.23
20:3 *n*-6	0.40	0.27	0.27
20:4 *n*-6	9.92	2.36	3.53
22:4 *n*-6	1.14	0.16	ND
22:5 *n*-3	0.37	ND	ND
22:5 *n*-6	0.90	0.55	0.83
22:6 *n*-3	2.07	0.60	0.93
SFA	26.34	33.92	36.80
MUFA	17.53	32.78	29.66
PUFA	36.33	32.48	32.86
n-6	33.74	31.44	31.67
n-3	2.59	1.03	1.19
n-6/*n*-3	13.84	30.49	26.67
SFA/PUFA	0.73	1.05	1.12

Source: Adapted from Watkins et al. (2003).
[a]SFA, total saturated fatty acid; MUFA, total monounsaturated fatty acid; PUFA, total polyunsaturated fatty acid; *n*-6, total omega-6 fatty acid; *n*-3, total omega-3 fatty acid.
[b]ND, not detected.

Egg Yolk Carbohydrates Few studies have characterized the carbohydrate content of egg yolk. (Nakano et al., 1994, 1996; Koketsu, 1997; Seko et al., 1997). Carbohydrates account for less than 1% of egg yolk content, with 0.3% present as free carbohydrate, mainly glucose, and the remainder represented primarily by sialic acid bound to glycoproteins and glycolipids (Li-Chan and Kim, 2008).

Egg Yolk Vitamins, Minerals, and Pigments The compositional analysis of the minerals and vitamins present in egg yolk is shown in Table 7. Minerals account for about 1% of egg yolk content, of which the major mineral is phosphorus, present primarily as a bound form in phospholipids (Sugino et al., 1997). Other minerals are calcium, chloride, potassium, sodium, sulfur, magnesium, and manganese. Hens' diets can be modified (e.g., selenium supplementation) to alter the composition of egg yolk minerals (see Chapter 28).

TABLE 7 Minerals and Vitamins Present in Whole Egg, Egg Albumen, and Egg Yolk

Constituent (Units)	Whole Egg	Egg Albumen	Egg Yolk
Minerals (mg)			
Ca	29.2	3.8	25.2
Cl	96.0	66.1	29.9
Cu	0.033	0.009	0.024
I	0.026	0.001	0.024
Fe	1.08	0.053	1.02
Mg	6.33	4.15	2.15
Mn	0.021	0.002	0.019
P	111	8	102
K	74	57	17
Na	71	63	9
S	90	62	28
Zn	0.72	0.05	0.66
Vitamins			
Vitamin A (IU)	264	—	260
D (IU)	27	—	27
E (mg)	0.88	—	0.87
B_{12} (μg)	0.48	—	0.48
Choline (mg)	11.0	2.58	8.35
Folic acid (mg)	237	0.46	238
Inositol (mg)	0.023	0.006	0.026
Niacin (mg)	5.94	1.52	4.35
Pantothenic acid (mg)	0.045	0.035	0.010
Pyridoxine (mg)	0.83	0.09	0.73
Riboflavin (mg)	0.065	0.008	0.057
Thiamine (mg)	0.18	0.11	0.07
	0.05	0.004	0.048

Source: Adapted from Watkins (1995).

Most of the vitamins found in eggs are present in the egg yolk rather than in the albumen (Table 7). Fat-soluble vitamins A, D, and E and water-soluble vitamin B_{12} are found exclusively in the egg yolk. Other water-soluble vitamins, such as folic acid, riboflavin, and niacin, are present in both egg yolk and albumen. Supplementation of hen diets has been investigated to produce vitamin-enriched eggs, in particular vitamin E (Kirunda et al., 2001; Mazalli et al., 2004; Li-Chan and Kim, 2008).

The presence of fat-soluble carotenoids (pigments) is responsible for the characteristic color of egg yolk, most of which consists of xantophylls such as lutein and zeaxanthin (Schlatterer and Breithaupt, 2006). The pigment composition can also be altered by the type and amount of pigment included in hens' diet (Nys, 2000).

Egg White

Egg White Structure Egg white (or egg albumen) comprises four distinct layers: (1) an outer thin layer next to the shell membrane, (2) a viscous or outer thick white layer, (3) an inner thin white layer, and (4) a chalaziferous or inner thick layer. The proportions of each layer are about 23.3, 57.3, 16.8, and 2.7%, respectively (Burley and Vadehra, 1989; Li-Chan and Kim, 2008). The proportions may vary based on hen breed, environmental conditions, size of the egg, and rate of production (Li-Chan et al., 1995). The viscosity of thick albumen is much higher than that of thin albumen because of its high content of ovomucin. In fresh eggs, thick albumen covers the inner thin albumen and the chalaziferous layer, holding the egg yolk in the center of the egg.

Egg white makes up about 60% of the total egg weight and is regarded as a complex mixture of globular proteins immersed in a large liquid medium (Li-Chan et al., 1995). In decreasing order, the major egg proteins are ovalbumin (54% of dry matter), ovotransferrin (12 to 13%), ovomucoid (11%), lysozyme (3.4 to 3.5%), G2 and G3 ovoglobulins (2%), and ovomucin (1.5 to 3%). Their physicochemical and biological functions are presented in Table 8. These major egg white proteins are the object of a later section. Other proteins, including ovostatin, ovoflavoproteins, and avidin, and enzymes (α-mannosidase, β-galactosidase, β-glucuronidase, β-*N*-acetylglucosaminidase, catalase, mono- and diphosphoesterases, peptidases, and α-amylase), occur in only minor amounts and are not discussed in this chapter (Vahedra and Nath, 1973; Li-Chan and Nakai, 1989).

Egg White Proteins Egg white proteins constitute more than 80% of egg albumen dry matter and are therefore considered to be the main actors contributing to the foaming and gelling properties of egg albumen. Eggs are therefore often responsible for the physicochemical and sensorial properties of the food in which they are incorporated. The multiple functionalities of egg white are products of complex interactions among its protein constituents, as discussed later.

1. *Ovalbumin*. Ovalbumin (OVA) represents the major egg white protein and constitutes more than half of the egg white proteins (54% w/w). It is a monomeric phosphoglycoprotein composed of 385 amino acids, with a relative molecular weight of 45,000 (Nisbet et al., 1981). It belongs to the serpin (serin protease inhibitor) superfamily but lacks inhibitory activity. Despite a number of investigations, its biological function remains largely unknown (Huntington and Stein, 2001). It contains one carbohydrate unit, none to two residues of phosphoserine, one disulfide bond, and four sulfhydryl (SH) groups. The amino acid sequence of ovalbumin has been determined (Nisbet et al., 1981), and a three-dimensional configuration has been proposed by Stein et al. (1991) on the basis of x-ray crystallography at 1.95-Å resolution, indicating three β-sheets and nine α-helices (Stein et al., 1991). The denaturation temperature of ovalbumin is close to 84°C.

TABLE 8 Physicochemical Properties of Proteins in Egg White

Protein	% (w/w)	p*I*	M_w(kDa)	T_d (°C)	Cysteines	–SH	S–S
Ovalbumin[a-e]	54	4.5–4.9	45	75–84	6	4	1
Ovotransferrin[a-d,f] (conalbumin)	12–13	6.0–6.1	77.7	61–65 (76.5, Al^{3+})	30	—	15
Ovomucoid[a,b,f,g]	11	4.1	28	77	18	—	9
Ovomucin[a,b,f,g]	1.5–3.5	4.5–5.0	110, 5500–8300, 220,000–270,000	—	(2)		
Lysozyme[a-c,f,g]	3.4–3.5	10.7	14.3–14.6	69–77	6	—	4
G2 ovoglobulin[a,b,f]	1.0	4.9–5.5	47–49				
G3 ovoglobulin[a,b,f]	1.0	4.8, 5.8	49–50				
Ovoflavoprotein[b,f,g]	0.8	4.0	32–35, 80	—	5	—	2
Ovostatin[b,f,g]	0.5	4.5–4.7	760–900				
Cystatin[b,f]	0.05	5.1	12				
Avidin[a,b,f,g]	0.05	10.0	55–68.3	—	2	—	1

[a] Mine (1995).
[b] Awadé and Efstathiou (1999).
[c] Hammershøj et al. (2002).
[d] Donovan et al. (1975).
[e] Kitabatake et al. (1988).
[f] http://www.food-allergens.de/symposium-vol 1(1)/data/egg-white/egg-composition.htm.
[g] Gossett and Rizvi (1984).

Ovalbumin is the main constituent responsible for the gelling properties of egg white (Mine, 1995).

Half of its residues are hydrophobic, and one-third is represented by charged residues, of which the majority is acidic, conferring on the protein an acidic isoelectric point (p*I*) of 4.5 (Li-Chan et al., 1995). Purification of ovalbumin is usually carried out using precipitation under specific conditions of pH and salt concentration (e.g., saturated ammonium sulfate), followed by ion-exchange chromatography (Croguennec et al., 2000). In its native form, ovalbumin was reported to be resistant to trypsin digestion but became susceptible to its action after heat denaturation or acid treatment (Ottensen and Wallevik, 1968). During the storage of egg, ovalbumin can be converted into *S*-ovalbumin, a more heat-stable form of the protein. Thorough information on the structural and physicochemical properties of ovalbumin can be found in published reviews and monographs (e.g., Huntington and Stein, 2001; Lechevalier et al., 2007). Ovalbumin also accounts for one of the dominant egg allergens (Mine and Yang, 2007).

2. *Ovotransferrin*. Ovotransferrin (OVT), formerly known as *conalbumin*, is a 686-amino acid glycoprotein with a molecular mass of 77 to 80 kDa, which belongs to the transferrin family, a class of proteins characterized by their strong capacity to bind ferric Fe^{3+} ions reversibly at a ratio of two ions per molecule (Mason et al., 1996). Similar to other transferrins, it has a two-lobe structure, each containing an iron-binding site. It possesses 15 disulfide bridges and no free sulfhydryl groups (Williams, 1982). Its use as a nutritional ingredient in iron-fortified products has been suggested (Superti et al., 2007) and it has been documented as a significant egg allergen (Walsh et al., 1998, 2005).

3. *Ovomucoid*. Ovomucoid (OVM) is a heat-stable glycoprotein of 186 amino acids with an approximate molecular mass of 28 kDa and contains 20 to 25% carbohydrates attached to the polypeptide chain at asparaginyl residues (Kato et al., 1987c; Li-Chan and Nakai, 1989). It represents 11% of total egg white proteins and belongs to the Kazal family of protease inhibitors (Li-Chan and Nakai, 1989). It comprises three homologous domains (domains I, II, and III) cross-linked by intradomain disulfides bridges, with a total of nine disulfide bonds and no free sulfhydryl groups. Ovomucoid contains six potential glycosylation sites (recognition sequence Asn–X–Thr/Ser), but only five of them are glycosylated (Réhault, 2007). The fifth Asn residue in ovomucoid domain III can be either glycosylated or unglycosylated (Li-Chan and Nakai, 1989). It is characterized by high resistance to heat- and urea 8M–induced denaturation under acidic conditions, as opposed to its sensitivity to heat denaturation in an alkaline environment (Deutsch and Morton, 1956, 1961; Li-Chan and Nakai, 1989). Other protease inhibitors found in egg white include ovostatin, ovoinhibitor, and cystatin. Of clinical importance, ovomucoid has been documented as the immunodomminant egg allergen in humans (Rupa and Mine, 2006; Rupa et al., 2007).

4. *Lysozyme*. Hen egg white lysozyme (HEL), referred to previously as ovoglobulin G1, is a highly basic protein of 129 amino acids and a molecular

mass of 14.3 to 14.6 kDa. Also known as *N*-acetylmuramoyl hydrolase, lysozyme is a small enzyme capable of hydrolyzing the β-1,4-linkage between muramic acid and *N*-acetyl glucosamine of mucopolysaccharides present in the wall of bacterial cells (Li-Chan and Nakai, 1989). Because of its basic character, lysozyme can bind to ovomucin, ovalbumin, and ovotransferrin (Li-Chan and Kim, 2008). Its antibacterial activity led to its widespread use as a preservative agent in the food industry, but it was also incorporated into pharmaceutical and medical applications. HEL remains one of the most widely investigated globular proteins for its structural and antigenic properties. It has also been documented to be as a significant egg allergen (Walsch et al., 1988, 2005).

5. *Ovomucin*. Ovomucin is a sulfated glycoprotein responsible for the jelly-like structure of egg white which consists of two subunits (α- and β-ovomucin) with different carbohydrate content (Li-Chan and Kim, 2008). Ovomucin is commonly divided into soluble ovomucin, which is the main component of the inner and outer albumen layers, and insoluble ovomucin, which is predominant in the thicker fraction of the albumen. It was reported that insoluble ovomucin contained 84 molecules of α-ovomucin and 20 molecules of β-ovomucin, whereas soluble ovomucin was composed of 40 α-ovomucin and 3 β-ovomucin molecules, resulting in molecular weights of 2.3×10^7 and 8.3×10^6, respectively (Sugino et al., 1997). Ovomucin is usually insoluble at neutral pH in nondenaturating solvents unless solubilized by mechanical treatments such as homogenization and sonication in mild alkaline conditions, or chemical treatments including denaturing solvents and reducing reagents (Mastudomi et al., 1985). Earlier studies have shown that ovomucin could be dissociated into smaller units by various treatments without degradation of its chemical composition (Hayakawa and Sato, 1976).

6. *G2 and G3 globulins*. Earlier studies documented the presence of three globulins, G1, G2, and G3, in egg white (Longsworth et al., 1940). G1 globulin was later identified as hen egg lysozyme. These proteins resemble albumins in that they are coagulated by heat and are soluble in mild saline solutions (Messier, 1991). They were each reported to represent 4% of egg white protein content (Li-Chan and Nakai, 1989); however, few studies have been conducted to characterize them thoroughly. Reports of their importance in the foaming properties of egg white (Sugino et al., 1997) have elicited some attention, and they are discussed in a later section.

7. *Recently identified egg white proteins*. The separation of egg white proteins has indicated more than 40 different constituents (Mine, 2002). Despite many efforts to develop efficient separation and purification procedures (Desert et al., 2001; Guérin-Dubiard et al., 2005), the full chemical composition of hen egg white remains to be completed. The presence of a mixture of major and minor proteins with a wide range of molecular weights requires high-resolution procedures. In the past decade, new proteins, such as HEP21 (Nau et al., 2003) and TENP (Guérin-Dubiard et al., 2006), have been identified in egg white and were investigated primarily for their biological functions.

Egg White Lipids Egg albumen contains only 0.03% lipids, as egg lipids are located almost exclusively in the yolk, in the form of lipoproteins (Li-Chan et al., 1995; Kovacs-Nolan et al., 2005). A recent study described the main fatty acids of albumen as palmitic, arachidonic, and stearic acids (Watkins et al., 2003).

Egg White Carbohydrates Egg white carbohydrates can be found in both free (mainly glucose) and conjugated forms (i.e., attached to proteins as N- or O-linked oligosaccharides) (Koketsu, 1997). Reducing sugars such as glucose are removed routinely before pasteurization, through a process known as desugarization, to prevent the browning reactions caused by the Maillard reaction (Sebring, 1995).

Vitamins and Minerals in Egg White Table 7 lists the content of a wide range of vitamins and minerals found in egg white, egg yolk, and whole egg. As mentioned earlier, the majority of vitamins contained in hen eggs are found in the yolk, and no fat-soluble vitamin can be found in albumen. However, a variety of water-soluble vitamins, including biotin, niacin, riboflavin, and folic acid, are present in significant amounts (Watkins, 1995; Li-Chan and Kim, 2008). The main minerals found in egg white are sodium, potassium, and sulfur (Table 7). Phosphorus, calcium, and magnesium are also present, but in much lower proportions.

FUNCTIONAL PROPERTIES OF EGG COMPONENTS

In food systems the term *functionality* has been defined as "any property aside from nutritional attributes that influences an ingredient's usefulness in foods" (Kinsella, 1976; Pour-El, 1981; Boye et al., 1997). The functional properties of a protein are related primarily to their physical, chemical, and conformational characteristics, such as size, shape, amino acid composition and sequence, net charge, and charge distribution. These parameters will in turn determine their hydrophilicity vs. hydrophobicity, the architecture of their secondary (e.g., α-helix, β-sheet, and random structures), tertiary and quaternary structures, the presence of inter- or intrasubunit bonds (e.g., disulfide cross-links), as well as their flexibility upon exposure to environmental changes (Damodaran, 1997a) and ultimately reflect the nature of their functional properties.

Understanding the unique functional properties of egg components has important consequences for the consumption of eggs and their targeted use in the food industry. The three most acknowledged functions imparted by eggs are their gelation (e.g., cakes and quiches), their foaming properties (e.g., baked goods and meringues), and their emulsifying components (e.g., batters and mayonnaise), which all contribute to the textural properties of egg-containing food products. These three properties are the main focus of this section. We describe how egg functional properties can be affected by environmental conditions (e.g., pH, ionic strength, types of salt present), processing operations (e.g., heating, drying, high-pressure treatment), and by their interactions with other ingredients present in the food system (e.g., lipids, types of salts).

Native Conformation and Protein Denaturation

The folding of a protein from a linear primary structure to a tertiary or quaternary structure is driven primarily by noncovalent interactions, such as van der Waals, electrostatic, and hydrophobic interactions as well as hydrogen bonding, and in some cases covalent bonds such as disulfide bridges. Under normal conditions of pH and temperature, each polypeptide assumes one specific conformation, called *native*. It corresponds to a thermodynamically stable and organized status characterized by minimal free energy (Anfinsen, 1973). The lowest state of free energy usually results from maximal interactions of polar groups with water and minimum interactions of nonpolar groups with water. A number of studies have, however, shown that egg proteins, in particular ovalbumin, could exist in a stable intermediate folded state known as a *molten globule state*. (Hirose, 1993; Mine, 1995). *Globule* refers to the native compactness, and *molten* refers to the increased enthalpy and the entropy on transition from the native structure to the new state (Ohgushi and Wada, 1983). The molten globule state may therefore be defined as a stable partially folded conformation that can be distinguished from either the native or the fully denatured forms (Mine, 1995).

Denaturation is commonly defined as a process during which a major change is induced in the native structure of a protein, which does not alter the primary amino acid sequence (DeMan, 1999) and usually leads to variations in the protein physicochemical or functional properties. Denaturation can be induced by a variety of physicochemical agents, including heat, pH, salts, and surface effects. As described in the following paragraphs, the denaturation of a food protein is often a prerequisite for the exhibition of any functional property. The extent to which proteins unfold and the conformation they assume upon denaturation affect the functional and nutritional quality of a food system (Boye et al., 1997).

Gelation Properties

Egg whites or yolks are often used as ingredients to enhance the water-holding capacity or gel strength of food products. The textural and rheological properties of many products (e.g., meringues and angel cakes) are dependent on the heat coagulation or gelation properties of egg proteins, in particular their irreversible heat coagulation. A thermally irreversible gel is defined as a viscoelastic solid formed upon heat application which does not revert to a viscous liquid upon reheating.

Components and Mechanism of Gel Formation A *gel* has been defined as a material containing a continuous solid network resulting from the assembly of particles or polymers, embedded in an aqueous solvent (Smith, 1994). Gels can be described by their capacity to immobilize liquids (water-holding capacity in food products), by their macromolecular structure, by their texture, and by their rheological properties (Phillips et al., 1994). In the case of globular proteins, the formation of a heat-induced gel network classically involves (1) a denaturation process, the extent of which will depend on the heating time, the temperature,

and the nature of the protein, followed by (2) an aggregation of the unfolded molecules into high-molecular-mass complexes, leading to the formation of a coagulum or a gel, depending on the conditions (Raikos et al., 2007).

The terms *coagulation* and *gel* are often used interchangeably, but earlier reports have distinguished *coagulum*, resulting from the formation of a disorganized protein cluster, from *gel*, which results from an ordered polymerization of protein molecules (Hayakawa and Nakai, 1985). Electron microscopy is a powerful technique for studying the architecture of solid gels (Clark et al., 1981; Tani et al., 1995). Using this technique, studies revealed that a transparent gel was composed primarily of a network of linear aggregates of heat-denatured molecules. On the other hand, heat-denatured molecules gathered into random agglomerates were found to form a turbid gel or coagulum. The conditions of protein denaturation are determining in nature in the formation of either type of structure. For example, changing pH and ionic strength conditions can form a variety of gel-like structures, ranging from highly ordered to randomly aggregated structures (Hermansson, 1988; Doi, 1993).

The mechanism of gelation involves the partial unfolding of egg white proteins induced by physical (e.g., heat), mechanical (agitation), or chemical means (acids, salts, or denaturing agents such as urea). Complete denaturation of the protein is usually not recommended for gelation, since extensive hydrogen-bonding or hydrophobic interactions between unfolded chains may then lead to the formation of insoluble precipitates. Under favorable conditions, the partially unfolded egg proteins are capable to form complexes that results in formation of a coagulum (in the case of a random interaction between egg proteins) or a gel (formation of a three-dimensional network exhibiting a certain degree of order) (Doi and Kitabatake, 1997). It is believed that the unfolding of protein molecules leads to the exposure of buried hydrophobic groups, and protein–protein hydrophobic interactions are therefore the main cause of subsequent aggregation (Campbell et al., 2003). However, disulfide and hydrogen bonding, as well as ionic interactions, have also been shown to be involved in the cross-linking of aggregates from denatured proteins. Studies investigating the heat-induced aggregation of ovalbumin molecules have reported the existence of an intermediate conformational state commonly known as *molten globule* (Hirose, 1993; Mine, 1995; Tani et al., 1995). The molten globule conformation state is a nativelike structure in which conformation of heat-denatured ovalbumin at the secondary structure level is not very different from that of the native molecule, but some of the buried reactive and hydrophobic sites become exposed upon heating.

Conditions for the formation of a transparent gel usually fall within a narrow range of pH and ionic strength. This range can be broadened, however, using a two-step heating procedure (Kitabatake et al., 1987). It has been shown that the initial heating of an ovalbumin solution produces a clear sol under salt-free conditions. When this sol is reheated after mixing with salt, the second heating yields a transparent gel even at high salt concentrations, whereas a turbid gel is formed after only a single heating. The basic unit of a transparent gel in a clear

sol was later identified as being composed of linear aggregates (Koseki et al., 1989a,b).

It has been suggested that the ability of certain proteins to form intermolecular disulfide bonds during heat treatment may be a prerequisite for their coagulation and gelation. Heat treatment can result in cleavage of existing disulfide bond structure or "activation" of buried sulfhydryl groups through unfolding of the protein. These newly formed or activated sulfhydryl groups can form new intermolecular disulfide bonds, essential for the formation of aggregate structures, through a process known as disulfide–sulfhydryl interchange reactions (Mine, 1995). The disulfide-exchange mechanism has been shown to be critical in the formation and stabilization of heat-induced gel structure with globular proteins (e.g., ovalbumin) (Mine, 1996)

Factors Affecting Gelation Properties Egg white proteins are the main actors in the gelation properties of eggs. The formation of a protein-based gel will be favored based on protein flexibility, such as their ability to denature and give extended chains, as well as the protein's ability to form extensive networks by cross-linking (Oakenfull et al., 1997). Earlier investigations on thermally induced changes of major egg proteins have been reviewed in excellent reports (Li-Chan and Nakai, 1989).

Gel strength and cohesiveness are minimal at pH values close to the isoelectric point, where the net charge is minimal (i.e., in the pH range 6 to 7 in egg white) (Woodward, 1990). Egg white ovalbumin has long served as a model to study the process of denaturation in heat-induced gels. Since ovalbumin makes up more than half of the albumen protein content, its behavior has a dominant effect on formation of a gel. It has been shown that the properties of heat-induced ovalbumin gels depend on factors such as pH, ionic strength, and protein concentration. They were shown to produce either transparent, opaque, or turbid ovalbumin gels (Hatta et al., 1986). The intermolecular interactions between heat-denatured ovalbumin molecules, which are still in a globular shape, are controlled by both the attractive hydrophobic and repulsive electrostatic interactions. The model presented in (Figure 6) has been suggested to explain the formation of OVA-based gels. When the electrostatic repulsion is relatively strong and the attractive hydrophobic interaction is restricted, the denatured ovalbumin molecules form ordered soluble linear aggregates which look like strings of beads. At high protein concentrations, these soluble linear aggregates are cross-linked and form a three-dimensional gel network. At low protein concentrations, the soluble linear aggregates do not form a gel network, but rather, a viscous transparent sol. On the other hand, when the electrostatic repulsion is repressed either by adjusting the pH too close to the isoelectric point and/or by increasing the ionic strength, the denatured protein molecules aggregate randomly, resulting in a turbid gel or suspension, depending on the protein concentration. Analyses by far-ultraviolet circular dichroism of the spectrum of heated ovalbumin confirmed this model (Koseki et al., 1989b).

Figure 7 shows in detail the impact of protein concentration, pH, and ionic strength on the type of heat-induced ovalbumin gels (Doi and Kitabatake, 1989).

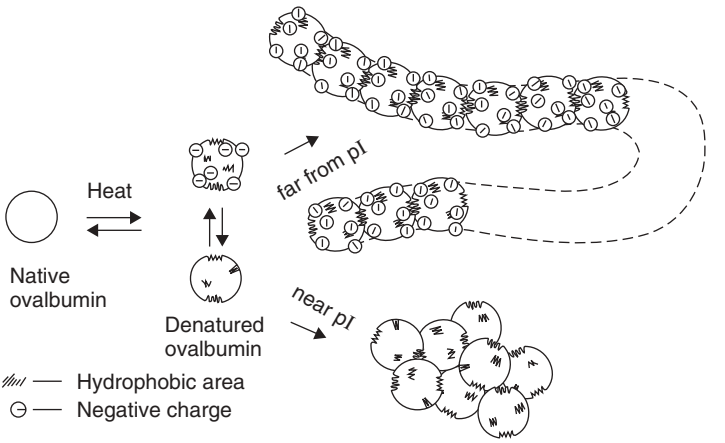

FIGURE 6 Model for heat denaturation and formation of aggregates of ovalbumin. (From Doi and Kitabatake, 1989.)

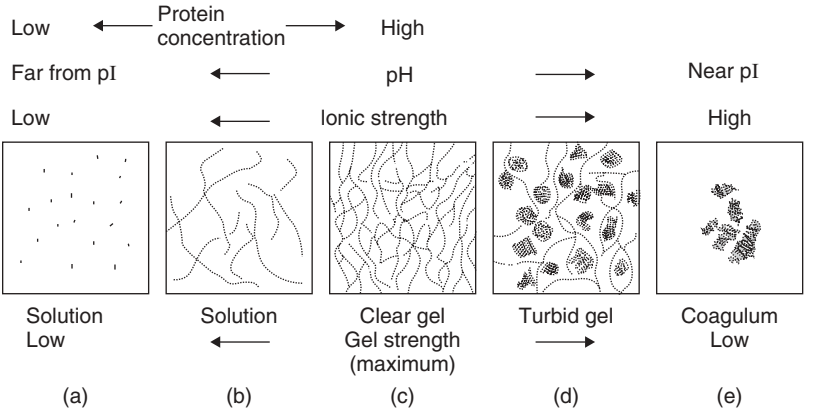

FIGURE 7 Factors affecting the texture of heat-induced ovalbumin gels. (a) At pH values far from the p*I* and at low ionic strength, linear aggregates are formed. (b) With decreasing electrostatic repulsion at low ionic strength or at $7.0 > \text{pH} > \text{p}I$, three-dimensional networks form a transparent gel. (d) At high ionic strength or at pH values near the p*I*, proteins aggregate to form a turbid gel composed of random aggregates. (c) At intermediate ionic strength of pH, both linear aggregates and random aggregates are formed. In this case, the linear aggregates form a cross-linked primary gel network and the random aggregates are interdispersed within this network. This mixed gel of linear and random aggregates has either a translucent or an opaque appearance, depending on the relative amounts of linear and random aggregates. Among these gel types, the transparent and opaque–translucent gels exhibit higher gel strength and water-holding capacity than the others. (From Koseki et al., 1989b.)

At a pH value far from pI and at low ionic strength, liner aggregates are formed. With decreasing electrostatic repulsion at low ionic strength or at $7.0 > \text{pH} > \text{p}I$, three-dimentional networks form a transparent gel. At high ionic strength or at pH values near pI, proteins aggregate to form a turbid gel composed of random aggregates. At an intermediate ionic strength or pH, both linear aggregates and random aggregates are formed. This mixed gel of linear and random aggregates has either a translucent or an opaque appearance, depending on the relative amounts of the linear and random aggregates. Among these gel types, the transparent and opaque–translucent gels exhibit higher gel strength and water-holding capacity (Mine, 1995; Campbell et al., 2003).

Ovotransferrin was shown capable of forming an opaque gel on incubation at nearly neutral pH and at room temperature with a thiol reagent such as 2-mercaptoethanol or glutathione (Hirose et al., 1986; Oe et al., 1986). The thiol-induced gelation was shown to be pH dependent, with hard gels formed at a pH range between 7 and 9. However, under very acidic or alkaline conditions, hard gels were also formed even in the absence of mercaptoethanol. The gel formation was explained by the cleavage of some disulfide bonds, accompanied by an increase in surface hydrophobicity, and followed by aggregation of the denatured molecules through intermolecular hydrophobic interactions.

Lysozyme does not exhibit significant functional properties in food systems (e.g., foaming, gelling, emulsification). However, because lysozyme is a very basic protein, it easily interacts with other proteins or components in food systems and may therefore influence its textural properties significantly. Studies have indeed shown that the properties of heat-induced ovalbumin gel are affected by the addition of lysozyme (Arntfield and Bernatsky, 1993). These effects were shown to be pH dependent: The gel network formation of ovalbumin gel was not affected by the addition of lysozyme at pH 5.5, whereas network strength was increased significantly at pH 7.0 and 8.5. Similar to ovotransferrin, the reduction of lysozyme (disulfide bridges) can increase the flexibility of the protein and was shown to further improve its gelling properties (Hayakawa and Nakamur, 1986; Tani et al., 1993). Earlier studies determined that major proteins such as ovomucoid and ovomucin were not heat-coagulable proteins (Johnston and Zabik, 1981b).

Yang and Baldwin have summarized the multiple factors that may influence the coagulation of eggs (Yang and Baldwin, 1995). The influences include parameters such as temperature, protein concentration, ionic strength, and pH conditions, and some of them were discussed earlier. However, the effects of combined influences on the gelling properties of egg white proteins have not been investigated widely. This was addressed in a recent study in which the authors investigated the combined effects of pH, sugar, and monovalent salts on the gelling properties of whole egg, as well as egg white and egg yolk, as separate entities (Raikos et al., 2007). The study determined that NaCl had a more significant inhibiting effect than sugar on egg protein gel formation, as shown by the increase in thermal transition temperature of egg proteins. Three distinct pH values (acidic, pH 2; alkaline, pH 8; and pH close to the isoelectric point of numerous egg proteins,

pH 5) were selected to investigate the influence of protein charge on egg gelation process. A linear relationship between firmness of heat-induced gels and pH was observed for whole egg and egg yolk gels, while egg white gels exhibited the highest values of gel strength at pH neighboring pI values. At pH 5 and pH 8, addition of sugar (3%) and salt (3%) seemed to produce a synergistic effect and led to formation of stronger gels with whole egg and egg yolk, whereas egg white gels were firmer in the absence of sugar and salt (Raikos et al., 2007).

Heat-induced gelation of egg yolk has also been reported and also represents an important functional property in the preparation of food products such as creams, cakes, and confectioneries (Kiosseouglou, 2003). Because egg yolk does not represent a solution of pure proteins, but rather, a dispersion of particles that are LDL micelles and HDL granules, the molecular mechanisms of egg yolk gelation have been more difficult to elucidate. However, it has been documented that the apolipoproteins of LDL micelles appear to dominate the gelation process (Anton et al., 2001; Kiosseouglou, 2003). Other studies tend to suggest that the yolk lipid molecules are also critically involved in gel structure formation (Paraskevopoulou et al., 2000).

Effects of Dry Heating on Gelation Alternatives were sought to reduce the damaging effects of commercial pasteurization on egg protein functionalities. Supplementation of eggs with chemical agents such as aluminum sulfate, lactic acid, and hydrogen peroxide has been reported (Li-Chan and Nakai, 1989). Subsequently, Kato et al. (1989) reported that the use of heating process on egg products in a dry state could significantly improve their functional properties (Kato et al., 1989). These findings revolutionized egg-processing methods employed in the food industry, and the approach has since flourished in a number of ways to improve the functional properties of egg components. For example, the relationship between protein structure and aggregation, as well as heat-induced gelling properties, of seven dried egg white (DEW) products was investigated (Handa et al., 2001). Strong correlations were found among hydrophobicity, surface – SH groups and average molecular weight of DEW, and physical properties of the gels obtained from DEW products. These data indicated that controlling the aggregation of DEW proteins in the dry state was crucial to controlling the gelling properties of DEW (Handa et al., 2001).

Foaming Properties

Foams represent colloidal systems in which air bubbles are dispersed within a liquid or solid continuous phase (Davis and Foegeding, 2007). Upon application of mechanical forces (blender or whipping apparatus) or by sparging gas through a protein solution, the egg proteins come into contact with the air–water interface, are adsorbed at the interface, and start unfolding. The egg proteins tend to expose their hydrophobic groups to the air phase, while their hydrophilic part remains in contact with the liquid phase (water). A good foaming agent often imparts

properties that are similar to those of an emulsifier. The film formed at the air–water interface traps air to form bubbles, and a stable foam occurs (Nakamura and Doi, 2000).

The best foaming agents found in the food industry are food-derived proteins: in particular, egg white proteins. The lightness of angel and sponge cakes, foamy omelets, meringue, soufflés, and mousses can be attributed to the foaming properties of egg white. In all of these products, egg white proteins are the main surface-active agents that help in the formation and stabilization of the dispersed gas phase. Reviews can be found of investigations conducted on the foaming properties of egg white (Li-Chan and Nakai, 1989; Murray and Ettelaie, 2004; Lomakina and Mikova, 2006; Murray, 2007).

Mechanism and Components of Foaming Earlier studies have determined that a good foaming agent is one that has the ability to adsorb rapidly at the air–water interface during whipping or bubbling, to unfold, and then to reorient quickly at the interface to form a stable interfacial film around the air bubbles which can resist gravitational and mechanical stresses (Johnson and Zabik, 1981a; Mine, 1995; Damodaran, 1996). The two most important features defining the quality of a foam are its volume and its stability. Foam volume depends on the ability of the foaming agent to adsorb at the interface (and rapidly reduce interfacial tension) as well as during the energy input (e.g., whipping). On the other hand, foam stability depends on the ability of the foaming agent to form a stable interfacial film, usually by forming a viscous continuous phase (Damodaran, 1997b).

Upon whipping, egg white proteins denature at the surface and interact with one another to form a stable, viscoelastic interfacial film (Mine, 2002). Some egg white proteins are commonly associated with carbohydrates. When these glycoproteins adsorb at the surface, the hydrophilic carbohydrate moieties bind to the aqueous phase, thereby increasing viscosity, reducing drainage, and contributing to foam stability. Addition of ingredients such as sugar will also increase viscosity and favor the foam stability. On the other hand, addition of the carboydrates sucrose, lactose, and dextrose is not recommended during the initial phase of beating/whipping, as they inhibit foam formation (Yang and Baldwin, 1995).

During excessive whipping, decreased elasticity occurs around the air bubbles, due to excessive insolubilization of proteins at the interface (Nakamura and Sato, 1964a; Johnson and Zabik, 1981c; Lomakina and Mikova, 2006) and leads to unstable foams. Unless heated, a protein-based foam will tend to collapse with time. A protein-based foam will collapse primarily due to either (1) lamellae rupture, as the attractive and repulsive forces cause bubbles to coalesce, or (2) water drainage, in which proteins are removed from the interfacial film, thereby decreasing its strength and causing air bubbles to coalesce (Lomakina and Mikova, 2006).

Foam stability is assured by a multitude of forces, including the viscosity of the liquid phase as well as the electrostatic and steric forces between proteins. On

the other hand, destabilizing forces such as electrostatic attractions or repulsions (in highly charged proteins) and hydrophobic attractions between the molecules will tend to minimize foam formation and break down the foam. (Walstra, 1996; Kristensson, 2006).

A number of studies pertaining to the interfacial behavior of isolated proteins, such as ovalbumin, have been reported and have been very useful in establishing an interfacial model of mechanisms. For example, the formation of disulfide linkages during foam formation and the foaming properties of ovalbumin were investigated in a study (Doi et al., 1989) which concluded that the essential factor in stable foam formation of ovalbumin was not the disulfide linkage formation but the network formed by noncovalent interactions. The role of disulfide bonding was, however, reported to contribute to stabilization of the protein structure, by constraining molecular unfolding and preventing total exposition of hydrophobic regions (Li-Chan and Nakai, 1991).

Interestingly, it has been reported that egg yolk can also be whipped into stable foam, using an optimum temperature of 72°C. Above that temperature threshold, foam volume drops and leads to protein coagulation unless the preparation is acidified (acetic acid). This process is often used in the manufacturing of highly stable sauces (Belitz et al., 2004b).

Differential Contribution of Egg Proteins to Foaming The foaming properties of egg white proteins have been investigated widely (Table 9). Earlier studies determined the importance of protein flexibility on the foaming properties of egg white proteins such as ovalbumin and lysozyme (Kato et al., 1986). With respect to their foaming and whipping properties, egg white proteins have been classified in order of importance as globulins, ovalbumin, ovotransferrin, lysozyme, ovomucoid, and ovomucin (Johnson and Zabik, 1981a,c).

Yang and Baldwin (1995) suggested that the presence of multiple proteins in egg white accounted for its good foaming ability, with each protein accomplishing

TABLE 9 Interfacial Properties of Egg White Proteins and Angel Food Cake Parameters

Protein	Viscosity-Density (cP × g/cm^3)	Surface Tension (mN/m)	Foaming Index (cm^3/g · min)	Angel Food Cake Volume (cm^3)
Ovomucin	ND[a]	ND	0.00	52
Lysozyme	1.53	42.0	0.12	107
Globulins	2.77	45.4	4.71	330
Ovomucoid	1.98	39.0	0.00	54
Ovotransferrin	1.55	42.4	0.34	157
Ovalbumin	1.62	51.8	0.59	308
Control[b]	2.02	46.7	3.08	272

Source: Compiled from Johnson and Zabik (1981a) in Mine et al. (1995).

[a]ND, not determined.

[b]Mixture of the six isolated proteins at levels normally found in egg white.

a different function (e.g., globulins contribute to foam formation, while ovomucoid and lysozyme contribute to foam stability). More specifically, the authors reported that meringues and egg white cakes could be made out of ovomucins and ovoglobulins alone. Nevertheless, the cake mass would collapse during the beating period in the absence of ovalbumin (Yang and Baldwin, 1995). On the other hand, when ovalbumin is used alone in an angel cake mixture, a longer beating period was required for foaming and a thicker texture was obtained (MacDonnel et al., 1955).

Ovomucin was long considered an important component of foam stabilization among egg white components. Earlier studies demonstrated, however, that ovomucin alone was not sufficient to insure satisfactory formation of egg white foam (Forsythe and Bergquist, 1951). Subsequent studies reported that the foam stability of egg white was markedly increased by the addition of ovomucin, while its foaming power could be decreased slightly (Nakamura and Sato, 1964a). The authors reported that ovomucin played a major role in foam stability but not in foam formation.

Ovoglobulins were shown to contribute to high viscosity and therefore to inhibit the drainage of liquids from the foam (Alleoni, 2006). The strong protein–protein interactions of ovomucins were suggested to be responsible for its viscous nature (Kato et al., 1985). Soluble ovomucin, α-ovomucin, and β-ovomucin were therefore compared for their foaming properties (foaming power and foam stability) in relation to their viscosity. The foaming properties of ovomucin were shown to decrease proportionally to decreases in viscosity (Kato et al., 1985).

Measurement of Foaming Properties Foaming capacity and foam stability are the parameters commonly used to evaluate foaming properties. The foam ability of a protein is often expressed as the *overrun*, referring to the amount of interfacial area created by the protein, and is defined as (Damodaran and Xu, 1996)

$$\text{Overrun} = \frac{\text{volume of foam} - \text{volume of initial liquid} \times 100}{\text{volume of initial liquid}}$$

Foam stability is often expressed as the time required for 50% of the liquid to drain from the foam, or as the time required for a 50% reduction in foam volume. Whip time is also a tool used in the measurement of ease of foaming. This is defined as the time required to beat a foam to a specified degree of aeration and is expressed as mL/g · s (Yang and Baldwin, 1995). The stability of egg white foams is generally based on the volume of liquid that drains from the foam in a specified time. Screens can be used as supports for meringues while drainage occurs (Gillis and Fitch, 1956). Increased stability of foams allows time for heat to penetrate the cakes and cause coagulation without the collapse of air cells. This prevents shrinkage of the cake during the last part of the baking period (Mine and Yang, 2006). For years, angel food cake has been the standard used to evaluate the foaming abilities of egg white. Although volume has been the

focus of much research, tenderness, texture, grain, and elasticity of the crumb are important monitors of the quality of albumen foam (Mine and Yang, 2006).

Specific gravity has also been used as an indirect measurement of foam volume. When specific gravity is low, volume is large. Specific gravity also indicates the stability of the foam: The lower the specific gravity, the lower the stability. Specific gravity between 0.15 and 0.17 usually provides sufficient air incorporation and leavening stability. The stage of maximum stability for egg white foams is just prior to maximum volume attainment (Yang and Baldwin, 1995).

Conductivity measurement has also been a very popular method of measuring the foaming properties of egg white, as it is noninvasive and can be monitored constantly, enabling study of a rapidly draining sample (Wilde and Clark, 1996). The conductivity of a foam was deemed proportional to its density.

Factors Affecting Foam Formation Protein concentration, the film thickness, the ionic strength, pH, temperature, and the presence of other components in the food systems, in addition to the physical–chemical properties of proteins, are all parameters affecting foaming properties. It is, for example, well known that any cross-contamination of egg white with egg yolk lipids greatly reduces foaming ability (Kim and Setser, 1982). In addition, the increase in protein concentration generally causes the formation of a thick lamellar film, which yields more stable foam (Phillips et al., 1994; Hammershøj and Qvist, 2001).

The quality of the foam is also a function of the initial quality of the egg albumen (e.g., ratio of firm vs. thin albumen), storage conditions, age of the eggs, and the hen's genetic background. For instance, the importance of hen genetic strain, hen age, and storage period on albumen height, and the whipping volume of the albumen have been investigated. Hammershøj and Qvist (2001) reported that the foam overrun of thin albumen decreased significantly with hen age, while the foam overrun of thick albumen was not affected significantly. Interestingly, whipping volume and albumen height were negatively correlated during increased storage time (Silversides and Budgell, 2004). Similarly, Alleoni and Antunes (2004) observed that increasing content of *S*-ovalbumin (during storage) yielded an increased volume of drained liquid from the egg white foam and decreased the foam stability (Alleoni and Antunes, 2004).

Structure–function relationships between protein conformational changes and foam properties were explored. Foaming properties were reported to be affected primarily by (1) the surface hydrophobicity of the protein (increased surface hydrophobicity usually results in better foam ability), (2) protein charge density and charge distribution (excessive charge leads to excessive repulsion and therefore poor foam stability), and (3) protein flexibility (increased flexibility leads to more rapid foam formation) (Damodaran, 1997b). These physiochemical properties are themselves highly influenced by the environmental conditions to which the proteins are exposed. Indeed, the same parameters that determine the structure and flexibility of a protein (e.g., electrostatic and hydrophobic interactions, disulfide linkages) will also determine the interfacial behavior of the protein (Phillips et al., 1994). The surface activity of a protein has been assessed based on the

irreversibility of its adsorption and its resistance to displacement from the interface by other surface-active proteins/peptides or low-molecular-mass surfactants (Halling, 1981).

Pasteurization of egg white resulted in longer whipping time to attain a foam as compared to use of unpasteurized albumen with regard to specific gravity. This was attributed to the irreversible denaturation of the ovomucin–lysozyme network (Lomakina and Mikova, 2006). A solution to increase the denaturation temperature of egg white protein network and to maintain their foaming properties was the addition of metallic ions (Fe, Cu, Al, or other) and salts of phosphoric and citric acids upon pasteurization (Hatta et al., 1997).

Kato et al. (1994) reported that heating egg white in a dry state (7.5% moisture at 80°C for 10 days) could improve its foaming power and foam stability fourfold without loss of the solubility (Kato et al., 1994). Analyses by the same author showed that an increase in molecular flexibility and surface hydrophobicity could explain the faster unfolding and increased intermolecular interaction, contributing to the formation of a strong cohesive film (Kato et al., 1990a).

Studies have explored the behavioral changes of egg foams under various pH conditions. Earlier investigations had reported that addition of minute amounts of 1 N H_2SO_4 or NaOH to liquid egg white could alter its foaming properties (Nakamura and Sato, 1964b). A number of studies have recently demonstrated that pH variations could induce a moderate unfolding and refolding regime, which could significantly improve the foaming properties of egg white (i.e., foaming capacity, stability, and rheological properties) (Liang and Kristinsson, 2005; Mleko et al., 2007). The improvements in foaming properties were attributed to the partial unfolding of egg albumen proteins (before foaming) as well as the interactions between egg albumen proteins through disulfide and/or hydrophobic groups (Liang and Kristinsson, 2005). The same authors reported that the foaming capacity of egg albumen was high near the isoelectric points of its major proteins (pH 4 to 5) and decreased as the pH went up. They reported recently that high-quality foams were typically produced at pH values ranging from 4 to 5 and from 8 to 9 (Kristinssen, 2006). More specifically, the study suggested that controlled acid and alkali denaturation of egg white, followed by pH readjustment to renaturing conditions, could improve its foaming properties significantly. The pH conditions used in the latter studies were claimed to allow tailored modifications of egg protein conformations, characterized by both increased hydrophobic and flexibility (Kristinssen, 2006).

Modification of Egg Foaming Properties To improve their foaming properties, investigations have considered the chemical modification of dried egg white (Ma et al., 1986). While succinylation of spray-dried egg white solids reduced both foam ability and foam stability significantly, carboxylation tended to improve the foaming properties (Table 10). The effect of enzymatic hydrolysis on the foaming properties of egg white was also explored using papain (Lee and Chen, 2002) or protease-peptone (Phillips et al., 1987; Lomakina and Mikova 2006).

TABLE 10 Foaming Properties of Spray-Dried Egg White Solids After Succinylation and Carboxylation

	Foamability (%)	Foam Stability[a] (%)
Unmodified	200 ± 10	33 ± 2
Succinylated[b]		
24.5%	145 ± 5	23 ± 2
91.6%	140 ± 5	20 ± 1
Carboxyl modified		
25.2%	210 ± 10	35 ± 2
68.5%	225 ± 15	37 ± 1

Source: Adapted from Lomakina and Mikova (2006).
[a]Foam remaining after 60 min.
[b]Modification.

Similar to the gelation properties of egg, a common approach that has been used to improve the foaming properties of egg proteins has been the use of heat-induced denaturation. A number of studies have demonstrated that foaming properties of proteins could be improved when heated above their denaturation temperature either in a dry state (Kato et al., 1981, 1989; Mine, 1997; Gauthier et al., 2001) or in solution (Zhu and Damodaran, 1994; Du et al., 2002).

The effect of irradiation on the foaming properties of egg white has been reviewed (Ma et al., 1994). Irradiation doses of 0.97 kGy on shell eggs did not significantly alter egg white overrun, but doses of 2.37 and 2.98 kGy did enhance the overrun. Furthermore, increasing doses also led to increases in the time for 50% drainage (Table 11a). Similarly, foaming properties of spray-dried egg white were improved significantly upon irradiation. In contrast, irradiation of frozen egg white led to a reduction in the overrun without affecting foam stability (Table 11b). More recently, Knorr and others reported that the combined use of ultrasound and high pressure could efficiently increase the foaming ability (percentage overrun) of liquid whole egg, due to a more even distribution of protein and fat particles (Knorr et al., 2004).

Earlier reports suggested that the addition of metallic ions, in particular copper Cu^{2+}, could improve the foaming properties of egg white (McGee et al., 1984). Addition of copper ions to spray-dried egg white submitted to heat treatment (Cotteril et al., 1992; Lominaka and Mikova, 2006) led to increased foam volume, explained by the protective effect of metallic ions on the heat denaturation of proteins such as ovotransferrin. Indeed, it was demonstrated that ovotransferrin in egg albumen can interact with Cu^{2+} and Fe^{3+} to form an ovotransferrin–metal complex and result in more stable foams (Nakamura and Doi, 2000).

A recent comparative study investigated the effect of heat denaturation on the interfacial properties of ovalbumin molecules (Croguennec et al., 2007). Ovalbumin molecules were heat-denatured in solution (10 g/L, pH 7, NaCl 50 mM) under controlled conditions (5 to 40 min at 80°C). Compared to unheated ovalbumin, heat treatment led to a more open structure, exhibiting higher hydrophobicity and increased exposure of sulfhydryl groups. This more open structure favored

TABLE 11 Foaming Properties of Albumen upon Irradiation Treatment of Shell Eggs[a]

Dosage (kGy) (m^2/g)	Overrun (%)	Time for 50% Drainage (min)
a. Nonirradiated and Gamma-Irradiated Shell Eggs		
0	1146	30
0.97	981	35
2.37	1354	42
2.98	1446	52
SEM	91.3	3.4
b. Nonirradiated and Irradiated Egg Products		
Frozen egg white		
0	815	40
1	870	35
2.5	779	42
4	666	42
SEM	19.3	1.8
Spray-dried egg white		
0	627	27
2	848	29
5	953	30
8	1105	34
SEM	22.0	0.70

Source: Lomakina and Mikova (2006).
[a]Averages of two or three determinations. SEM, standard error of the mean.

a fast adsorption rate of the aggregates at the air–water interface, despite their larger hydrodynamic size. Establishment of rapid contacts between aggregates was observed as evidenced by faster increases in surface pressure and shear elastic constant, thus preventing premature foam destabilization. Nonheated ovalbumin was slower to develop intermolecular contacts and therefore exhibited lower foam stability (Croguennec et al., 2007).

Emulsifying Properties

The exceptional emulsifying properties of egg yolk make it one of the most commonly used ingredients in the food industry. A recent review describes some essential aspects of yolk functionality with regard to the role of plasma (LDL and livetins) and granules (HDL and phosvitin) in the stabilization of oil-in-water emulsions (Kiosseoglou, 2003). Even though studies have been scarce in the past decade, recent findings have been reported on the structure of interfacial film and its formation and are presented in this section. Emulsifying properties of egg white proteins are also discussed.

Components of Emulsification Fluid emulsions are thermodynamically unstable mixtures of immiscible liquids such as vegetable oil and water (Mangino, 1994),

and their formation therefore commonly requires the application of energy (e.g., homogenization). Upon prolonged storage, increased surface energy can lead to a rapid phase separation or coalescence, a phenomenon that can prevented by the addition of active molecules known as *emulsifiers*. An emulsifier is usually an amphiphilic compound containing both a water-soluble and a nonpolar moiety. A good emulsifier has a strong propensity to adsorb at the oil-in-water interface and to form a strong film responsible for the stability of food emulsions (Anton and Gandemer, 1999). Phospholipids (e.g., lecithin) and lipoproteins found in egg yolk are examples of naturally occurring amphiphilic molecules. In fact, egg yolk plasma constituents (LDL and livetins) have been shown to be outstandingly soluble in the common pH and salt concentrations ranges found in food emulsions (Saari et al., 1964; Sirvente et al., 2007). For example, mayonnaise provides a typical example of an oil-in-water emulsion: 50 to 85% edible oil and 5 to 10% egg yolk, supplemented by vinegar, salt, and seasonings (Belitz et al., 2004a).

Earlier evidence of the critical role of LDL apoprotein adsorption at interfaces was provided by studies showing that interfacial tension reaches a minimum at pH values close to the isoelectric region of yolk proteins (Anton and Gandemer, 1999; Mel'nikov, 2002). More recent investigations demonstrated unambiguously that LDL were the main contributors to the emulsifying properties of egg yolk, in particular the protein part of LDL (Martinet et al., 2002, 2003; Anton et al., 2003; Jolivet et al., 2006). The apoproteins present in LDL have recently been explored with regard to the emulsifying properties of egg yolk (Jolivet et al., 2006). Analyses by liquid chromatography–tandem mass spectrometry allowed identification of two particular apoproteins (apovitellenin I and apo-B) as major protein components of hen egg yolk LDL.

Measurements of Emulsifying Properties Emulsifying properties usually encompass measurement of emulsion activity (e.g., droplet size) and emulsion stability (e.g., flocculation and protein adsorption) (Speroni et al., 2005). Emulsifying activity has also commonly been determined by the method of Pearce and Kinsella, based on measurement of solution turbidity. According to this method, the maximum amount of oil emulsified by a standard amount of protein denotes its emulsifying capacity (Pearce and Kinsella, 1978).

Currently, the emulsifying properties of proteins are also assessed by measuring the particle size and distribution of droplets using methods such as light scattering (Dalgleish, 2004). However, light-scattering methods often require the suspension of particles to be highly diluted. Therefore, alternative methods of particle sizing based on ultrasonic acoustic spectroscopy have been proposed (Coupland and McClements, 2004). More recently, nuclear magnetic resonance–based techniques have also shown considerable potential in studies of food emulsion properties (Denkova et al., 2004).

Operationally, a stable emulsion is one that is very slow to undergo the processes resulting in separation of the oil and water phases. These changes include resistance to coalescence of oil droplets and emergence of an aqueous layer, denoted as *creaming*. The emulsion stability against creaming can be determined

by measuring changes in characteristics of the emulsion with time (Yang and Baldwin, 1995) or after accelerated aging (e.g., centrifugation).

Interfacial Film Structure and Formation Hypotheses on mechanisms of film formation in food emulsion suggested that the breakdown of lipoproteins at the interface proceeded by the adsorption of apoproteins and the coalescence of neutral lipids with oil droplets (Mine, 2002). A common approach to the study of lipid–protein film formation consists of adding lipids to an interfacial film of proteins. The displacement of the protein layer by lipids has been described as the orogenic displacement, literally meaning "mountain-generating process" (Mackie et al., 1999). It is described as a three-phase mechanism: (1) the film compression phase, in which the protein surface area decreases due to the adsorption of lipids but is not accompanied by an increase in film thickness; (2) a stage that occurs when the film is no longer compressible and its thickness increases to compensate for the decrease in protein surface area; and (3) a last phase in which the protein network breaks down due to high surface pressure and results in desorption of small molecules or protein aggregates (Dauphas et al., 2007a).

In recent years, the advent of new analytical tools such as atomic force microscopy (AFM) has initiated elucidation of the structural properties of egg yolk LDL interfacial films (Morris et al., 2001). LDL film structures were investigated at the air–water interface using AFM following Langmuir–Blodgett transfer onto a mica sheet (Dauphas et al., 2007a). Authors reported that at surface pressures above 30 mN/m, LDL films were characterized by circular morphologies composed of small separated grains surrounded by smooth, flat, concentric domains with irregular edges. The most interesting results were those from images obtained after the apoprotein–lipid transition, in which three distinct structures were observed: (1) a multilayer structure formed of thick, smooth domains, (2) a smooth intermediary structure, and (3) a rougher structure. To distinguish between protein and lipid structures, the interfacial films were imaged before and after lipid solubilization with butanol. Figure 8a and 8b present images taken in air and in butanol after the apoprotein–lipid transition (i.e., surface pressure at 45 mN/m). The results suggest that addition of butanol eliminated the thick smooth blocks, suggesting that they were composed primarily of lipids. The study reported that these lipids were mainly *neutral* lipids. On the other hand, protein structures (in air) appeared as a rough structure in the presence of butanol (Figure 8a, left panel and 8b, left panel), but the authors also believed that protein components are present in the three types of structures, as indicated in Figure 8a (arrows). A subsequent study by the same authors investigated the impact of surface pressure and pH variations on the rheology and structure of LDL films at an air–water interface (Dauphas et al., 2007b).

Functional Properties of Yolk Granule vs. Yolk Plasma We noted earlier that the two main components of egg yolk, granule vs. plasma, have very different profiles with regard to their composition and structure. These differences are also reflected in their emulsifying properties. Whereas yolk plasma exhibit greater emulsifying activity, granules exerted better emulsion stability (Anton

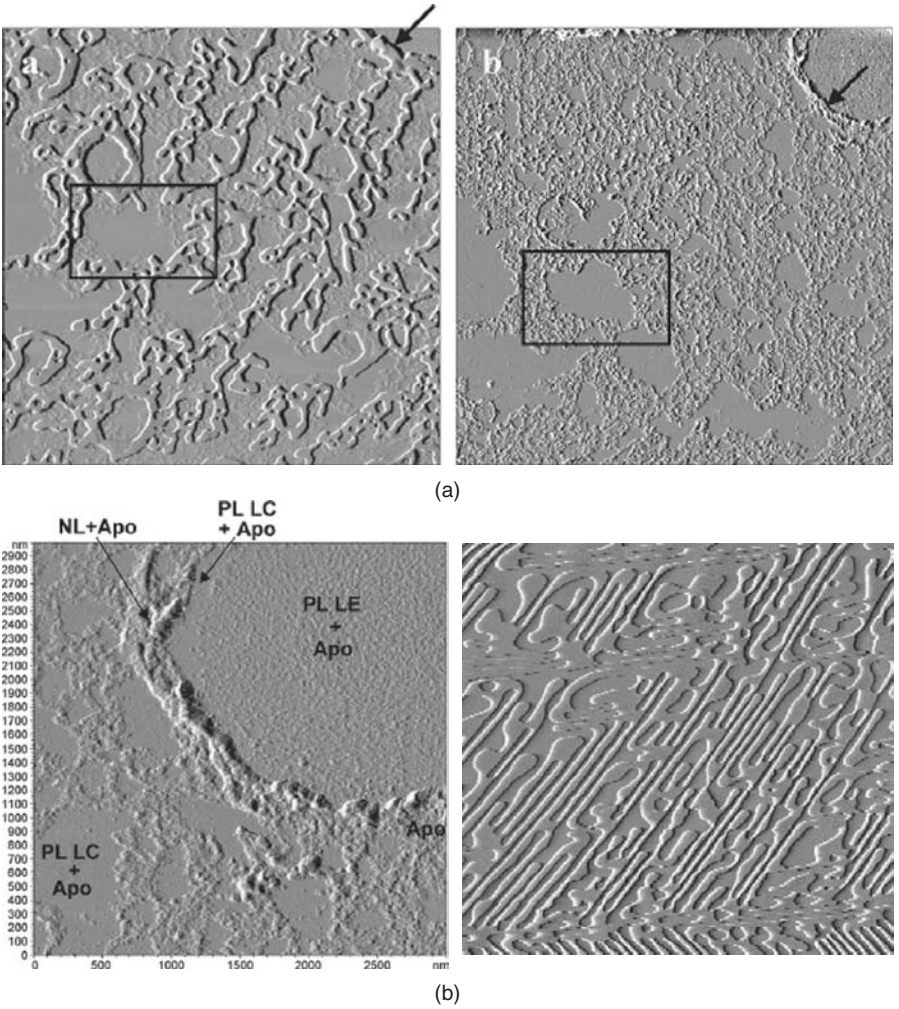

FIGURE 8 Atomic force microscopy images of LDL films formed at the air–water interface. (From Dauphas et al., 2007.)

and Gandemer, 1997). The effect of thermal treatment on their functional properties was also investigated. During the production of egg formulations, thermal pasteurization is used routinely to eradicate pathogenic microorganisms (such as *Salmonella*). The main goal is to design thermal procedures that will not significantly affect the functional properties of egg yolk. Le Denmat and co-workers have shown that egg yolk granules were more resistant to heat treatment than plasma or whole yolk, as evidenced by polyacrylamide gel electrophoresis under nondenaturing conditions and assessment of their emulsifying properties (creaming rate and final oil volume fraction). The study reported a severe decrease in plasma emulsifying activity after heating at 72°C, although the same treatment

did not alter the activity of egg yolk granules. The substitution of granules for whole yolk in food emulsions has been suggested to address the incomplete eradication of microbial flora and limited shelf life of egg yolk sometimes encountered during food processing (Le Denmat et al., 1999).

Factors Affecting Emulsifying Properties Similar to gelation properties, the composition of interfacial films and properties of food emulsion formed by egg components depend largely on conditions such as pH, ionic concentration, and protein concentration. Although egg white proteins have been reported to be good emulsifying agents, due to their capacity to behave in a manner similar to that of surface-active agents (Mine et al., 1991), they do not surpass the emulsifying properties of egg yolk. Nevertheless, isolated egg white proteins have served as useful models in the study of food emulsions. Studies sought to clarify the relationships between protein structure and lipid–water interface adsorptivity. Earlier studies indeed determined the importance of protein surface hydrophobicity and flexibility on the emulsifying properties of egg white proteins such as ovalbumin and lysozyme (Kato et al., 1986). Emulsifying properties of ovomucins were also shown to be dependent on surface hydrophobicity (Kato et al., 1985). Other parameters, such as oil-phase volume and the presence of salts (0.2 M NaCl vs. 10 mM $CaCl_2$) and protein concentrations (greater than 0.5% under given conditions of pH and salt concentrations) were also deemed to affect the emulsifying properties (emulsion activity and stability) of ovalbumin protein.

The emulsifying properties of ovalbumin were investigated by Mine et al. (1991), who reported that pH conditions were critical parameters affecting emulsifying properties. pH variations commonly modify the balance between electrostatic and hydrophobic interactions. Detailed analyses by circular dischroism and fluorescence measurements determined that the structural changes occurring at acidic pH (optimal pH 3.0) were responsible for enhanced flexibility and surface hydrophobicity of the protein. Optimal pH conditions were also investigated in the formation of egg yolk emulsion. Based on measurements of droplet size, protein solubility, and adsorption kinetics, and interfacial protein concentration, authors suggested that egg yolk emulsification be prepared at pH values of 6 rather than pH 3 or more alkaline pH 9, and that pH conditions be adjusted subsequently if required (Anton and Gandemer, 1999).

To explore the influence of surface charges, the emulsifying properties of phosvitin were investigated based on the chemical (alkaline treatment, calcium ions) and enzymatic (phosphatase) removal or neutralization of phosphate anionic groups (Kato et al., 1987b). The authors demonstrated that these modifications could significantly decrease the emulsifying properties of phosvitin, with a greater impact observed on the emulsion stability rather than the emulsion activity. Using an enzymatic treatment (neuraminidase), the same authors showed earlier that the repulsive forces created by the presence of sialic acid groups could have deleterious effects on the emulsifying properties of ovumucin. On the other hand, foaming properties of ovomucin were shown to be increased by neuraminidase treatment (Kato et al., 1987a).

Modification of Egg Emulsifying Properties Earlier studies determined that the emulsifying properties of ovalbumin could be improved by coupling the protein to dextran (Kato et al., 1990b) or by processes using freeze drying and spray drying (Kitabatake et al., 1989). The potential to use high-pressure treatment (200, 400, and 600 MPa) for the manufacture of more stable oil–water emulsions has recently been investigated (Speroni et al., 2005). Indeed, high-pressure treatment has been suggested as an alternative means of ensuring microbial safety in egg-based products, since it was reported as a less denaturing and milder approach than thermal treatment. The study showed that under alkaline pH conditions (pH 8 vs. pH 3), high-pressure treatment of LDL suspension did not affect their adsorption capacity at the oil–water interface. The high-pressure treatment did, however, lead to a significant decrease in depletion and bridging flocculation, explained by enhanced protein aggregation and denaturation. The same authors reported that mechanical treatments such as high-pressure homogenization may have led to preformation of aggregates capable of efficient adsorption at the oil–water interface (Sirvente et al., 2007), as speculated by earlier studies (Aluko and Mine, 1998; Anton et al., 2000a). Interestingly, a high-pressure treatment of LDL dispersions combined with alkaline pH (pH 8) was shown to lead to more stable oil–water emulsions. At an alkaline pH, aggregation and protein denaturation were shown to be enhanced without altering the capacity of LDL adsorption at the oil–water interface, as measured by the percentage of protein adsorbed (Speroni et al., 2005).

MODIFICATION OF EGG PROTEIN FUNCTIONALITIES

Because egg components are being used more and more extensively as ingredients in the food industry, intensive efforts have been oriented toward improving their functional properties. Some aspects were mentioned earlier when discussing chemical (e.g., carboxylation) and physical (e.g., high pressure, irradiation, dry heating) modifications. Next, we provide further details on the various approaches.

Improving Functionality Using a of Dry-Heating Process

Dehydration represents a standard method used in food processing for the preservation of food components such as egg white. In the food industry, egg white dehydration is commonly achieved by spray-drying processes. The making of dried egg powder also presents practical advantages associated with ease of transportation and storage, and convenient dosage when used as an ingredient in food products (Bergquist, 1995; Van der Plancken et al., 2007). More interestingly, the beneficial effects of dry heating on the functional properties of egg white powders (gelling, foaming, and emulsifying) have been documented widely. The beneficial effects of dry-heating treatment on egg white functional properties (especially foaming and gelling) were first reported in the late 1980s. Functional properties of heated dried egg white were reportedly maximized by heating in the

dry state (80°C, 7.5% moisture content) for 10 days (Kato et al., 1989). Currently, storage at temperatures ranging from 75 to 80°C for 10 to 15 days has become routine practice in the food industry. In addition, controlled heating at alkaline pH (<9.5) in the dry state (75°C, 8.5% moisture content) for 5 days was shown to improve the gelling properties of dried egg white (Mine, 1997). Interestingly, it was also shown that the soluble aggregates formed upon dry heating could inhibit the formation of turbid coagulates upon reconstitution as well as when egg white powder is added to fresh egg white, before heating (Xu et al., 1998; Watanabe et al., 1999, 2000).

Dry heating at 80°C with a moisture content of 7.5% was shown to lead to a significant increase in foaming power (Kato et al., 1990a). In a recent study, authors investigated the effect of moisture content (ranging from 0.8 to 9.9%) during a dry-heating process at 80°C on the foaming properties (ability, density, and stability) of freeze-dried egg white as well as selected physicochemical properties such as solubility (Van der Plancken et al., 2007). The conformational changes induced by dry heating were shown to be markedly dependent on the moisture content, as evidenced by a marked decrease in denaturation enthalpy and a broadening of the endothermic peaks corresponding to the unfolding of lysozyme, ovotransferrin, and ovalbumin. The extent of protein denaturation was shown to be larger at a higher moisture content. Optimal conditions were determined to be moisture content below 6.8% when using a dry-heating temperature of 80°C.

Distinct studies reported that the dry heating of egg white proteins in the presence of orthophosphate enhanced functional properties of egg white proteins such as heat stability and calcium phosphate-solubilizing capacity (Li et al., 2003). Subsequently, these authors showed that dry heating of EW proteins in the presence of pyrophosphate represented an efficient means of enhancing their emulsifying and heat-induced gelation properties (Li et al., 2004). An increase in surface hydrophobicity suggested a better unfolding of the egg white proteins and resulted in markedly enhanced emulsifying properties (activity and stability). The obtention of a firmer and transparent heat-induced gel suggested that the introduction of phosphate groups favored the formation of soluble linear aggregates (Tani et al., 1995).

The details of the molecular basis of the structural changes brought about by phosphorylation were investigated further using isolated preparation of ovalbumin (Li et al., 2005). Purified ovalbumin was subjected to phosphorylation by dry heating in the presence of pyrophosphate (pH 4 85°C for 1 and 5 days). Increase in surface SH groups concomitant with a decrease in total SH content suggested the occurrence of an SH–SS exchange reaction and SH oxidation upon dry heating, which was enhanced further in the presence of pyrophosphate. Analyses by circular dichroism indicated only very slight changes upon phosphorylation, whereas differential scanning calorimetry profile revealed a marked decrease in thermodynamic stability and denaturation temperature. The study confirmed phosphorylation-induced formation of molten globule state-like conformational changes.

Improving Functionalality Using the Maillard Reaction

Earlier reviews reported that succinylation of proteins could improve their functional properties, such as heat stability and emulsifying, foaming, and gel-forming properties (Feeney and Whitaker, 1977). Moreover, it was demonstrated that acetylation and succinylation of egg white proteins enhanced their heat stability and foaming properties (Sato and Nakamura, 1977). However, chemical modifications of food proteins are not readily accepted by consumers. Therefore, more consumer-friendly alternatives were sought.

Among the approaches that have been investigated for the modification of egg functionalities, use of the Maillard reaction has been considered one of the safest and most promising strategies. The Maillard reaction (or nonenzymatic browning) is a chemical reaction that occurs during processing or storage of protein foods that contain reducing carbohydrates or carbonyl compounds (Cheftel et al., 1985). During the reaction, a covalent cross-link is formed between the amino groups of proteins and the reducing-end carbonyl groups in polysaccharides. The Maillard reaction has long been regarded as a negative phenomenon, so desugarization has often been performed before pasteurization or dry-heating procedures to reduce browning reactions and diminution of the shelf life of egg products.

Initial studies determined that carbohydrate moieties could improve the stability of globular proteins against denaturation. Studies showed that polymerization of ovalbumin with glucose or glucose-6-phosphate could improve its heat stability significantly (Kato et al., 1995). A number of studies subsequentlyly reported an improvement in egg protein (white, in particular) functional properties upon conjugation with polysaccharide moieties (Kato et al., 1993; Delben and Stefanich, 1998; Handa and Kuroda, 1999). For example, improved emulsifying properties were attributed to the amphiphilic nature of the conjugated molecule, with the hydrophobic residues of the unfolded proteins oriented toward the oil phase and the hydrophilic residues carried by polysaccharides oriented toward the aqueous phase, thus inhibiting the coalescence of the oil droplets.

After reporting on the beneficial effects of dry heating on the functional properties of egg white, Kato et al. were also among the first to apply this procedure to the preparation of protein–polysaccharide conjugates (e.g., ovalbumin–dextran) with improved functionality (Kato et al., 1990b). Subsequently, it was demonstrated that lysozyme–galactomannan conjugates were capable of exerting excellent emulsifying properties (Nakamura et al., 1992). Other studies conducted by the same group of authors pursued these investigations through conjugation of egg white protein with guar gum (in the form of galactomannan, a mannase hydrolysate of guar gum), a more economical approach to the use of dextran, and an ingredient commonly found as a thickener or binding agent in food systems (Kato et al., 1993). Formation of conjugates between total egg white protein and galactomannan revealed much better emulsifying activity and emulsion stability than for a dried egg white protein mixture without a Maillard reaction. Comparison with commercial emulsifiers (e.g., sucrose–fatty acid ester, glycerin–fatty acid ester) determined that dried egg white–galactoman conjugates exerted better emulsifying properties (Kato et al., 1993). The stability of

these conjugates was assessed for potential application in food systems. The dried egg white–galactoman conjugates were shown to be very stable and to maintain excellent emulsifying properties at acidic pH (pH 3) as well as upon heat application (100°C for 3 min), suggesting that they may withstand the pasteurization procedures used in the sanitation process of many food systems.

Aoki et al. (1999) reported that modification of ovalbumin with glucuronic acid through the Maillard reaction markedly improved heat stability and the emulsifying property, but suffered from the development of browning and the polymerization of ovalbumin during incubation. The same authors later reported that use of oligogalacturonic acid (obtained from pectin and pectic acid) instead of glucuronic acid could successfully enhance the heat stability of ovalbumin without the negative browning and polymerization reactions (Aoki et al., 2001).

Handa and Kuroda (1999) investigated the gelling properties of Maillard-reacted dried egg white products and described the advantages of using Maillard-reacted dried egg white (DEW) in the preparation of food products such as surimi and meat products. Maillard-reacted DEW not only presented the advantages of not releasing the hydrogen sulfide flavor, but also markedly improved their gelling properties. Analyses of sugar-preserved DEW revealed an increase in surface SH groups concomitant with a decrease in total SH groups as heating time increased. The water-holding capacity and firmness of Maillard-reacted DEW improved significantly as well.

More recently, Matsudomi et al. (2002) examined the properties of DEW–galactoman conjugates obtained through the Maillard reaction through a wide range of pH (3 to 9) and range of NaCl concentrations (0 to 500 mM). Most Maillard-reacted DEW samples were found to form turbid gels at pH 4 and 5. At pH values of 3 and above pH 7, the Maillard-reacted DEW samples formed transparent gels using NaCl concentration below 100 mM. The chicken egg white ovoinhibitor was also subjected to conjugation with galactomannan through the Maillard reaction in a controlled dry-heating state (60°C and 65% relative humidity) and resulted in a conjugate with greater heat stability and improved emulsifying properties potentially useful for industrial applications (Begum et al., 2003).

Glycation of ovalbumin with monosaccharides (reducing sugars) has also been investigated. Modification of the structural and gelling properties after glycation of ovalbumin with D-psicose, a rare ketohexose, was compared to glycation with D-glucose and D-fructose, two commonly used alimentary sugars. The superior cross-linking activity of D-psicose was suggested to contribute to the enhanced gelling properties of ovalbumin (Sun et al., 2004).

High-Pressure, Irradiation, and Pulse-Electric Field Treatments

In many countries the pasteurization of liquid egg products is a measure enforced by governmental bodies to eliminate pathogenic organisms such as *Salmonella*. Earlier reports documented that thermal treatment could lead to denaturation of egg protein, thereby negatively affecting their functionalities (Cunningham,

1995). Therefore, a major concern of the egg industry has been to ensure a supply of food products free of pathogenic microbial contamination while preserving the unique functional properties of egg components.

Irradiation has been regarded as an attractive alternative to heat pasteurization due to the heat sensitivity of shell eggs. A number of studies have documented that irradiation of egg products (liquid and egg dried powder) with a dose of 2 to 3 kGy of gamma rays was adequate to inactivate *Salmonella* without significant changes in sensory and functional (foaming) properties (Katusin-Razem et al., 1992; Narvaiz et al., 1992). Wong et al. (1996) reported that irradiated samples of liquid egg white showed lower microbial growth rate, lower foam drainage, and more stable viscosity than those of thermally pasteurized samples. Similarly, it was reported that irradiation of fresh eggs led to improvements in their functional properties, including foam overrun, emulsifying activity, gel rigidity, and angel cake volume (Ma, 1996). Irradiation of frozen and spray-dried egg white did not markedly affect their functional properties, although in some cases a slight decrease was observed. On the other hand, the whipping properties of spray-dried egg white and angel cake performance of frozen egg white were improved. Mayonnaise made with irradiated frozen egg yolk showed increased stiffness and stability. Gamma irradiation (1 to 4 kGy) of frozen liquid egg white did not affect scanning calorimetric profiles or electrophoretic patterns of egg protein constituents, and protein functional properties were maintained (Ma et al., 1993).

Irradiation has been shown to be less denaturing and more economical approach than thermal pasteurization of liquid egg products, and subsequent studies have suggested the alternative use of electron beam radiation to that of γ-irradiation, to avoid the accumulation of radioactivity waste. Huang et al. (1997) investigated the effects of electron beams on the functional properties of egg yolk during frozen storage. It was demonstrated that the emulsion capacity of irradiated samples was significantly higher than that of nonirradiated samples, noticeable within the first 7 days of frozen storage. More recently, the effect of electron beam irradiation (1 vs. 2 kGy) was investigated on whole table shell eggs (Min et al., 2005). Irradiation caused a twofold decrease in the viscosity of egg white. On the other hand, foam density in the egg whites was enhanced, as the dose of irradiation increased while foam stability decreased. Analyses of egg white gel textural properties and sensory assessment of hard-cooked eggs did not reveal any significant differences between irradiated and nontreated samples.

High-pressure processing has been assessed as an alternative approach to both ensure microbiological treatment and preserve egg functional properties. The U.S. Food and Drug Administration and Department of Agriculture have in fact recently approved high-pressure processing as a post-package pasteurization technology for the manufacture of shelf-stable high-acid foods and pasteurized low-acid food products (21CFR114 and 21CFR113). Prior studies have described the structural changes induced by high-pressure treatment of isolated preparation of ovalbumin (Iametti et al., 1998) and reported that pressure-induced modification on free thiol groups of ovalbumin played a prominent role in the formation of insoluble aggregates (Iametti et al., 1999).

The continuous processing of egg white with high-voltage pulsed electric fields has also been explored. Fernandez-Diaz et al. (2000) demonstrated that application of electric pulses (ca. 31.5 kV/cm) could efficiently inactivate microbial growth when applied to solutions of ovalbumin (1.88% of protein w/v) without causing any significant modifications in protein conformation. When the same treatment was applied to dialyzed egg white (8.9% of protein w/v), no protein precipitation or marked alteration of gelling properties was observed.

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PART VII

SANITATION AND SAFETY

30

CHEMICAL RESIDUES: PESTICIDES AND DRUGS (β-AGONISTS AND ANTIBIOTICS)

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INTRODUCTION

Primary production and processing for poultry use several sources of potential chemical risk, which may be introduced at different points through the production and processing chain. The poultry meat product chain is divided into four distinct stages: primary production, processing, retail, and consumer. At each of these stages, poultry meat products may be exposed to chemicals intentionally or unintentionally. The origins of potential risks that may be introduced into poultry

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meat product may vary. Exposure to chemicals may occur at the primary production stage through feed and water, but also through veterinary treatment, air, soil, or housing materials. Furthermore, along the processing chain, poultry meat products may undergo chemical inputs such as food additives, processing aids, and chemicals that migrate from packaging materials. Finally, when prepared by the domestic consumer, poultry products may be exposed to additional household chemicals and other contaminants. Figure 1 shows the principal chemical contaminations at different points of production.

PESTICIDES

Pesticides are defined as any agent used to control or kill undesired insects, diseases, weeds, rodents, mold, and other organisms, such as bacteria. Under the term *pesticide* are herbicides, insecticides, fungicides, rodenticides, and disinfectants, some of which remain on food as residues. There has been a serious concern for several years about the potential that exists in adulterating poultry products with pesticide residues. The problem has considerable international implications because very large quantities of poultry products and poultry feed ingredients are traded between nations throughout the world. The increased use of pesticides in crop protection fosters the possibility of feed contamination and consequent exposure of poultry to these products. Poultry feed, which is composed of a large number of ingredients, may contain high levels of pesticide residues (Pierson et al., 1982). Organochlorine compounds have been particularly effective in the control of pests and diseases, but their resistance to degradation has resulted in their being universal contaminants in water and to some extent in foods (Caldas et al., 1999). The chemical properties of organochlorine pesticides, such as low water and high fat solubility, stability to photooxidation, and low vapor pressure, are the main elements not only for the efficiency of these compounds as pesticides, but also in their persistence in the environment. Although the use of organochlorine pesticides has been discontinued for a considerable period of time in many countries, the residues continue to have a significant impact on a number of ecosystems (Jong-Hun and Smith, 2001).

Aulakh et al. (2006) monitored organochlorine pesticide residues in poultry feed, chicken, and eggs at a selected poultry farm throughout the year. All the pesticide residues present in the poultry feed were detected in the muscle at much lower levels than was poultry feed, indicating that muscle is not a good accumulation site. Residues detected in eggs at the farm indicated a higher accumulation of pesticides in eggs compared to their corresponding values in muscle. The presence of pesticide residues in poultry feed at the farm revealed that there was no apparent seasonal variability for the presence of residues. It is concluded that high levels of organochlorine pesticide residues in poultry feed, including total lindane and DDT and their presence in muscle and eggs at these farms, indicated that poultry feed could be one of the major sources of contamination for chicken tissue and eggs.

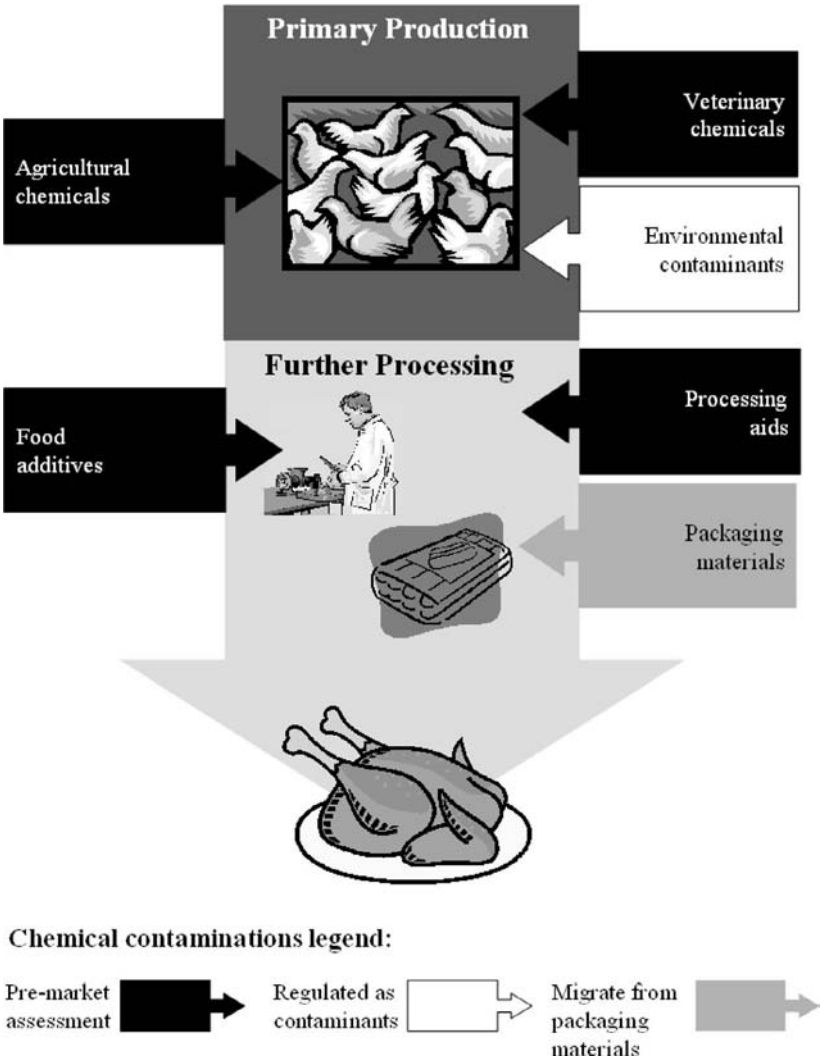

FIGURE 1 Main chemical contaminants during primary poultry production in farms (veterinary, agricultural, and/or environment) or during further processing in food plants and homes (additives during processing and packaging or during cooking).

Pesticide Toxicity Garg et al. (2004) evaluated the chronic toxicity of 20 synthetic pyrethroid, organophosphate, and chlorinated pesticides on the bone health of broiler chicks. Body mass and serum calcium and phosphorus levels were unaffected by pesticide treatment. Roentogenography revealed destructive changes in the upper part of the femur in the monocrotophos group. On the other hand, "farmer's lung" is associated with handling moldy feed and has increased prevalence in northern latitudes. For farmers, a history of a high-pesticide-exposure

event was strongly associated with a diagnosis of farmer's lung. Many people with farmer's lung continue to farm decades after diagnosis (Hoppin et al., 2008).

DRUGS: β-AGONISTS AND ANTIBIOTICS

Clenbuterol

Veterinary and chemical drugs that have anabolic effects are used for therapeutic and prophylactic purposes as well as for improved breeding efficiency. In general, these substances are added illegally to act as growth promoters, improving feed conversion efficiency, and increasing the lean/fat radio. The gain in protein deposition is thus based on an improved feed conversion rate. However, these substances may remain in all treated derived foods (Toldrá and Reig, 2006).

For many years, poultry selection has concentrated on growth velocity in meat lines, producing improvements in growth that have not been without consequence for muscle structure, metabolism, and meat quality. Higher growth rates may induce morphological abnormalities, larger fiber diameters, a higher proportion of glycolytic fibers, and a lower proteolytic potential in the muscles. After death, the faster development of rigor mortis increases the likelihood of paler color and reduced water-holding capacity and the poorer quality of products processed further. Reduced proteolytic potential is likely to increase the toughness of poultry meats (Dransfield and Sosnicki, 1999).

To improve performance, athletes are often tempted to use dietary supplements called *prohormones* or *anabolic steroids* (Van Poucke et al., 2007). Various β-adrenergic agonists have been shown to be capable of improving weight gain when added to the feed of various domestic species. One of the key features observed when β-adrenergic agonists are added to feed is a reduction in the proportion of fat in tissue, an increase in nitrogen accretion, and a reduction in the saturated fatty acid concentration within the fat associated with muscular fibers (Takahashi et al., 1993). Clenbuterol, an β_2-adrenergic agonist licensed as an antiasthmatic in human and veterinary medicine only in the European Union (EU), has progressively found an illegal worldwide use as a growth-promoting agent, due to its capability to elicit lypolysis and to promote muscle hypertrophy through stimulation and the corresponding tissues receptors, leading to the production of lean meat, particularly appreciated by consumers (Brambilla et al., 2007). Ocampo et al. (1998) assumed that the use of clenbuterol at 0.25 ppm could reduce the incidence or severity of the ascites syndrome, a multifactor disease in broilers with a common triggering factor: reduced cardiovascular reserve. In a study by Hamano et al. (1998) on the effects of the β-adrenergic agonist clenbuterol (1 mg/kg diet) on the growth and muscle composition in female broiler chickens (14 to 32 days of age) fed on diets containing various concentrations of protein (220, 240, or 260 g protein/kg), the rate of gain was significantly higher in clenbuterol-treated chickens than in control birds. It was concluded that clenbuterol-treated chickens require increased dietary protein to maintain

maximal growth and that increased protein consumption is an important factor in improving growth in clenbuterol-fed broilers.

The use of β-agonists for growth promotion in food-producing animals is not approved in the EU, the United States, and most other countries. Malucelli et al. (1994) studied the possibility of the illegal use of these compounds in broiler production, showing that clenbuterol demonstrated the highest accumulation in the tissues analyzed. A withdrawal period of greater than 2 weeks was required for residues in edible tissues to decline below detectable levels.

Toxicity of Clenbuterol Several cases of foodborne clenbuterol poisoning have been described. In Spain, outbreaks were reported after the ingestion of cow's liver; one outbreak, affecting 135 persons, occurred in the central part of the country. Studies in Mexico by Martínez-Navarro (1990) found that illegal use of these compounds for cattle has already led to several cases of intoxication in humans after consumption of contaminated animal liver. In France, an incident of food poisoning by residues of clenbuterol in veal liver was described by Pulse et al. (1991). A total of 22 persons from eight families in two cities were affected.

Antibiotics

The growth promoter effect of antibiotics was discovered in the 1940s, when it was observed that animals fed dried mycelia of *Streptomyces aureofaciens* containing chlortetracycline residues improved their growth. The mechanism of action of antibiotics as growth promoters is related to interactions with an intestinal microbial population (Dibner and Richards, 2005). Antibiotic use has facilitated the efficient production of poultry, allowing the consumer to purchase, at a reasonable cost, high-quality meat and eggs. Antibiotic use has also enhanced the health and well-being of poultry by reducing the incidence of disease. The risk concerning residues of antibiotics in edible tissues and products that can produce allergic or toxic reactions in consumers is known to be negligible because only antibiotics that are not absorbed in the digestive tract are authorized as growth promoters. The use of antibiotics can contribute to the development of resistant bacteria to drugs used to treat infections. Antibiotic resistance in feed animals is associated with resistant infections in humans. The fate of antibiotics in the environment, especially antibiotics used in animal husbandry, has been the subject of recent studies. The assumed quantity of antibiotics excreted by animal husbandry adds up to thousands of tons per year. Some antibiotics seem to persist in the environment a long time, especially in soil, while others degrade very fast. Since the beginning of antibiotic therapy, more and more resistant bacterial strains have been isolated from environmental sources showing one or more types of resistance (Kemper, 2008). As antibiotics are poorly adsorbed in the gut of animals, the majority is excreted unchanged in feces and urine. Land application of animal waste as a supplement to fertilizer is a common practice in many countries (Sarmah et al., 2006). Schlusener and Bester (2006) studied the persistence of antibiotics such as macrolides, tiamulin, and salinomycin in soil.

TABLE 1 Antibiotics Permitted as Additives in Poultry Feeds

Antibiotic	Poultry
Tetracycline, chlortetracycline, oxytetracycline	Poultry (except ducks, geese, laying hens) up to 10 weeks old
Penicillin-G-potassium, penicillin-G-sodium	Poultry (except ducks, geese, laying hens) up to 10 weeks old
Spiramycin	Poultry (except ducks, gesse, laying hens) up to 4 weeks old
Virginiamycin	Laying hens
Bactracin zinc	Laying hens
Oleandomycin	Poultry (except ducks, geese, laying hens) up to 4 weeks old

The half-lives were 20 days for erythromycin, 27 days for oleandomycin, 8 days for tylosin, 16 days for tiamulin, and 5 days for salinomycin. The concentration of roxithromycin remained nearly unchanged during the 120 days of experiment.

The World Health Organization and the Economic and Social Committee of the EU concluded that the use of antimicrobials in food animals is a public health issue and that antimicrobial availability should be limited to therapeutic use for prescription. The recommendations are precautionary, based on the potential for reservoir in food animals of an antibiotic-resistant bacterial population that could be transferred to humans (Donoghue, 2003; Dibner and Richards, 2005). In the Table 1 are listed antibiotics permitted in the EU as feed additives in poultry feeds (Castanon, 2007). Chapman and Johnson (2002) studied the quantitative aspects of the use of antibiotics and roxarsone (an arsenical drug used to improve weight gain) during the last six years, concluding that there were no significant differences in calorie conversion but an increased cost of production.

Alternative for Antibiotics Serum therapy is the administration of immune serum from immunized animals or convalescent humans for the prevention or treatment of infectious diseases. This routine was abandoned due to a number of drawbacks, such as the occurrence of serum sickness, the risk of disease transmission, and lot-to-lot variations of different serum preparations, but the most important factor reducing the application of serum therapy was certainly the advent of antibiotic therapy (Casadevall, 1996).

Antibody therapy and proprophylaxis have a natural place in animal agriculture. In poultry, maternal antibodies are transmitted to the offspring via the yolk of the eggs. The egg yolk was the first source of antibodies used routinely for prophylaxis and therapy of infectious diseases in an agricultural setting. The systemic administration of highly purified egg yolk is a theoretical possibility (Berghman et al., 2005). Bacteriophages are viruses that infect and kill bacteria and might be used to prevent infection bacterial. Huff et al. (2005) demonstrated that bacteriophages can be used to prevent and treat colibacillosis in poultry and may provide an effective alternative to antibiotic use in animal production.

NEW PERSPECTIVES

Organic livestock productions is a means of food production with a large number of rules directed toward a high level of animal welfare, care for the environment, restricted use of medical drugs, and production of a healthy product without residues: pesticides or medical drugs. The disease prevention in organic production is based on the assumption that feeding, housing, and care of the animals is such that they have an optimal natural resistance to combat diseases (Kijlstra and Eijck, 2006). On the other hand, organic animal husbandry has been strongly criticized by veterinarians, who have claimed that organic livestock often are not treated properly when sick because of the longer withdrawal times prescribed by the organic standards and because alternative medicine is preferred and also because animals have been malnourished and more heavily infected with parasites because of restrictions in the administration of anthelmintics (Lund and Algers, 2003). Castellini et al. (2006) compared conventional and organic poultry production in terms of energy analysis. The energetic costs for housing the birds were very similar in both systems: To maximize environmental sustainability, food safety, and biodiversity, specific farming protocols should be developed. Furthermore, organic farming requires additional research.

CONCLUSIONS

The ban on growth promoters demands the improvement of hygiene on farms; it was shown that under good production conditions it is possible to reach good and competitive production results for the rearing of poultry without the continuous use of antibiotics and hormones in feeds. Organic farms may be a good alternative, but more investigation is necessary.

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FACTORS AFFECTING MICROBIAL GROWTH IN FRESH POULTRY

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INTRODUCTION

The increased consumption of poultry products by consumers can be linked to a demand for products that are perceived as healthy, low-fat alternatives to red meats, the ability of the product to be prepared in a variety of ways, and the

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product's ability to accept a wide variety of flavors. Over the past 15 years, poultry meat production worldwide has increased rapidly, with an annual growth rate of 11% (Salazar et al., 2005; Gatfield, 2006). This increased demand for poultry products has led to intensive animal production, with an increase both in the number of farms and in flock size. Both have raised specific problems, including contamination with human and animal pathogens, as well as environmental problems.

The most serious meat safety issues resulting in immediate consumer health problems and recalls from the marketplace of potentially contaminated products are associated with microbial and bacterial pathogens. Bacteria that are easily removed from a carcass pose a greater risk to public health (through cross-contamination of other foods) than bacteria that are present inside the carcass or firmly attached to the carcass and would be killed during cooking (Buhr et al., 2005). Contaminated food is reported to be the major vehicle for cases of enteric disease, with poultry constituting the largest percentage of food items associated with illness. Broiler carcasses have been implicated as prime carriers of human pathogens (Rodrigo et al., 2006).

Live poultry for meat production are normally raised on litter floors. This production method may lead to contamination of poultry with human pathogens such as *Salmonella, Campylobacter, Listeria, Escherichia coli, Clostridium,* and *Staphylococcus aureus*. Additionally, spoilage microorganisms, mainly psychrotrophs such as pseudomonads, lactic acid bacteria, and yeasts, are commonly present on live animals (Berrang et al., 2000). Only occasionally do young animals show symptoms of bacterial infection, with most being healthy carriers of pathogens such as *Salmonella* and *Campylobacter*. During poultry processing, hygienic measures can be used to control contamination levels and avoid cross-contamination, both between products and between equipment and product.

To address the issues of pathogens present at the various points in poultry processing, the Food Safety and Inspection Service (FSIS) initiated the pathogen reduction, hazard analysis and critical control point (PR-HACCP) program to reduce the risk of foodborne illness. The pathogens that PR-HACCP focuses on include *E. coli* and *Salmonella*. According to the U.S. Centers for Disease Control and Prevention (CDC), there are approximately 2.4 million cases of human campylobacteriosis and 1.2 million cases of human salmonellosis infections in the United States each year (CDC, 2007). The most commonly implicated source for these illnesses is handling of raw poultry or consumption of undercooked poultry and poultry products. As poultry meat is typically not consumed raw, the epidemiological outbreaks are caused by secondary contamination.

To address the growing concern of contamination in poultry, FSIS announced its *Salmonella* initiative for poultry inspection in February 2006. Prior to this initiative FSIS had seen a four-year rise in *Salmonella*-positive samples in its monitoring of broiler plants (Sofos, 2008). Data collected at the end of 2007 show a slight decrease in the number of plants with positive samples (Thorton, 2008). The FSIS *Salmonella* testing program is designed to assess the performance of individual plants, not to estimate the national prevalence of *Salmonella* in raw poultry, because it does not account for production volume or regional and seasonal effects (Sofos, 2008).

MICROBIAL GROWTH IN POULTRY

Poultry has a very complex biota, which is partly of intestinal origin, due to the production system, flocks of large numbers of fast-growing animals, and being reared in climatized houses on litter floors. Kotula and Pandya (1995) found high numbers of human pathogens on the feathers and skin of broilers entering a processing plant. Bacteria that come in contact with feathers, skin, or meat surfaces will attach either by physical forces or chemical means such as polysaccharide bonds (Firstenberg-Eden, 1981).

The primary reason that poultry spoilage is restricted to surfaces involves the length of contact that the organism had with poultry. The inner portions of poultry tissue are generally sterile, or contain relatively few organisms, which generally do not grow at low temperatures. The spoilage biota is restricted to surfaces and skins, where it is deposited from water, processing, and handling. The surfaces of fresh poultry stored in an environment of high humidity are susceptible to the growth of aerobic bacteria such as pseudomonads (White et al., 2007). These organisms grow well on surfaces, where they form minute colonies that later coalesce to produce the sliminess characteristic of spoiled poultry. To address the microbial growth that occurs on poultry, one needs to consider the intrinsic and extrinsic parameters that affect the growth potential of those microbes. By taking these natural phenomena into account, an effective use of these mechanisms can be employed to prevent or retard the growth of pathogenic and spoilage organisms (Davies and Board, 1998).

Intrinsic Parameters

The intrinsic parameters are those that are an inherent part of the tissue. These parameters include pH, moisture content, nutrient content, and biological structures. By determining the extent to which each of these intrinsic mechanisms exists in the poultry, one can predict the general types of microorganisms that are likely to grow and, consequently, the overall stability of the poultry.

pH With respect to the keeping quality of meats, it is well established that meat from fatigued animals spoils faster than that from rested animals and that this is a direct consequence of final pH attained upon completion of rigor mortis. Sofos (2008) noted that the microbial counts of poultry were lower on well-rested flocks than on flocks under heightened stress. He also noted that the pH range for chicken at the time of death is 6.2 to 6.4. Upon the death of a well-rested animal, the 1% glycogen found in muscle tissues is converted to lactic acid, which directly causes a depression of pH values. When the skin is removed from a fresh chicken carcass, leg muscles are more likely to spoil faster than breast muscles since the pH of the former is typically in the pH range 6.3 to 6.6, whereas the latter is between 5.7 and 5.9 (Sofos, 2008).

Moisture Content All living organisms must have a source of water if they are to survive. The water requirements for microbial growth should be defined in

terms of the water activity (a_w) in the environment. This parameter is defined as the ratio of the water vapor pressure of a food substrate to the vapor pressure of pure water at the same temperature. Pure water has an a_w value of 1.00. In general, bacteria require higher values of a_w, with gram-negative bacteria having higher requirements than gram-positive bacteria. Most spoilage bacteria do not grow below an a_w value of 0.91. *S. aureus* can grow at as low a value as 0.86, whereas *Clostridium botulinum* does not grow below 0.94. In general, bacteria require higher values of a_w for growth than fungi do. Just as yeasts and molds grow over a wider pH range than bacteria, they also grow in a wider a_w range.

The surfaces of fresh poultry stored in an environment of high humidity are susceptible to the growth of aerobic bacteria such as pseudomonads. Gill et al. (2004) investigated the microbiological conditions of moisture-enhanced chicken breasts. The log total numbers of aerobes and coliforms recovered from injected breasts and circulated brines indicated bacterial numbers per milliliter of brine 30 min after the start of processing were about 0.5 log unit more than the numbers per gram of meat 15 to 30 min after processing. Cooking by grilling or broiling of the breasts to even an underdone condition destroyed most bacteria in the deep tissues, including all coliforms and *E. coli*. A few *Listeria* organisms, however, were recovered from the breasts in both underdone and well-done breasts, indicating that additional cooking may be necessary to eliminate all *Listeria* spp. from moisture-enhanced poultry (Gill et al., 2004).

Nutrient Content To grow and function normally, the microorganisms in foods require water, a source of energy, a source of nitrogen, vitamins and related growth factors, and minerals. As sources of energy, foodborne microorganisms may utilize sugars, alcohols, and amino acids. Some microorganisms are able to utilize complex carbohydrates such as starches and cellulose as sources of energy by first degrading these compounds to simple sugars. In general, gram-positive bacteria are the least synthetic and must therefore be supplied with one or more of these compounds before they will grow. The gram-negative bacteria and molds are able to synthesize most or all of their requirements.

Biological Structures The natural covering of poultry by the skin and feathers provides excellent protection against entry and subsequent damage by spoilage organisms. Research performed by Berrang and Dickens (2004) reported numbers of 5.4 log CFU/g for feathers and 3.8 log CFU/g for skin before scalding. *Campylobacter* was recovered in high numbers from the carcasses after scalding and plucking. Feathers can be contaminated with feces during transport, and *Campylobacter* originally associated with feathers can be transferred to the skin during the plucking process. Data collected by Berrang and Dickens (2004) confirm that defeathering caused an increase in *Campylobacter* counts under the conditions of flock, plant, and processing day used in that experiment.

In an attempt to reduce the high numbers of *Campylobacter* on broiler carcasses associated with automatic feather removal, Berrang et al. (2006) applied distilled white vinegar to the cloaca just prior to scalding. *Campylobacter* numbers increased from 1.3 log CFU/sample before defeathering to

4.2 log CFU/sample after feather removal in untreated carcasses. Although *Campylobacter* numbers increased in vinegar-treated samples, that increase was significantly smaller, with numbers increasing from 1.6 log CFU/sample before defeathering to 2.6 log CFU/sample after defeathering.

Extrinsic Parameters

The extrinsic parameters include the properties of storage environment that affect both foods and their microorganisms. Those of greatest importance to foodborne organisms are storage temperature, relative humidity of the environment, and the presence and concentration of gases in the environment (Davies and Board, 1998).

Storage Temperature Temperature is considered the most important factor affecting meat spoilage (Koutsoumanis et al., 2006). Giannakourou et al. (2001) found that temperature conditions higher than 10°C are not unusual during transportation, retail storage, and consumer handling. Temperature fluctuations above the acceptable range may cause an unexpected loss of quality of the product. Just as molds are able to grow over wider ranges of pH, osmotic pressure, and nutrient content, they are also able to grow over wider ranges of temperature than bacteria. Berrang and Dickens (2004) found that chilled carcasses revealed lower *Campylobacter* counts than those from carcasses sampled immediately following defeathering. *Campylobacter jejuni* was also shown by Hanel and Atanassova (2007) to be present on turkey meat after 2 weeks of storage at refrigerator temperatures.

Relative Humidity The relative humidity (RH) of the storage environment is important both from the standpoint of a_w within foods and the growth of microorganisms at the surfaces. When the a_w of a food is set at 0.60, it is important that this food be stored under RH conditions that do not allow the food to pick up moisture from the air and thereby increase its own surface and subsurface a_w to a point where microbial growth can occur. Foods that undergo surface spoilage from molds, yeasts, and bacteria should be stored with low RH. Improperly wrapped whole chickens experience surface spoilage in the refrigerator, due to the generally high RH.

Environmental Gases Carbon dioxide (CO_2) is the single most important atmospheric gas currently used to control microorganisms in foods (Ellis et al., 2006). Chlorine dioxide (ClO_2) is rapidly gaining attention, however, for use as an antimicrobial agent in active packing systems. Ellis et al. (2006) examined the quality of fresh chicken breasts refrigerated for 15 days using ClO_2 combined with modified-atmosphere packaging. They found that after 9 and 12 days of storage, the total plate counts for chicken stored without ClO_2 and fast-release ClO_2 sachets were not different ($p < 0.05$) but those with slow-release ClO_2 sachets were about 1 log lower ($p > 0.05$) than untreated samples or samples

with fast-release sachets. After 15 days of storage, samples with fast-release sachets in 100% N_2 were lower ($p < 0.05$) (7.31 log CFU per chicken breast) than the samples that were untreated or those packaged in slow-release sachets. These results show that ClO_2 was effective in reducing microbial growth on the surface of chicken breasts (Ellis et al., 2006).

MICROBIAL LOADS ON POULTRY

The internal tissues of healthy slaughter animals are free of bacteria at the time of slaughter, assuming that the animals are not in a state of exhaustion (Scherer et al., 2006). When that same fresh poultry is examined at the retail level, varying numbers and types of microorganisms are found. Whole poultry tends to have a lower microbial count than cut-up poultry. Most of the organisms on such products are at the surface, so surface counts/cm^2 are generally more valid than counts on surface and deep tissues. Mulder (1996) showed how the surface counts of chickens build up through successive stages of processing. In a study of whole chickens from six commercial processing plants, the initial mean total surface count was $\log_{10}$ 3.30 CFU/cm^2. After the chickens were cut up, the mean total count increased to $\log_{10}$ 3.81 CFU/cm^2. After packaging, an increase of $\log_{10}$ 4.08 CFU/cm^2 was observed. The conveyor over which these birds moved showed a count of $\log_{10}$ 4.76 CFU/cm^2. When the procedures were repeated for five retail grocery stores, Mulder (1996) found that the mean count before cutting was $\log_{10}$ 3.18, which increased to $\log_{10}$ 4.06 after cutting and packaging. The cutting block was shown to have a total count of $\log_{10}$ 4.68/ cm^2. *Salmonella* spp. remain at high levels on carcasses because of firm attachment to poultry skin (McCrea et al., 2006). Young chickens, especially those less than 2 weeks of age, are extremely susceptible to infection by *Salmonella* spp. In contrast, colonization by *Campylobacter* spp. appears to be most common in broiler chickens older than 2 weeks of age (Neill et al., 1984).

As poultry undergoes spoilage, off-odors are generally noted before sliminess, with the former being detected first at a level of about 7.2 to 8.0 log CFU/cm^2. Sliminess generally occurs shortly after the appearance of off-odors, with the $\log_{10}$ CFU/cm^2 about 8 (Lillard, 2000). As bacteria enter the deep tissue, increased hydration of muscle protein occurs.

PATHOGENS ASSOCIATED WITH POULTRY

The most serious meat safety issues related to consumer health problems and recalls of potentially contaminated products are associated with microbial pathogens (Sofos, 2008). The importance of microbiological safety of meat and poultry products for industry, consumers, and public health officials has gained global attention. Approximately 2.2 million cases of foodborne disease occur worldwide each year (Bohaychuk et al., 2006). In recent years, some highly

publicized outbreaks of foodborne disease, caused by pathogenic bacteria, have increased the public's concern with the safety of the meat supply.

Poultry meat is considered one of the most common foods that cause foodborne infection and intoxication (Anang et al., 2007). Most of these illnesses have been attributed to cross-contamination with human pathogenic organisms such as *Salmonella* and *Campylobacter*. Poultry processing consists of various processes that provide opportunities for contamination with these bacterial pathogens.

Salmonella

Salmonella has been linked to the consumption of contaminated poultry products. Human infection is usually attributed to cross-contamination in the kitchen, inadequate cooking, and improper storage temperatures (Payne et al., 2008). *Salmonella* is responsible for an estimated 300,000 to 4,000,000 cases of foodborne illness in the United States and an estimated 30.6% of the deaths associated with foodborne illness (Kiessling et al., 2002). According to Lillard (2000), the results of investigations carried out by the FSIS indicate that 4 to 5% of broilers arriving at a poultry slaughterhouse are infected with *Salmonella* spp., while 35 to 36% of the carcasses leaving a plant are contaminated. Contamination of slaughter chickens with *Salmonella* spp. was at its lowest after stunning and at its highest before cooling (Mikolajczyk and Radkowski, 2002).

To combat contamination of poultry products, PR-HACCP programs have been developed and implemented in all U.S. processing plants under federal inspection as a means of identifying and controlling or eliminating potential food safety hazards. This federally mandated program calls for the testing of the poultry processing plant environment and carcasses for the presence of *Salmonella* and generic *E. coli*. The PR-HACCP final rule has four components: formulation of standard operating procedures for sanitation, development of establishment-specific HACCP plans, testing by establishment for *E. coli*, and testing by the FSIS for *Salmonella* in meat and poultry products (Eblen et al., 2006).

Before PR-HACCP implementation, *Salmonella* contamination in broiler carcasses was estimated at 20%. In 2002, the FSIS reported a *Salmonella* prevalence of 11.5% on broiler carcasses (USDA–FSIS, 2003). *Salmonella* incidence of 33.9% was reported by Simmons et al. (2003) in whole chicken carcasses at retail, which is substantially higher than the 20% reported by the FSIS. Although the FSIS PR-HACCP *Salmonella* testing program is not designed to estimate the prevalence of *Salmonella* in raw meat and poultry products in the United States, it does provide comprehensive publically available information regarding *Salmonella* contamination. White et al. (2007) evaluated sampling data from FSIS between 1998 and 2003. *Salmonella enteritidis* was isolated from 0.06% of the 293,938 total samples and from 1.32% of the 12,699 *Salmonella*-positive samples analyzed in that study. This high incidence warrants further investigation at the farm level to determine whether *S. enteritidis* is becoming more prevalent in broiler chickens. Additional research is needed to determine the incidence of *Salmonella* in retail poultry and the relative contributions of various differences in samples and methods.

Campylobacter

Campylobacter is reported as one of the most frequent causes of foodborne illness in both industrialized and developing countries, especially in children, the elderly, and immunosuppressed patients (Stern and Pretanik, 2006; Wong et al., 2006, Klein et al., 2007). Most cases of campylobacteriosis are associated with handling raw poultry, eating raw or undercooked poultry meat, or cross-contamination of raw or cooked foods (Corry and Atabay, 2001). In the United States the CDC estimates that approximately 1.6 million cases of campylobacteriosis are reported, with 15 people per 100,000 infected annually (CDC, 2006). The German national average for campylobacteriosis is 16 cases per 100,000 inhabitants (Hanel and Atanassova, 2007). Cases in Denmark quadrupled between 1980 and 2001, with 86 cases per 100,000 inhabitants being reported (Wingestrand et al., 2006). The estimated prevalence of *Campylobacter* on raw chicken ranges from a few percent to 100%, depending on geographical location and season (Stern et al., 2003; Lindblad et al., 2006).

Recent raw chicken surveys in the United Kingdom have reported *Campylobacter* isolation rates ranging between 68 and 87% (Scherer et al., 2006). Shih (2000) showed that almost 50% of the chicken products at the retail level in Taipei were contaminated by *Campylobacter*. The percentage of poultry products contaminated with *Campylobacter* was found to be 18.5% in a study carried out in Belgium (Mikolajczyk and Radkowski, 2002).

Uyttendaele et al. (1999) collected 772 samples of poultry carcasses from retail markets in Belgium to be analyzed for the presence of *Salmonella* spp., *Salmonella enteritidis, Campylobacter jejuni, Campylobacter coli*, and *Listeria monocytogenes*. A significantly ($p < 0.05$) lower pathogen contamination rate was noted for *Salmonella, C. jejuni*, and *C. coli* for skinned poultry cuts compared to unskinned poultry cuts. An increase in pathogen contamination rate was noticed during cutting and further processing. To diminish *C. jejuni, C. coli, Salmonella*, and *Listeria monocytogenes* contamination rates, hygienic rules of slaughter and meat processing must be observed rigorously (Uyttendaele et al., 1999).

There is great variation in the results of confirmed cases. Results are dependent on the sample type (whole carcass or portions, fresh or frozen), sample preparation (rinsing the carcass or homogenizing the skin), and quantification method (direct count or MPN method). Differences in these and other data collection factors often prevent direct comparison of data (Scherer et al., 2006).

Other Microorganisms

The isolation rates of *S. aureus, E. coli, Listeria aeromonas*, and *Clostridium* spp. from poultry have increased over time; however, the incidence of human foodborne infection does not reflect this trend (Mulder, 1996). Taormina et al. (2003) collected data on the contamination of raw poultry with pathogens and concluded that very little information is available on the new pathogens *Yersinia, Hafnia, Bacillus*, and *E. coli* O157:H7. The spoilage microorganisms *Acinetobacter, Brochothrix, Pseudomonas*, lactic acid bacteria, and yeasts grow relatively

rapidly at low temperatures and have a major impact on the shelf life of fresh poultry products. *L. monocytogenes* easily enters the human food chain and may multiply rapidly (Farber and Peterkin, 1991).

SPECIALTY MARKET POULTRY

Most studies examining bacterial counts found on poultry are performed using chicken broilers. The potential for the transmission of food safety pathogens to humans through specialty poultry products is increasing with the increase in specialty poultry consumption.

McCrea et al. (2006) conducted a study examining the overall prevalence of *Campylobacter* and *Salmonella* among squab, poussin, duck, guinea fowl, quail, and free-range chickens at the farm. Their findings show that the levels of pathogens in these products varied greatly. Squab had a very low prevalence of *Campylobacter* spp. The prevalence of *Salmonella* spp. was also lower among squab than among the other specialty poultry products. Results of samples taken from ducks found that all samples contained *Campylobacter jejuni. Campylobacter* prevalence ranged from 5 to 15% in guinea fowl and 14 to 41% in quail. No *Salmonella* was isolated from either species. Poussin and free-range chickens were the two groups that had the highest prevalence of *Campylobacter*-positive birds; poussin were 80 to 97% positive, and free-range chickens were 32 to 68% positive. Organic free-range flocks had a higher prevalence of *Campylobacter*-positive flocks than did conventional broiler flocks.

Salmonella was more prevalent in the free-range (31%) and all-natural (25%) chickens surveyed than in chickens from the U.S. commercial poultry industry in 2003 (Bailey and Cosby, 2005). McCrea et al. (2006) indicated that critical control points (CCPs) for reducing bacterial contamination are not the same across all species and suggested that HACCP plans for *Campylobacter* and *Salmonella* control may need to be designed specifically to accommodate differences in free-range and all-natural chickens.

CONCLUSIONS

Food safety and shelf life are both important microbial concerns in relation to broiler meat production. Focus is placed primarily on the absence or control of potentially pathogenic microbes, but other spoilage bacteria also play a role. The primary target for food safety should be the production of pathogen-free live animals.

Efforts to reduce human infection from foodborne *Salmonella, Campylobacter, Listeria, E. coli, Clostridium, S. aureus*, and other pathogens must focus on the implementation of farm-to-table prevention strategies. Preharvest interventions such as the National Poultry Improvement Plan SE Clean program for meat-type breeders, best production practices, and microbiological monitoring in production

houses are essential prevention strategies. Public health regulations should be based on the principles of PR-HACCP and aimed at reducing the spread of foodborne pathogens.

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BASIC PRINCIPLES OF THE HACCP SYSTEM IN THE POULTRY INDUSTRY

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Handbook of Poultry Science and Technology, *Volume 1: Primary Processing*, Edited by Isabel Guerrero-Legarreta and Y.H. Hui

INTRODUCTION

Meat and poultry products are often contaminated with pathogenic bacteria, viruses, and parasites. Meat and poultry also provide an excellent environment for microbial growth, which eventually transfers to consumers and results in foodborne illnesses. To improve product safety, the food-processing industries have adopted a system to prevent health hazards known as the hazard analysis and critical control point (HACCP) system (FSIS, 1996).

HACCP is a systematic approach to controlling any chemical, physical, or microbiological hazards that may arise in a food-processing facility or food supply chain. The HACCP system identifies specific hazards and measures for their control to ensure that the product is safe. This is a technique based on the anticipation and prevention of problems rather than through end-product inspection and testing. The main objective of HACCP is to enhance assurance of food safety in order to prevent foodborne illness more effectively. Additionally, it reduces the costs of control and wasted food and protects the food processor and the entire food industry.

HACCP was developed in the 1960s by the Pillsbury Company when it was trying to develop microbiologically safe foods for the NASA space program. The U.S. National Academy of Sciences recommended in 1985 that the HACCP approach be adopted in food-processing establishments to ensure food safety (NAS, 1985). In 1995, the Food Safety and Inspection Service (FSIS) in the United States proposed the new pathogen reduction-HACCP proposal, which is a broad, long-term strategy to improve the safety of meat and poultry products to better protect public health (FSIS, 1995). Since January 1998, the largest meat- and poultry-processing plants in the United States have been required to implement a HACCP system to control contamination in their facilities (FSIS, 1998). The HACCP approach is also recognized internationally as being effective in ensuring the safety and suitability of food for human consumption and in international trade (CAC, 2003).

The HACCP system marks a departure from traditional endpoint analysis of previous food systems. Instead of trying to detect contaminations in food products at the end of the production process, the goal of a HACCP system is to minimize contamination by establishing control points during food processing. Therefore, the HACCP system provides prevention and is thus a cost-effective approach to food safety. Depending on the procedures used to process different foods, hazard points for the entry of contamination are identified and critical controls are developed. Implementation of these control points is monitored throughout the process to ensure that contamination is controlled. To improve food safety, the entire food supply system is examined to determine control points at which prevention steps can be implemented. If not properly implemented, it may not be an effective control system. A HACCP plan is specific to the particular food and processing application and is applicable to any food system despite the size of the facility. Today, HACCP-based food safety assurance systems have been made legal and mandatory requirements in most countries (FAO, 1997).

THE PRINCIPLES OF HACCP

The HACCP system consists of seven basic principles which provide a basis for implementing a HACCP plan effectively (NACMCF, 1998):

1. Conduct a hazard analysis.
2. Identify the critical control points (CCPs).
3. Establish critical limits.
4. Establish a system to monitor control of the CCPs.
5. Establish the corrective action plan.
6. Establish procedures for verification.
7. Establish documentation concerning all procedures.

Principle 1. Conduct a Hazard Analysis

This step identifies where significant hazards could occur. A process flow diagram is put together describing all the steps in the process, from incoming materials to finished product. The HACCP team, which consists of experts in quality assurance, research and development, management, and food science, identifies all the hazards that could occur at each step from raw materials to the point of consumption. Hazards may be biological, chemical, or physical in nature and could cause a product to be unsafe for consumption. Biological hazards, which include pathogens, are the primary hazards that most food industries focus on to provide safe products to consumers.

Points that should be considered while performing a hazard analysis may include the likely occurrence of hazards and the severity of their adverse effects, the survival or multiplication of microorganisms of concern, and the production or persistence of toxins, chemicals, or physical agents in a food. Hazard analysis is a key element in developing a HACCP plan. It is essential that this process be conducted in an appropriate manner; thus, hazard analysis represents the foundation for building a HACCP plan. The hazard analysis procedure can be divided into the following activities:

- Review incoming material for potential hazards (hazard identification).
- Evaluate processing operations for hazards.
- Observe actual operating practices.
- Take measurements.
- Analyze the measurements.

Upon completion of the analysis, the hazards associated with each step in the production of a food should be listed along with any measures that are used to control the hazards.

A *hazard* is a factor (biological, chemical, or physical) present in the food product which can cause adverse health effects for the consumer. The first step

in performing the hazard analysis of a HACCP plan is to identify hazards that may be encountered in production. *Critical control points* are the stages in a processing plant where food safety hazards must be controlled.

Biological Hazards Biological hazards can be either macrobiological (flies, insects) or microbiological. Potential microbiological hazards in meat and poultry include bacteria, viruses, protozoans, parasites, and toxins (Mortimore and Wallace, 1998). Of all these hazards, bacteria are the most important group since they are responsible for approximately 90% of all foodborne illnesses (Mead et al., 1999). The strategy to improve meat and poultry safety is based on reducing the numbers of pathogenic microorganisms on meat (FAO, 1997).

The following pathogenic bacteria may be found in meat and poultry products (FSIS 2005):

- *Campylobacter* spp.
- *Clostridium perfringens*
- *Escherichia coli* O157:H7
- *Listeria monocytogenes*
- *Salmonella* spp.
- *Shigella* spp.
- *Staphylococcus aureus*
- *Yersinia enterocolitica*

All of these pathogens have been implicated in numerous foodborne disease outbreaks associated with the consumption of meat and poultry products (NACMCF, 1999). It is necessary to identify all types of microorganisms associated with a particular food product that may be hazardous when present in meat. The first approach is to determine whether or not these bacteria are present in the raw materials used. The next step is to determine whether they can be destroyed during processing. Recontamination during processing should also be assessed.

Depending on the type of processing method, the bacteria present in the raw materials will be affected in different ways. If the product is going to be frozen, attention must be given to reducing the existing microflora to the critical levels. When a cooking step is involved in the process, it is necessary to determine whether bacterial spores will be eliminated.

Meat and poultry are subjected to a variety of contaminants starting at the slaughter stage. The digestive tract of all animals and birds, as well as their skin and feathers, are a major source of contamination. Therefore, implementation of HACCP in the slaughterhouse is extremely important. Prerequisite programs such as good manufacturing practices (GMPs) at the farm level will reduce the initial load of pathogens, especially *Salmonella*, which is often used as an indicator of the confirmation of the effectiveness of HACCP systems (FSIS, 2005).

A secondary biological hazard associated with pathogens are toxins, which are produced mainly by *C. perfringens* and *S. aureus* in foods. These bacteria are common in the environment and are often found in carcasses. Proper cooking can prevent the growth of bacteria. However, cooking will not destroy most of these toxins once they are formed in food.

Although less common than pathogenic bacteria, viruses have been responsible for several foodborne illness outbreaks in the recent past. A great number of outbreaks are due to hepatitis A virus and norovirus. The presence of viruses in food is often associated with contaminated food workers. Good hygienic practices are very important to avoid such contamination.

Chemical Hazards Chemical contamination of food materials can happen at any stage of their production. The effect of chemical contamination on the consumer can be long or short term. Chemical hazards include cleaning chemicals (one of the most significant chemical hazards), pesticides, allergens, toxic metals, environmental pollutants (e.g., PCBs, dioxins), chemical additives, and veterinary residues.

Physical Hazards A variety of physical items can enter a food system as foreign materials. Glass, stones, wood, plastic, and intrinsic materials such as bones in meat could be major physical hazards.

Principle 2. Identify Critical Control Points

A critical control point is a point, step, or operation in the flow of a food-processing chain that will prevent, eliminate, or reduce hazards to acceptable levels. The HACCP team establishes the points where control is critical to the safety of the product. A CCP can be related to raw materials, processes, or practices applied along the food chain. Critical control points are crucial to ensuring product safety because CCPs govern all factors that are basic to the prevention of foodborne diseases. The information developed during the hazard analysis is essential in identifying the CCPs.

Principle 3. Establish the Critical Limits for Preventive Measures

The critical limits describe the difference between safe and unsafe at each CCP. Critical limits are important tools required for the HACCP plan to function properly. Measurable and observable criteria include temperature, time, moisture level, pH, water activity, and sensory parameters. Critical limits must be specified and validated for each CCP identified. A critical limit represents the boundaries that are used to judge whether an operation is producing safe products. The critical limits should meet requirements set out by government or company standards, and most of all, should be supported by scientific data. Once the critical limits are established, they are recorded on the proper form, together with a description of the process step, CCP number, and hazard description.

Principle 4. Establish a System to Monitor Control of the CCPs

Monitoring is the scheduled observation or measurement of a CCP to assess whether a CCP is under control. The HACCP team needs to evaluate data to carry out corrective actions when problems occurred. Planned monitoring is necessary to keep the process under control, prevent any deviations, and confirm the effectiveness of the HACCP plan. Monitoring critical steps is essential in assuring that the process is under control, and if there is a trend toward a loss of control, in identifying where a loss of control has occurred. There are many ways to monitor the critical limits of a CCP. Most commonly, monitoring can be done on a continuous basis or on the basis of every batch analysis. Continuous monitoring is preferred, where feasible, because it is more reliable. The higher the frequency of monitoring, the less product will be affected when there is a loss of control at the CCP. When critical limits are established for the elimination of pathogens or their reduction to an acceptable level, microbiological testing can be used to verify the HACCP plan's effectiveness and to ensure that the microbiological limits identified have not been exceeded.

Principle 5. Establish a Corrective Action Plan

Specific corrective actions must be developed for each CCP in the HACCP system. It is assumed that deviations can occur in any system. When monitoring indicates that a particular CCP is not under control, a corrective action must be introduced. Corrective actions must specify steps that should be taken to bring the CCP under control and ensure that potentially unsafe products are not marketed. If it is necessary for a system to be modified and reoccurrence of the problem prevented, any corrective action taken should be documented and communicated to management. Corrective action procedures also require follow-up monitoring and reassessment to ensure that the action taken is effective.

Principle 6. Establish Procedures for Verification

Verification is the application of methods, procedures, tests, and other evaluations, in addition to monitoring, to determine compliance with the HACCP plan and to confirm that the HACCP system is working correctly. Verification is a process to look at the HACCP plan as it is being carried out and should be undertaken by appropriately qualified persons who are capable of detecting deficiencies in the plan. The verification may be carried out:

1. After each HACCP plan elaboration
2. As part of a continuous revision established by the program to demonstrate that the HACCP plan is efficient
3. When there is any change that affects hazard analysis or changes the HACCP plan in any way

Verification activities are carried out by employees within a company, third-party experts, and/or regulatory agencies. A detailed guide for verification procedure has been issued by the USDA (FSIS, 2005).

Principle 7. Establish Documentation

Efficient and accurate record keeping is crucial throughout the flow of food production. All procedures and records appropriate to these principles and their application should be documented. A record shows process history, monitoring, deviations, and corrective actions. Accurate documentation and record keeping is essential to the application of a HACCP system. There are four types of records:

1. *Support documentation for developing the HACCP plan*. This includes data used for the establishment of critical control points, control measures, critical limits, and so on.
2. *Records generated by the HACCP system*. These records describe all activities and documentation required to prove adherence of a HACCP system to the original plan.
3. *Documentation of methods and procedures*. These documents relate to the safety of the product and therefore should be maintained for possible auditing by regulatory authorities.
4. *Records of employee training programs*. Employees are trained to understand the appropriate procedures or methods and actions to intervene when critical control limits are threatened.

DEVELOPING A HACCP PLAN

To develop and implement a successful HACCP plan, commitment by and support of management is necessary. Management must offer financial support to provide necessary training regarding food safety to plant employees. Developing a HACCP plan involves teamwork, and team members should come from different areas of production and processing. The first task in developing a plan is to assemble a HACCP team. The team should have experts in various fields, such as quality control, sanitation, microbiology, process engineering, and research and development. A coordinator can be chosen to work with the team and to develop the plan. There are six stages in developing and implementing HACCP:

1. Perform a HACCP study (during which the elements of the system in line with the seven principles of HACCP are established).
2. Develop a plan.
3. Train personnel in their function.
4. Implement the plan.

5. Verify the plan.
6. Modify the plan, if necessary.

Developing a HACCP plan is based on the seven principles. However, application of the principles consists of several additional steps. Figure 1 shows the standard procedure for developing a plan. Processing plants are required to set up a HACCP plan for each product produced by the company. A detailed description of each product and of the raw ingredients used to make the product is required. This description should include the name of the product, the types of packaging materials to be used, the shelf life of the product, labeling instructions, and other information pertinent to the specific product. Intended use and consumers of the food should also be described. A complete flow diagram outlining each step involved in the process is necessary. The team should perform an on-site review of the operation to verify the flow diagram. Employee training is a very

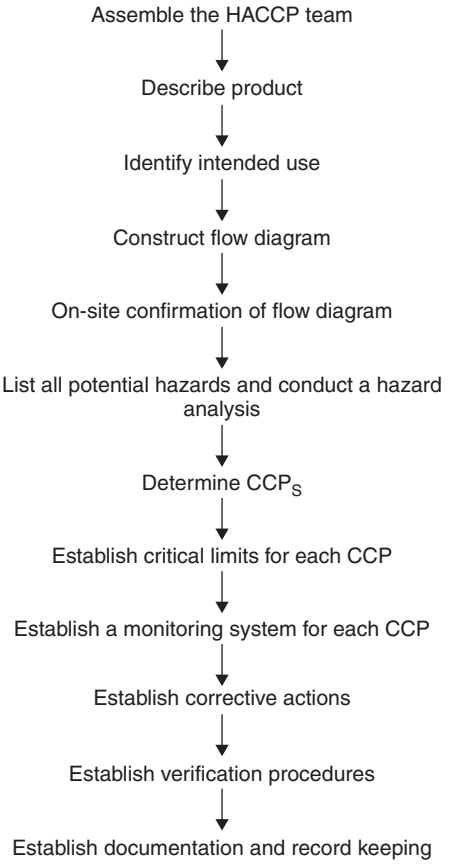

FIGURE 1 Developing a HACCP plan. (From WHO, 1997.)

important step in HACCP planning. Extensive training for line workers is critical, as they are the people responsible for the entire process. Everyone in the processing facility should receive and review the plan, procedures, and policies.

HACCP VALIDATION

Throughout the use of a HACCP system, various confirmation activities are required to validate that the system is effective. These activities need to take place at all stages of the HACCP system. For example, confirmation is needed that critical limits are appropriate and that identified hazards are reduced to acceptable levels, or eliminated. A validation program should include review of hazard analysis, determination of CCPs and justification of critical limits, as well as the determination of adequacy of monitoring activities, corrective actions, record keeping, and verification procedures. Since validation deals with product formulation, processes, storage conditions, preparation, and use, it should be performed before the results of the HACCP study are approved and implemented. Therefore, validation requires professional skills to determine the procedures are correct.

PREREQUISITES OF A HACCP SYSTEM

Prerequisites are the practices and conditions needed prior to and during the implementation of HACCP. Application of HACCP alone to ensure product safety is not enough; a support network is essential to ensure food safety management. Prerequisite programs provide the basic environmental and operating conditions that are necessary for the production of safe food and are important for a HACCP plan to function effectively. Prerequisite programs are normally established as part of a HACCP system. The prerequisite programs include current good manufacturing practices (cGMPs), premises, personnel and training, statistical process control, and incident management. Such programs help in reducing the potential hazards in the operation system. The effectiveness of prerequisite programs should be assessed during the design and implementation of each HACCP plan. All prerequisite programs should be documented and regularly audited.

IMPLEMENTATION OF A HACCP SYSTEM

A properly implemented HACCP system will provide benefits to consumers, industry, and governments. Progress in its implementation varies from facility to facility and often depends on the size of the facility. It also depends on the commitment and recognition of management as well as the availability of funds. In some geographical locations, lack of expertise and resources for training are two major weaknesses to progress in its implementation. Both progress and problems encountered in implementation of the HACCP system must be monitored,

and guidance on this subject should be provided. Before implementation, there should be enough time to allow opportunities for training people to be involved in both private and government sectors. The evaluation of the premises is the first step for the implementation of HACCP in a food-producing or food-processing plant. For chemical and biological hazards, a GMP certificate should accompany all products and raw material entering the plant. For physical hazards beyond the GMP certificate, a visual inspection of the entrance, metal detectors, magnets, and filters (depending on the substance) may be of great help.

It is expected that in the initial stages, implementation of a HACCP system would require enormous resources in terms of qualified personnel, technical support facilities, and financial inputs, particularly to ensure the necessary training. It is important to recognize that employees must understand what HACCP is and then learn the skills necessary to make it function properly. Training in HACCP for food inspectors and personnel in food businesses will be a key prerequisite to its successful implementation.

MAINTAINING A HACCP SYSTEM

A HACCP system is an effective tool for food safety assurance. Its use in the prevention of foodborne diseases is very valuable. Once a system is developed and implemented, continuous maintenance is important to ensure that the system remains effective. An assessment checklist is essential to maintain an effective HACCP system. A checklist is an assessment tool for the entire application, including prerequisites, design, implementation, and maintenance of the plan. The checklist includes questions regarding generic or specific and detailed aspects to be covered during the audit. An audit is a systematic and independent examination to determine whether activities comply with the documented procedures. The list also helps to maintain focus and objectivity, helps to ensure completeness of assessment, and acts as a record of assessment.

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HACCP IN POULTRY SLAUGHTERHOUSES

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PRINCIPLES OF HACCP

A hazard analysis and critical control point (HACCP) system is a logical science-based system designed to assure the safety of food. The idea was developed in the 1960s in the United States to assure the safety of foods used on manned space flights. It was recognized at that time that it was not possible to ensure that any food was safe by end-product testing alone. The HACCP system was conceived to identify potential food safety hazards and to establish controls which ensure that these hazards have been eliminated or reduced to an acceptable level.

Handbook of Poultry Science and Technology, *Volume 1: Primary Processing*, Edited by Isabel Guerrero-Legarreta and Y.H. Hui

Definitions

Definitions and principles of HACCP as given in the CAC standard CAC-RPC (CAC, 1969) and in ISO standard 22000 (ISO, 2005) are paraphrased below.

- *HACCP:* a system that identifies specific hazards and preventive measures for their control.
- *Hazard:* a biological, chemical, or physical agent or condition of food with the potential to cause an adverse health effect.
- *Critical limit:* a value that separates acceptability from unacceptability.
- *Critical control point (CCP):* a point, step, or procedure at which control can be exerted and a food safety hazard can be prevented, eliminated, or reduced to an acceptable level.
- *Corrective action:* action to be taken when the results of monitoring a CCP indicate a loss of control.
- *Monitor:* to conduct a planned sequence of observations or measurements to assess whether a CCP is under control.
- *Verify:* to confirm the integrity of the monitoring process.
- *Validate:* to obtain evidence that a HACCP plan is effective.
- *Seven principles*. The HACCP system identifies specific hazards and preventive measures for their control according to seven steps.

The Role of GMPs and Prerequisite Programs

It must be emphasized that the implementation of HACCP-based food safety assurance systems must be based on the solid foundations of good manufacturing practices (GMPs), good hygiene practices (GHPs), and sanitation standard operating procedures (SSOPs). The common name for all these practices and procedures is *prerequisite program* (PRP). Without these prerequisites, HACCP is doomed to failure. In fact, any attempt to implement HACCP without effective prerequisite programs will only redirect valuable scarce resources. Certain PRPs can be selected as operational PRPs (oPRPs) according to ISO (2005), and their role as a risk management tool can be as important as are the CCPs.

PRACTICAL TASKS IN A HACCP PROGRAM

A. Establish a HACCP team and make sure that it has resources.
B. Describe the products and their use.
C. Draw flow diagrams of the product or group of products.
D. Confirm the accuracy of the flow diagrams.
E. Audit the prerequisite programs.
F. Conduct the program according to the seven principles of HACCP:

1. Identify the potential hazards associated with food production at all stages, from growth, processing, manufacture, and distribution up to the point of consumption. Assess the likelihood of occurrence of these hazards and identify the preventive measures for their control.
2. Determine the points, procedures, and operational steps that can be implemented to control and/or eliminate the hazard or to minimize its likelihood of occurrence. A step is any stage in food production and/or manufacture, including raw materials, their receipt and/or production, harvesting, transport, formulation, processing, storage, and so on.
3. Establish critical limits that must be met to ensure that the CCPs are under control.
4. Establish a system to monitor control of the CCPs by scheduled testing or observation.
5. Establish the corrective action to be taken when monitoring indicates that a particular CCP is not under control.
6. Establish procedures for verification which include supplementary tests and procedures to confirm that the HACCP system is working effectively.
7. Establish documentation concerning all appropriate procedures and records.

G. Validate the HACCP and prerequisite program as a wholesome food safety management system.

PRACTICAL TASKS IN A HACCP PROGRAM IN A POULTRY SLAUGHTERHOUSE

A. *Establish a HACCP team and ensure that it has resources*. In addition to time and money, the HACCP team needs knowledge on hazards, HACCP systems, quality control, preventive measures at primary production, the process (plant engineering), and sanitation. When a company does not have the required expertise, external advisors or consultants should be brought into the team.

B. *Describe the products and their use*. Since the shelf life and labeling of the product can be related to the management of hazards, the description part should be carried out in as much detail as possible. An example is given in Table 1.

C. *Draw flow diagrams of the product or group of products*. An example is given in Figure 1.

D. *Confirm the accuracy of the flow diagrams*. There is a lot of commonality between poultry-slaughtering businesses, and flow diagrams can be found through Web sites (University of Wisconsin, 2007; FMRI, 2008); however, the slaughtering lines are always unique. Use of a flow diagram published

TABLE 1 Table Description of Poultry Meat Product Groups

Product Group	Packaging	Users	Shelf Life and Intended Use	Transportation	Potential Abuse: Preventive Measures
Carcasses	Vacuum/MAP[a]	Retail consumers	10 days; to be cooked	Cold, 2–4°C	Undercooking: cooking instructions
Parts of carcasses	Vacuum/MAP	Retail consumers	10 days; to be cooked	Cold, 2–4°C	Undercooking: cooking instructions Cross-contamination: parts are ready for the oven; no need to cut or handle
Frozen carcasses	Packaged	Retail consumers	4 months as frozen; to be cooked	Frozen	Undercooking: cooking instructions Cross-contamination: frozen carcasses are labeled "unfreeze hygienic in separate container"
Carcasses and parts	Bulk, covered	Own use	Further process	Immediate transfer	
Giblets	Covered in boxes	Own use	Further process	Immediate transfer	
Mechanically deboned meat	Covered in boxes	Own use	3 months as frozen	Immediate transfer to frozen department	

[a]MAP, modified-atmosphere packaging.

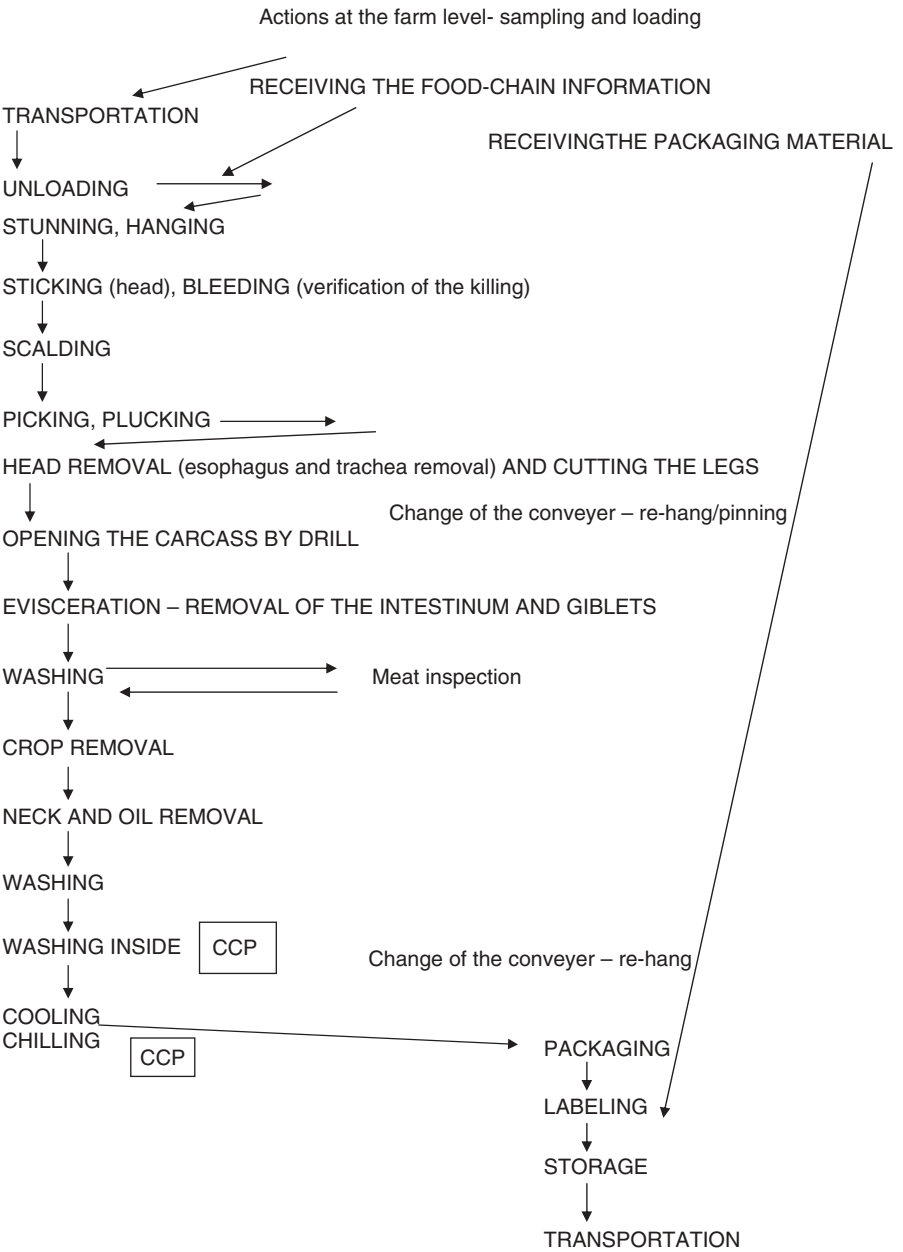

FIGURE 1 Flow diagram of poultry processing.

in a general guide without confirming its accuracy can mislead. The flow diagram used should include all the steps and be accurate in every way.

E. *Audit the prerequisite programs*. The most important PRPs for poultry production are:
   1. *Checks on food-chain information*. Food-chain information on the *Salmonella* status and general health conditions of the birds and information on feed and veterinary drugs given to the birds are essential to carry out hazard analysis. Audits undertaken to check that all the needed information is available at slaughterhouses are important.
   2. *Design and maintenance of premises and equipment*. The slaughter of poultry is a highly automated process. Processing, especially, hygienic processing, is not possible without hygienic design and continuous maintenance of the premises and equipment.
   3. *Preoperational, operational, and postoperational hygiene*.
      - Preoperational hygiene programs involve control at receiving for both the birds and the packaging material. The requirement of certification for packaging material as to its suitability for use in contact with food, and the control of cleaning of equipment, are also preoperational hygiene programs.
      - Operational hygiene programs involve a description of working methods and processes.
      - Postoperational hygiene programs involve cleaning and sanitizing, including the cleaning of crates used for transportation and of the waste and sewage disposal facilities.
   4. *Personal hygiene*
      - The medical examination of workers is carried out to prevent the transmission of pathogens by workers.
      - Guidelines on handwashing procedures, clothing, and covering cuts and wounds are given to workers.
      - Certain unhygienic behavior (e.g., smoking and eating in the production area) is forbidden.
   5. *Training in hygiene and work procedures*. All workers, including maintenance personnel, have regular general hygiene education and are informed on all PRPs that affect their work. Workers who have duties related to oPRPs or CCPs are informed on their special responsibilities and on the meaning of their work as a risk management tool.
   6. *Pest control*. Preventive measures to avoid creating an environment conducive to pests, monitoring of the possible existence of pests, and active eradication methods against pests are needed.
   7. *Water quality*. Since large amounts of water are used in poultry processing, the quality of the water is controlled.

8. *Temperature control*. Maintenance of the cold chain after chilling is the basic prerequisite program used to control the growth of pathogens on poultry meat.

F. *Conduct the HACCP program according to the seven principles of HACCP*

1. *Conduct a hazard analysis on poultry products and process steps*. According to the HACCP principles, every establishment undertakes its own hazard analysis, based on data and knowledge on the prevalence of hazards recorded by the establishment and on recalls and complaints related to its products. Existing common knowledge such as that of Lindblad et al. (2006b) on the prevalence of hazards in poultry can also be used.

   Since the production of poultry is highly integrated, a lot of attention is paid to preventive measures existing in the entire production chain. Information on preventive measures acquired at the farm level and food-chain information from farms have an effect on the assessment of the likelihood of hazards, especially *salmonella*. Hazards are listed and the likelihood of their occurrence and the severity of health effects is assessed. The results of the assessment of hazards related to raw material (birds and packaging material) can be obtained in several ways. An example is given in Table 2. According to FFDIFF (2006), the likelihood of a hazard is considered likely when the frequency of the hazard is more than 5%.

   Hazards related to processes and the working environment can be listed as hazards related to raw material, as in Table 2, or can be assessed step by step as is done in Table 3. There are also data programs such as Hygram 2.0 (Tuominen et al., 2003) which can be used in assessing hazards. Working environment–related hazards can be general and relevant in all steps, or their occurrence can be more likely in certain steps. Examples of these working environment hazards are:

   - Missing food-chain information data
   - Residues from disinfecting equipment
   - Broken conveyor
   - Delays between process steps and disturbances of the optimal line speed
   - Overloading the chilling capacity

   The adverse health effects of hazards related to the working environment are mostly indirect (e.g., if a conveyer gets broken, biological hazards may multiply or a foreign object hazard may occur).

   A common method of hazard analysis is to describe the process steps according to the flow diagram (Table 3) and assess the hazards step by step (University of Wisconsin, 2007; FMRI, 2008). In every process step the severity and likelihood of the hazard is assessed and the basis for this assessment decision is given. If there are any preventive measures, they are listed. Some hazards related to raw material can increase

TABLE 2 Likelihood and Severity of Hazards Related to the Raw Material

	Severity of the Hazard		
Likelihood of a Hazard	Mildly Severe	Severe	Very Severe
Likely	Moderate *Clostridium perfringens*	Serious *Campylobacter* *Listeria*	Intolerable
Possible	Immoderate *Bacillus cereus* Foreign object such as a needle or something the birds have eaten Foreign object derived from the packaging material Parasites Residues from veterinary drugs	Moderate *Salmonella* *S. aureus*[a] *Yersinia*	Serious *Clostridium botulinum*[a]
Unlikely	Unimportant Viruses Chemical residues derived from the packaging material	Immoderate Chemicals Dioxin Residues Biogenic amines Heavy metals Radioactivity	Moderate

[a]The most important hazards related to incoming raw material (birds) are pathogenic bacteria such as *Salmonella*, *Campylobacter*, and *Listeria*. The prevalence of *S. aureus* is high (Lindblad and Lindqvist, 2003); however, a high number of bacteria is not likely, which is why the likelihood is assessed as only possible. There are few data on the frequency of *C. botulinum*, and the likelihood is assessed to be possible.

or decrease in different process steps. The number of *Campylobacter* decreases after scalding and increases after defeathering and evisceration. The chilling method can affect the number of *Campylobacter*. Water chilling increases their number, whereas air chilling decreases their number (Lindblad et al., 2006a).

2. *Determine the CCPs*. There are some essential questions to bear in mind when determining CCPs:
   - Is the hazard eliminated at this step, or is the likelihood of the hazard minimized at this step?
   - Will the characteristics of the product change so that the hazard is eliminated or reduced to an acceptable level or so that an increased hazard is eliminated?

TABLE 3 Likelihood and Severity of Hazards Related to the Process and the Working Environment

Process Step	Hazards	Is the Hazard Severe and Likely?	Basis for the Decision	Management and Preventive Measures	Is the Step CCP?
Receiving the food-chain information	Missing data related to biological or chemical hazards	Yes	There are *Salmonella*- and *Campylobacter*-infected farms.	The information must be checked.	No, it is oPRP
Receiving the packaging material	Biological: microbiological contamination	No	Inspection of the material.		
	Chemical: non-food-grade materials	No	Certification of suitability to be used in contact with food. Known supplier.		
	Physical: none				
Transportation of living birds	Biological: pathogens	Yes	Crates can be the source of pathogens.	The crates are sanitized.	No
	Chemical: none				
Unloading	Biological: pathogens	Yes	Living birds can be infected.	Contamination of the meat is prevented in later steps by the slaughtering technique and decreased later by chilling.	No
	Chemical: residues from veterinary drugs	No	Unlikely according to surveillance.		

(*continued overleaf*)

TABLE 3 (*Continued*)

Process Step	Hazards	Is the Hazard Severe and Likely?	Basis for the Decision	Management and Preventive Measures	Is the Step CCP?
	Physical: foreign object such as a needle	No	Unlikely, not found in four years.		
	Foreign object the bird may have eaten	Yes	Recently found.	The crop is opened carefully.	No
Stunning	Biological, chemical, physical: none				
Sticking	Biological: pathogens	Yes	Skin and feathers are possible sources of contamination.	Contamination of the meat is prevented by the slaughtering technique.	No
Bleeding	Chemical, physical: none				
Scalding	Biological: pathogens	Yes	Cross-contamination is likely.	Contamination of the meat is decreased later by rapid chilling.	No
	Chemical, physical: none				
Picking	Biological: pathogens	No	Cross-contamination is not significant.		
Plucking	Chemical, physical: none				
Head removal	Biological: pathogens	No	Cross-contamination is not significant.		
	Chemical, physical: none				
Opening the carcass	Biological: pathogens	Yes	Skin and intestines are sources of pathogens.	Contamination of the meat is prevented by the slaughtering technique.	No
	Chemical, physical: none				

Evisceration	Biological: pathogens	Yes	Intestines are the source of pathogens. The equipment can be the source of cross-contamination.	Contamination of the meat is prevented by the slaughtering technique. Sanitation of the equipment.	No
	Chemical, physical: none				
Washing	Biological: pathogens	Yes	Cross-contamination is very likely, especially if hoses are not directed properly.	The direction of the water hoses is checked.	No
	Chemical, physical: none				
Crop removal	Biological: pathogens	Yes	Possible source of pathogens.	Contamination is prevented by the slaughtering technique.	No
	Chemical: none				
	Physical: foreign objects	Yes	Foreign objects have been found.	The crop is opened carefully.	
Neck and oil removal	Biological: pathogens	Yes	Contamination of the meat is possible.	Contamination is prevented by the slaughtering technique.	No
	Chemical, physical: none				
Washing	Biological: pathogens	Yes	Cross-contamination is very likely, especially if the hoses are not directed properly.	The direction of the hoses is checked and unclean carcasses are removed.	Yes
	Chemical, physical: none				
Cooling, chilling	Biological: pathogens	Yes	Possible growth of the pathogens.	Chilling is rapid and a time limit is set.	Yes
	Chemical, physical: none				

(*continued overleaf*)

TABLE 3 (*Continued*)

Process Step	Hazards	Is the Hazard Severe and Likely?	Basis for the Decision	Management and Preventive Measures	Is the Step CCP?
Packaging	Biological: pathogens Growth of pathogens Chemical, physical: none	Yes	Possible growth of the pathogens.	Packaging should be rapid.	
Labeling	Biological: growth of microbes because of the wrong shelf-life Chemical, physical: none	Yes	Reclamation.	The dates are checked.[a]	No
Storage	Biological: pathogens Chemical, physical: none				
Transportation	Biological: pathogens Chemical, physical: none	Yes	Growth of the microbes.	The temperature is controlled during transport.	

[a]In addition to this, the safe-handling instructions described in Table 1 are given.

- Is there something to measure and monitor related to eliminating or minimizing the likelihood of hazard?
- Are there corrective actions to be taken?
- Is there something to verify?

3. *Establish critical limits*.
4. *Establish a monitoring system*.
5. *Establish corrective actions*.
6. *Establish verification*. The results of HACCP steps 3 to 6 are summarized in Tables 4 to 6. The critical points, CCPs and oPRPs, are listed in Table 4. The CCPs chosen are the washing and chilling of carcasses, and the oPRP chosen is the receiving of food-chain information. These CCPs and opRPs are given as an example. There is no ultimate truth as to which steps of the process should be chosen as CCPs or oPRPs. Various solutions are possible in different lines and production systems.

   When washing is the CCP, monitoring is the control of cleanliness of carcasses, and this monitoring is carried out for 5 min every hour (Table 5). The unclean carcasses are removed and the critical limit is the number of unclean carcasses. If the percentage of unclean carcasses is

TABLE 4 Critical Points in Poultry Slaughtering

Critical Points	Monitoring	Verification
Critical control points		
Control of cleanliness of carcasses	Checking the cleanliness	Reviewing the cleanliness monitoring data and observing the monitoring
Chilling	Checking the temperature	Reviewing the temperature monitoring data and observing the monitoring
Operational prerequisite programs		
Receiving food-chain information		

TABLE 5 Monitoring Cleanliness of Carcasses

	Monitoring			
Critical Limit	What	How	Frequency	Who
Number of unclean carcasses less than 5%[a]	After washing carcasses and before chilling	Visual control of 5 min	Every hour during slaughtering	Worker on the line

[a]The establishment must set the critical limit and/or an alarm limit.

TABLE 6 Monitoring the Chilling

	Monitoring			
Critical Limit	What	How	Frequency	Who
Temperature of carcasses below 4°C 3 h after start of chilling	At chilling department 2 h after start of chilling	Measuring the inside temperature of the carcass	Every batch controlled	Worker on the line

higher than the limit chosen, all the carcasses that had been slaughtered after previous monitoring should be checked and monitored. The number of slaughtered carcasses is usually very high, and especially when water chilling is used, monitoring carcasses during chilling is impossible (Lepistö, 2006). The common procedure is to set an alarm limit (e.g., 5% in Table 5) and check the process if there is an overdraft of this limit. Checking the process means checking the direction of water hoses and checking that the plucking and evisceration equipment is in working order.

When chilling is the CCP, monitoring is the temperature control (Table 6). The critical limit is for the temperature to be below 4°C 3 h after the start of chilling. To avoid nonconformity of the actual critical limit, the temperature monitoring is done 2 h after the start of chilling. Receiving the food-chain information as the operational prerequisite program (Table 7) means that there are instructions as to how the information is checked, and this checking, as well as possible nonconformity and corrective actions, are recorded.

7. *Establish documentation*. The HACCP plan and the records must both be documented. If the assessment of likelihood and severity of hazards is based on general information given in guides and books, this knowledge must be reviewed briefly through documentation. All the monitoring and verification data of CCPs and oPRSs must be saved. Especially important are the data concerning nonconformity and corrective actions (Table 8). All records and documents concerned with monitoring CCPs and corrective actions must be signed or initialed and

TABLE 7 Operational Prerequisite Program in Poultry Slaughtering

oPRP	Guide Instruction	Verification
Receiving the food-chain information	Check the information.	Recording of checking, possible nonconformity, and possible corrective actions

TABLE 8 Corrective Actions and Verification Related to Critical Control Points

Critical Control Point	Corrective Actions	Verification
Cleanliness of carcasses	All unclean carcasses are removed; if their number is higher than 5%[a], the process is checked.	Cleanliness monitoring records are reviewed every week. Cleanliness monitoring is observed once a month.
Chilling	The efficiency of the chilling is increased and the temperature is measured again after an hour to control the nonconformity of critical limits.	Temperature monitoring records are reviewed every week. Measuring temperature is observed once a month.

[a]5% is an alarm limit.

dated by the person doing the monitoring and by the person responsible for the corrective action.

G. *Validate the HACCP and prerequisite program as a wholesome food safety management system*. The CCPs and oPRPs chosen are validated continuously. The CCPs are validated against microbiological test results on bacterial counts on carcasses. This validation is done every week or every other week. The oPRP food-chain information is validated against results on pathogen and residue analyses done by the establishment or by authorities. This validation is done monthly. The HACCP and prerequisite programs must be reviewed after a product fails to meet performance standards and following changes in the production process, to the intended use of the product, and in distribution arrangements.

In addition, the HACCP plan itself and the operation of the plan must be validated in depth at predetermined intervals (e.g., annually or every second or third year). This review should take into consideration:

- Technical changes
- New and emerging pathogens and other hazards
- New knowledge on identified hazards
- New or modified products
- Changes in the production process
- Changes in product distribution arrangements
- Changes in the intended use of the product

Validation of a HACCP plan for poultry meat should ensure that it is effective in meeting a performance objective (PO) or performance criteria (PC), taking into account the degree of variability in the presence of hazards normally associated with different lots of animals presented for processing (CAC, 2005). If a general or national risk assessment is carried out for a certain hazard, this risk assessment can be used in setting the POs

and planing the validation. An example of this type of risk assessment is the work of Aarnisalo et al. (2008), where the marinated broiler legs were found not to be a significant *L. monocytogenes* risk. Although *Listeria* is considered a likely and severe hazard (Table 2) related to poultry, it is not a significant risk at the point of consumption; and there is no need to validate the HACCP plan for raw poultry products against *Listeria* as there is a need for this validation against *Campylobacter*.

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ONLINE INSPECTION

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INTRODUCTION

Today, more poultry is produced in the United States than in any other country in the world. Combined broiler, egg, turkey, and other poultry production accounts for more than $20 billion in on-farm revenues (USDA–ERS, 2007). In recent years, broiler production has increased dramatically to meet rising market demand. Domestic per capita consumption of broilers increased from 59.5 lb in 1990 to 76.9 lb in 2000, and reached 87 lb in 2006. U.S. poultry slaughtering plants now process over 8.8 billion broilers annually (USDA–NASS, 2007). The 1957 Poultry Product Inspection Act mandated postmortem inspection of every bird carcass processed by a commercial facility. Since then, U.S. Department of

Handbook of Poultry Science and Technology, *Volume 1: Primary Processing*, Edited by Isabel Guerrero-Legarreta and Y.H. Hui

Agriculture (USDA) inspectors have conducted on-site organoleptic inspection of all chickens processed at U.S. poultry plants for indications of disease or defect. Inspectors of the USDA Food Safety and Inspection Service (FSIS) examine, by sight and by touch, the body, the inner body cavity surfaces, and the internal organs of every chicken carcass during processing operations.

With the 1996 final rule on pathogen reduction and hazard analysis and critical control point (HACCP) systems (USDA–FSIS, 1996), FSIS implemented the HACCP and pathogen reduction programs in meat- and poultry-processing plants throughout the country to prevent food safety hazards, to set specific food safety performance standards, and to establish testing programs to ensure that performance standards are met through the use of science-based process control systems. More recently, FSIS has also been testing a HACCP-based inspection models project (HIMP) in a small number of volunteer plants (USDA–FSIS, 1997). HIMP requirements include zero tolerance for unwholesome chickens exhibiting symptoms of "septox," a condition of either septicemia or toxemia. Unwholesome birds must be removed from the processing line. Wholesome chickens do not exhibit symptoms of septox.

Septicemia is caused by the presence of pathogenic microorganisms or their toxins in the bloodstream, and *toxemia* results from toxins produced by cells at a localized infection or from the growth of microorganisms. Septox birds are considered to be unwholesome. USDA inspectors remove these birds from processing lines during their bird-by-bird inspections, which can, by law, be conducted at a maximum speed of 35 birds per minute (bpm) for an individual inspector. The inspection process is subject to human variability, and the inspection speed restricts the maximum possible output for processing plants while making inspectors prone to fatigue and repetitive injury problems. This limit on production throughput, combined with increases in chicken consumption and demand over the past two decades, places additional pressure on both chicken production and the safety inspection system.

Most poultry-processing plants in the United States currently use one of two evisceration configurations: either a streamline inspection system (SIS) or a new efficient line speed (NELS) system. Under SIS, an evisceration line operates at 70 shackles per minute and includes two USDA inspection stations. A NELS evisceration line runs at 91 shackles per minute with three USDA inspection stations. At each inspection station, the USDA inspector works with the aid of a helper and a trimmer. Figure 1 shows the typical layout of a poultry slaughter system with one kill line feeding two evisceration lines. On the kill line, birds are stunned, bled, scalded, defeathered, and heads and paws are removed before they are re-hung onto the evisceration line.

Developing an automated inspection system for operation on the kill line presents two major benefits. First, with a single rejection point on the kill line, no condemnable birds would enter the evisceration line. This helps to reduce the risks of cross-contamination between carcasses and reduces the number of empty shackles on the evisceration line, which normally occurs from removal of unwholesome birds just prior to the final washing stages. Second, working with

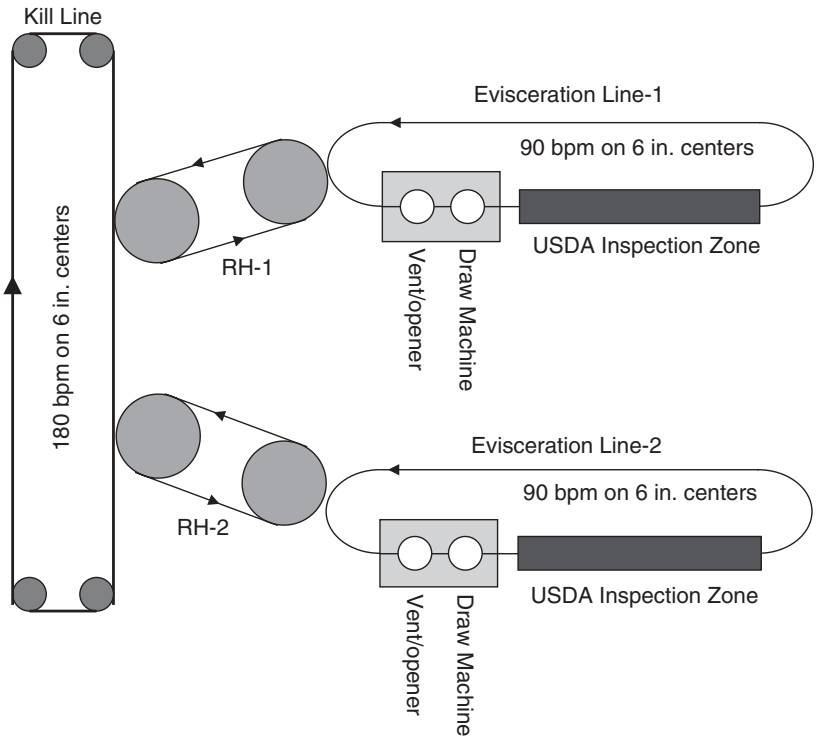

FIGURE 1 Poultry processing line layout. RH, re-hanger; bpm, birds per minute.

known technology to remove rejected birds from the kill line, such a system would be easily integrated into product-tracking systems. To operate on the kill line, any automated inspection system must be able to function at the high speeds of the kill line, currently 140 or 180 bpm.

For the past decade, machine vision technologies have been under development to address a variety of food- and agricultural-processing applications. Various sensing techniques, such as RGB (red/green/blue) color imaging (Daley et al., 1994), visible and near-infrared (Vis/NIR) spectroscopy and imaging (Delwiche, 2003; Windham et al., 2003; Lu, 2007), fluorescence spectroscopy and imaging (Kim et al., 2003), and x-ray imaging (Chen and Tao, 2001), have been investigated for potential use in food-processing and online inspection applications.

Since 1998, the Agricultural Research Service of the USDA has been conducting research to develop automated poultry inspection systems that can operate online in real time (at least 140 bpm) in the slaughter plant environment. The current spectral imaging system was developed based on research for spectroscopy methods and spectral-imaging techniques for differentiating wholesome and unwholesome chicken carcasses and viscera, including laboratory and

in-plant testing of methods and equipment. Color imaging inspection of chicken viscera demonstrated successful detection and classification of a variety of unwholesome bird conditions using RGB spectral data (Chao et al., 1999). Laboratory research also developed Vis/NIR spectroscopy techniques to analyze spectral characteristics associated with various conditions of chicken carcasses. Results demonstrated that Vis/NIR techniques could effectively identify systemically diseased chicken carcasses (Chao et al., 2003). Laboratory techniques for spectral measurement and analysis were further developed for automated machine vision applications for chicken-processing lines, first using spectroscopy systems and then using faster spectral imaging systems. The spectroscopy-based techniques were tested online successfully for a commercial kill line operating at 140 bpm (Chao et al., 2004). Implementation of spectral methods for high-speed image-based inspection was tested successfully on both a commercial 70-bpm evisceration line and commercial 140- and 180-bpm kill lines. Dynamic thresholding for the decision-making process was developed and was found capable of identifying near 100% of systemically diseased birds (Chao et al., 2007). Using this method of dynamic thresholding, the spectral imaging system inspected over 100,000 chickens on a commercial 140-bpm kill line during continuous operation and achieved over 99% accuracy in identifying wholesome chickens and over 98% accuracy in identifying systemically diseased chickens. These methods were incorporated into the automated line-scan imaging system that was ultimately developed for online chicken carcass inspection that is described below.

MATERIALS AND METHODS

High-Throughput Spectral Imaging Inspection System

The spectral imaging system (Figure 2) consists of an electron-multiplying charge-coupled-device (EMCCD) camera, an imaging spectrograph, a C-mount lens, and a pair of high-powered broad-spectrum white light-emitting-diode (LED) line lights. The EMCCD camera (PhotonMAX 512b, Roper Scientific, Inc., Trenton, New Jersey) has approximately 512×512 pixels and is thermo-electrically cooled to approximately -70°C (via a three-stage Peltier device). An imaging spectrograph (ImSpector V10E, Specim/Spectral Imaging Ltd., Oulu, Finland) and a C-mount lens (Rainbow CCTV S6x11, International Space Optics, S.A., Irvine, California) are attached to the EMCCD imaging device. The spectrograph aperture slit of approximately 50 μm limits the instantaneous field of view (IFOV) of the imaging system to a thin line. Light from the linear IFOV is dispersed by a prism-grating/prism line-scan spectrograph and projected onto the EMCCD imaging device. The spectrograph creates a two-dimensional (spatial and spectral) image for each line scan, with the spatial dimension along the horizontal axis and the spectral dimension along the vertical axis of the EMCCD imaging device. The imaging device is coupled with a 16-bit digitizer (CCI-23, Andor Technology Limited, Connecticut) with a pixel-readout

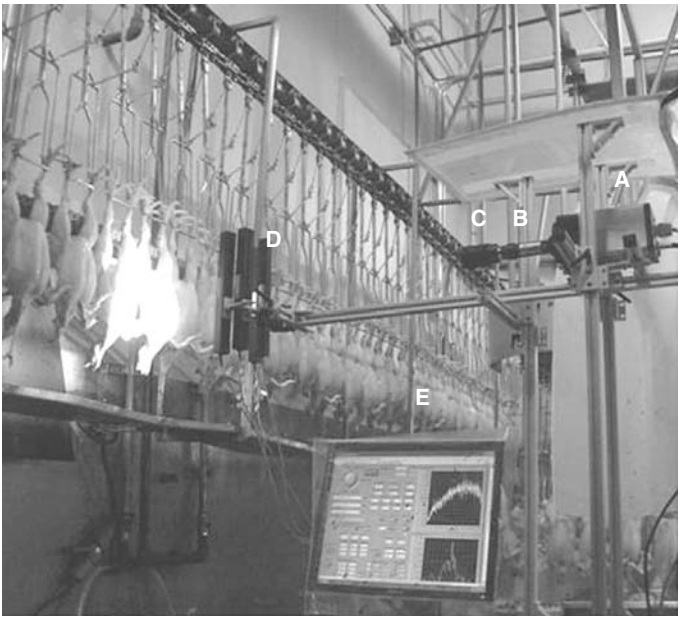

FIGURE 2 Hyperspectral/multispectral imaging inspection system on a commercial chicken-processing line. A, electron-multiplying charge-coupled-device (EMCCD) camera; B, line-scan spectrograph; C, lens assembly; D, LED lighting system; E, data-processing unit.

rate of approximately 10 MHz. The digitizer performs rapid analog-to-digital conversion of the image data for each hyperspectral or multispectral line-scan image. These data are then processed by the computer for image analysis and classification of wholesome and unwholesome pixels in the line-scan images.

The spectral imaging system requires calibration before line-scan images can be acquired. Recalibration is generally not required unless the physical arrangement of the components of the imaging system is disturbed. The first step in the calibration process was to cool the imaging system to its operating temperature of -70°C. The next step was to set image binning, which is determined by the spectral distribution of useful wavelengths and the size of spatial image features to be processed for the application. The original image size, 512×512 pixels, was reduced by 1×4 binning to result in line-scan images with a spatial resolution of 512 pixels (512 divided by 1) and a spectral resolution of 128 pixels (512 divided by 4) in the spectral dimension. The binning process adds together photons from adjacent pixels in the detector array and was performed by the shift register of the EMCCD imaging device. This produced a reduced number of pixels to be digitized by the 16-bit A/D PCI board for the computer to process. Reducing total pixel readout time decreased the acquisition time of each line-scan image, which allowed higher image acquisition

speed for the EMCCD imaging device. Because the useful spectrum of light did not span the entire width of the EMCCD detector, the first 20 and the last 53 spectral bands were discarded, resulting in a line-scan image size of 512×55 pixels.

The next step in the calibration process was spectral waveband calibration, which identified each spectral channel with a specific wavelength. A neon–mercury calibration lamp (Oriel Instruments, Stratford, Connecticut) was utilized for spectral calibration; the mercury peaks at 435.84 and 546.07 nm were found to correspond to the 8th and 25th bands, respectively, and neon peaks at 614.31, 640.23, 703.24, and 724.52 nm corresponded to the 35th, 39th, 49th, and 52nd bands, respectively. The following second-order polynomial regression was calculated from the reference wavelength peaks of the mercury and neon spectra to calibrate the spectral axis:

$$\lambda = 0.01n_c^2 + 6.03n_c + 393.70 \qquad (r^2 = 0.9999) \tag{1}$$

where λ is the wavelength in nanometers and n_c is the spectral channel number. The hyperspectral imaging data ranged from 399.94 nm (the first band) to 750.42 nm (the 55th band), with an average bandwidth of 6.02 nm. The distance between the lens and the IFOV target area was 914 mm, with the LED line lights illuminating the IFOV target area from a distance of 214 mm. The IFOV spanned 177.8 mm, which translated into 512 spatial pixels, with each pixel representing an area of 0.12 mm^2.

Following system calibration, the spectral imaging system was ready to use for the acquisition of reference line-scan images. Prior to acquiring hyperspectral chicken images, acquisition of a white reference image was performed using a 99% diffuse reflectance standard (Spectralon, LabSphere, Inc., North Sutton, New Hampshire) illuminated by the lighting system; acquisition of a dark reference image was performed by acquiring an image with the lens covered by a nonreflective opaque black fabric. These reference line-scan images were used to calculate the pixel-based relative reflectance for raw line-scan images as follows:

$$I = \frac{I_0 - D}{R - D} \tag{2}$$

where I is the relative reflectance, I_0 is the raw reflectance, D the dark reference, and R the white reference.

Procedures Following spectral and spatial calibration of the imaging system, hyperspectral line-scan images were acquired for 5549 wholesome chicken carcasses and 93 unwholesome chicken carcasses on a 140-bpm commercial processing line in March 2007. The wholesome or unwholesome condition of the birds on the line was identified by an FSIS veterinarian who observed the birds before they passed through the illuminated IFOV, where the imaging system

acquired 55-band hyperspectral data for the chicken carcasses. These hyperspectral images were analyzed for region of interest (ROI) optimization and selection of one key wavelength and two ratio wavebands based on average spectral differences between wholesome and unwholesome birds. Random track mode on the imaging system was implemented for multispectral inspection using only the key wavelength and ratio wavebands. LabView software (National Instruments Corp., Austin, Texas) was used to develop software modules for detecting the starting and ending points of each bird, and for implementing classification algorithms based on fuzzy logic. During two 8-h shifts in July 2007, the imaging system conducted multispectral inspection for over 100,000 birds at a commercial processing line. A FSIS veterinary medical officer identified bird conditions during several 30 to 40-min periods for verification of system performance.

Hyperspectral Image Analysis

Analysis of the hyperspectral relative reflectance images began with removal of the background. A relative reflectance threshold value of 0.1 was set for the 620-nm waveband. For any spatial pixel in the hyperspectral reflectance image, the pixel was identified as a background pixel if its reflectance at 620 nm was lower than the 0.1 threshold value. The value of the relative reflectance for every pixel identified as a background pixel was reassigned to be zero, thus removing these pixels from further image analysis.

Background-removed relative reflectance line-scan images were compiled to form hyperspectral image cubes of entire wholesome and unwholesome chicken carcasses. Using MATLAB software (MathWorks, Natick, Massachusetts), the hyperspectral chicken images were then analyzed to optimize the spatial ROI within the chicken images. The optimized ROI was one that provided the greatest spectral difference between averaged wholesome pixels and averaged unwholesome pixels across all 55 wavebands, which was obtained as follows. Within a bird image, the potential ROI area spanned from an upper border across the breast of the bird to a lower border at the lowest nonbackground spatial pixel in each line scan, or to the last (512th) spatial pixel if no background pixels were present at the lower edge of the image. The average relative reflectance spectrum was calculated across all ROI pixels for all wholesome chicken images, and the average relative reflectance spectrum was calculated across all ROI pixels for all unwholesome chicken images. The difference spectrum between the wholesome and unwholesome average spectra was calculated. This calculation was performed for potential ROIs of varying size, as defined by the number of ROI pixels and their vertical coordinate locations within each line scan, to optimize the ROI size and location by selecting the ROI that produced the greatest maximum value in its difference spectrum. Using the optimized ROI, the waveband corresponding to the greatest spectral difference between averaged wholesome chicken pixels and averaged unwholesome chicken pixels was identified as a key waveband for differentiation of wholesome and unwholesome chicken carcasses by relative reflectance intensity. Again using the optimized ROI, the average wholesome and

average unwholesome spectra were analyzed and potential two-waveband ratios were identified as several ratios using wavebands at which the average wholesome and average unwholesome chicken pixel spectra showed local maxima and local minima. The value of each potential band ratio was calculated for the average wholesome chicken pixels and for the average unwholesome chicken pixels. The two-waveband ratio showing the greatest difference in ratio value between average wholesome and average unwholesome chicken pixels was identified for use in differentiating wholesome and unwholesome chicken carcasses. Multispectral imaging inspection used the key wavelength and the two-waveband ratio to differentiate between wholesome and unwholesome chicken carcasses.

Multispectral Inspection of Chicken Carcass

Effective multispectral imaging inspection of wholesome and unwholesome chicken carcasses on a processing line required the capacity to detect individual bird carcasses, classifying the condition of the chicken carcass, and generating a corresponding output useful for process control, at speeds compatible with online processing-line operations. LabVIEW 8.0 (National Instruments Corp., Austin, Texas) was used to control the spectral imaging system to perform the tasks required for multispectral inspection of chicken carcasses on a poultry-processing line. The line-by-line mode of operation was the basis of the following algorithm, developed to detect the entry of a bird carcass into the IFOV.

Figure 3 shows the line-by-line algorithm for multispectral inspection to detect and classify wholesome and unwholesome chicken carcasses on a processing line. First, a line-scan image was acquired that contains only raw reflectance values at the two key wavebands needed for intensity and ratio differentiation, the raw reflectance data were converted into relative reflectance data, and background pixels were removed from the image (Figure 3, box 3.1). The line-scan image was checked for the presence of the starting point (SP) of a new bird (Figure 3, box 3.2); if no SP was present, no further analysis was performed for this line-scan image and a new line-scan image was acquired. If the line-scan was found to contain an SP, the ROI pixels were located (Figure 3, box 3.3) and the decision output (D_o) value was calculated for each pixel in the ROI of the line-scan image (Figure 3, box 3.4). With each new line-scan image acquired (Figure 3, box 3.5), the ROI pixels were located, and the decision output value of D_o was calculated for each pixel until the ending point (EP) was detected (Figure 3, box 3.6), indicating no additional line-scan images to be analyzed for the bird carcass. The average D_o value for the bird was calculated (Figure 3, box 3.9) and compared to the threshold value (Figure 3, box 3.10) for the final determination of wholesomeness or unwholesomeness for the bird carcass (Figure 3, boxes 3.11 and 3.12).

With the acquisition of each new line-scan image at the start of the detection algorithm (Figure 3, box 3.1), the relative reflectance at 620 nm was examined for each of the first (uppermost) 256 pixels of the line-scan image. The value

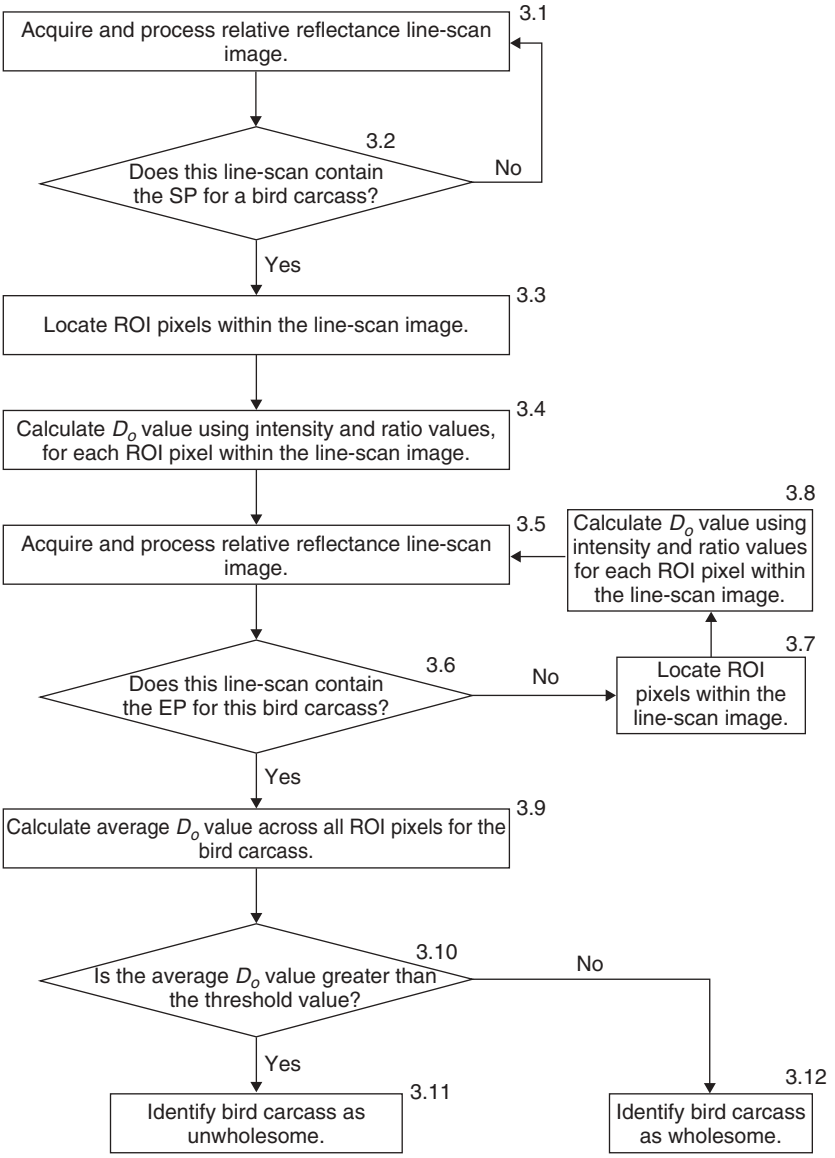

FIGURE 3 Method for online multispectral line-scan imaging inspection of chickens for wholesomeness.

of the relative reflectance at 620 nm was always at a low intensity (below 0.1) for these pixels when no chicken carcass was present in the IFOV. When the relative reflectance at 620 nm increased above 0.1 for any single pixel among the uppermost 256 pixels in the line-scan image, this indicated that a chicken carcass had entered the IFOV. This indication assumed that the inverted chicken

carcass was hung correctly from the processing line shackle by both legs and that the entry of the first leg into the IFOV was triggering the detection. The detection algorithm examined only the uppermost 256 pixels in order to disregard carcass wings, which were always overlapped between adjacent carcasses on the processing line. After detecting a line-scan image with a single pixel among the uppermost 256 exhibiting relative reflectance greater than 0.1 at 620 nm, subsequent line-scan images were monitored as additional pixels within the 256 pixels began showing relative reflectance values greater than 0.1 (Figure 2, box 2.2). Between the first pixel detected and the 256th pixel, pixels below the first pixel detected began increasing in relative reflectance as the chicken continues to move across the field of view. There would eventually be a line-scan image with one (or several) remaining low-intensity pixel located below the first pixel detected, and above or at the 256th pixel, which was followed immediately by another line scan in which the previous line scan's last low-intensity pixel(s) had increased above 0.1. The last low-intensity pixel, or the pixel in the center of the last contiguous group of remaining low-intensity pixels, was identified as the starting point of the bird carcass and represented the junction between the thigh and the abdomen on the leading edge of the carcass.

Similar to the algorithm above, the following algorithm was developed to detect the last relevant line-scan image for each bird as it passed through the IFOV (Figure 3, box 3.6). After the SP was detected, each subsequent line-scan image was analyzed to determine if the relative reflectance intensity at 620 nm for the pixel matching the vertical coordinate of the SP was above or below 0.1. When a line-scan image was acquired for which that pixel had a relative reflectance intensity at 620 nm that was below 0.1, this pixel was identified as the ending point of the bird carcass, indicating that the main body of the bird had already passed through the IFOV and no further line scans should be analyzed for that specific bird carcass.

After the initial identification of the SP for a bird carcass, the line-scan image containing the SP and subsequent line-scan images up to the one containing the EP were analyzed, line by line (Figure 3, boxes 3.3 to 3.8), using the following algorithm to classify the bird carcass. For each line-scan image, fuzzy logic membership functions were used to produce two decision outputs for each nonbackground pixel in the line-scan image that was located within the ROI, using the ROI and waveband parameters determined previously through hyperspectral imaging analysis. For each pixel, two fuzzy logic membership functions were used to generate wholesome and unwholesome fuzzy membership values w_1 and u_1, corresponding to wholesome and unwholesome chickens, from the key wavelength reflectance intensity value for that pixel. Two additional fuzzy logic membership functions were used to generate wholesome and unwholesome fuzzy membership values w_2 and u_2, corresponding to wholesome and unwholesome chickens, from the ratio value for that pixel. The fuzzy inference engine executed a min–max operation (Chao et al., 1999) to obtain a decision output (D_o) value for each pixel based on n membership functions as follows, where n

is the number of criteria input used (in this case, $n = 2$):

$$D_o = \max[\min\{w_1 \cdots w_n\}, \min\{u_1 \cdots u_n\}] \quad (3)$$

For each pixel, the value of D_o was between 0 and 1, where 0 indicates 100% possibility of wholesomeness and 1 indicates 100% possibility of unwholesomeness. When the EP for that bird carcass was encountered, the average D_o value for all ROI pixels for that bird was calculated (Figure 3, box 3.9). The bird carcass was identified as being unwholesome if the average D_o value was greater than 0.6; otherwise, the chicken carcass was identified as being wholesome (Figure 3, boxes 3.10 to 3.12).

RESULTS AND DISCUSSION

The hyperspectral images were analyzed to optimize the ROI size and location and the key wavebands for differentiation by reflectance intensity and by waveband ratio. Figure 4 shows a contour image of two examples of chicken carcasses with the SP and EP marked and connected by a line on each. The possible size and location of the ROI is described by parameters m and n, which extended below the SP–EP line. The values of m and n indicated, by percentage of the pixel length between the SP–EP line and the farthest nonbackground pixel below the SP–EP line, the location of the upper and lower ROI borders. The possible locations of the upper ROI border ranged between a 10% and a 40% distance below the SP–EP line, and the possible locations of the lower ROI border range between a 60% and a 90% distance below the SP–EP line.

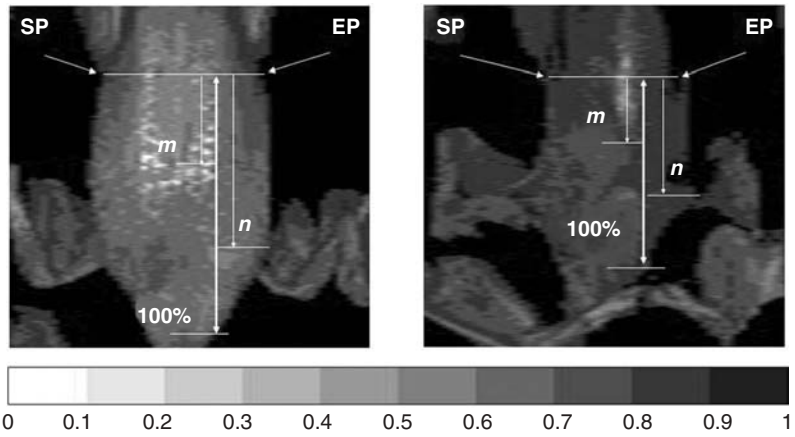

FIGURE 4 Contour images of two chicken carcasses marked with example locations of the SP, EP, m, and n parameters used for locating the region of interest.

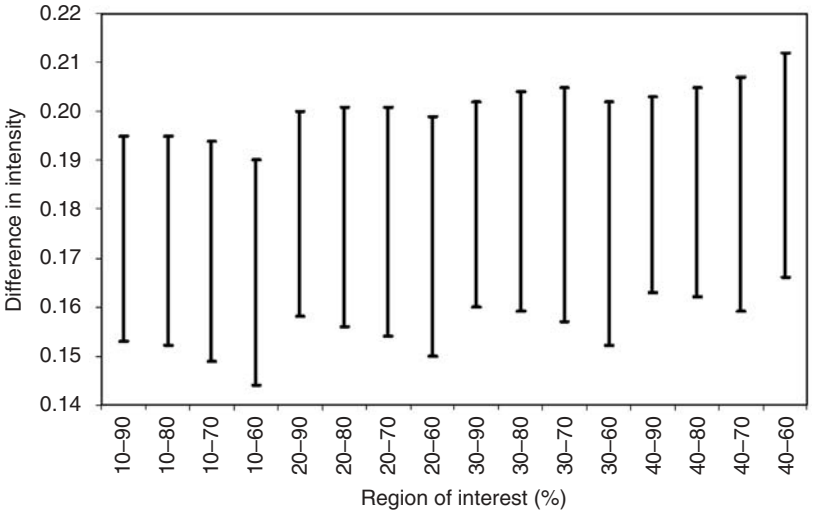

FIGURE 5 Range, for possible ROIs, of difference values between average wholesome and average unwholesome chicken spectra, for optimizing the ROI to be used for inspection of chickens.

For each possible ROI, the average spectrum across all ROI pixels from the 5549 wholesome chicken carcasses, and the average spectrum across all ROI pixels from the 93 unwholesome chicken carcasses, were calculated. The difference between the average wholesome and average unwholesome values at each of the 55 bands was calculated, and their range for each possible ROI is shown in Figure 5. Because the 40 to 60% ROI showed the range with the greatest difference values between the average wholesome and unwholesome spectra, this ROI was considered the optimized ROI to be used for multispectral inspection. As shown in Figure 6, the 30th band showed the greatest difference between the average wholesome and the average unwholesome spectra from among all 55 bands for the optimized ROI; this band, corresponding to 580 nm, was selected as the key waveband to be used for intensity-based differentiation of wholesome and unwholesome chicken carcasses.

Figure 7 shows the average wholesome and average unwholesome chicken spectra, marked with the wavebands that were investigated for differentiation of wholesome and unwholesome chicken carcasses by a two-waveband ratio. The average wholesome and average unwholesome ratio values were calculated for three possible two-waveband ratios, using wavebands at 440 and 460 nm, 500 and 540 nm, and 580 and 620 nm. The following differences were then calculated:

$$W_{440}/W_{460} - U_{440}/U_{460} = 0.003461$$

$$W_{500}/W_{540} - U_{500}/U_{540} = 0.038602$$

$$W_{580}/W_{620} - U_{580}/U_{620} = 0.115535$$

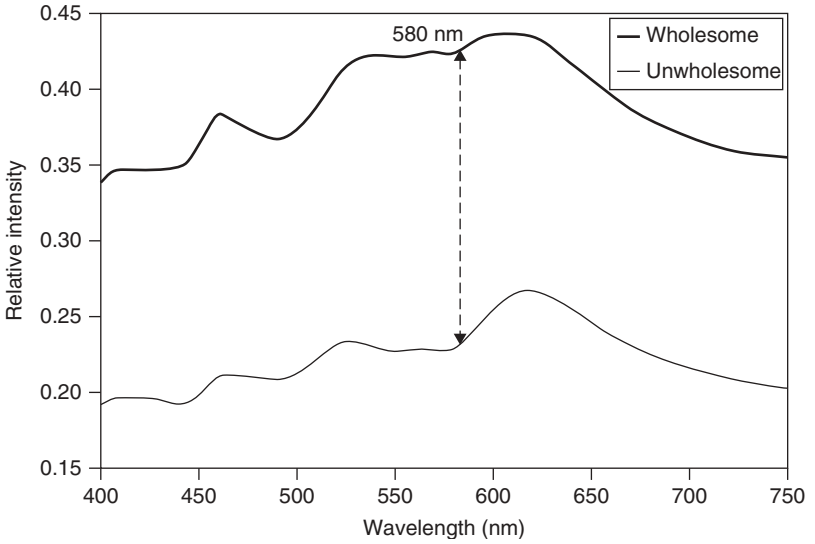

FIGURE 6 Averaged wholesome and unwholesome chicken spectra, highlighting the 580-nm key waveband that can be used for intensity-based differentiation of wholesome and unwholesome chickens.

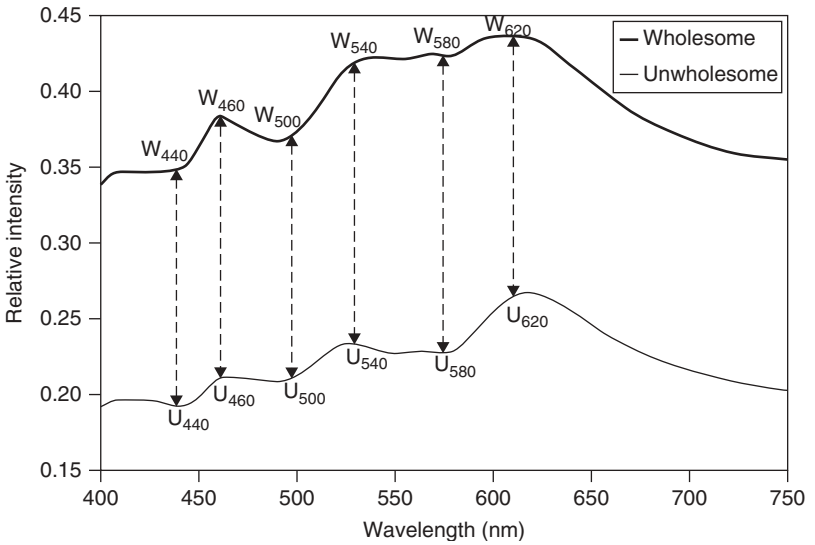

FIGURE 7 Averaged wholesome and unwholesome chicken spectra, for possible key wavebands that can be used for two-waveband ratio differentiation of wholesome and unwholesome chickens.

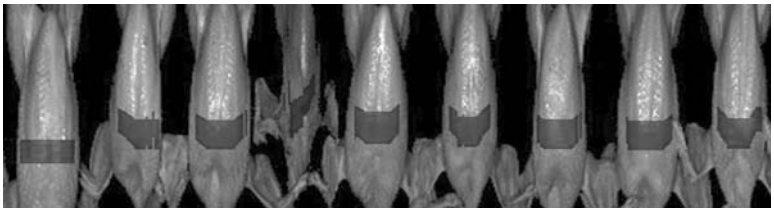

FIGURE 8 Nine chicken images with the optimized ROI highlighted on each chicken.

The last ratio, using the 580- and 620-nm wavebands, showed the greatest difference between the average wholesome and average unwholesome chicken spectra and was thus selected for use in differentiation by two-waveband ratio.

The optimized ROI and key wavebands determined from the hyperspectral data analysis were used for multispectral inspection of over 100,000 chickens on a 140-bpm processing line during two 8-h shifts at a commercial poultry plant. Figure 8 shows examples of chicken images highlighting the ROI that was used for online inspection. The inspection program specifically determined the 40 to 60% ROI for each bird, which was clearly affected by the size and position of the bird. The ROI was a regular rectangular area for a bird whose body extended past the lower edge of the image, such as the first bird in Figure 8. For other birds, the presence of background pixels near the lower edge of the image resulted in irregularly shaped ROIs.

Table 1 shows the mean and standard deviation values for relative reflectance at 580 nm for wholesome and unwholesome birds in three data subsets drawn from the hyperspectral data analysis using the 40 to 60% ROI and each of the two inspection shifts. Table 2 shows the mean and standard deviation values for the two-waveband ratio using 580 and 620 nm for wholesome and unwholesome birds for the same three data subsets. Paired t-tests showed no significant differences ($p = 0.05$) between the three data sets for the wholesome means, and similarly, no significant difference between the three data sets for the unwholesome means. This demonstrates that when the spectral imaging system is appropriately and consistently operated to maintain proper distance and illumination conditions, hyperspectral data collected by the system can be used appropriately for multispectral inspection conducted at different times and locations.

TABLE 1 Mean and Standard Deviation (SD) Values for Reflectance Intensity at 580 nm for Wholesome and Unwholesome Chicken Images

	Wholesome		Unwholesome	
	Mean	SD	Mean	SD
Hyperspectral analysis	0.378	0.088	0.243	0.076
Inspection shift 1	0.419	0.115	0.253	0.069
Inspection shift 2	0.398	0.083	0.253	0.075

TABLE 2 Mean and Standard Deviation (SD) Values for Two-Waveband Ratio Using 580 nm and 620 nm for Wholesome and Unwholesome Chicken Images

	Wholesome		Unwholesome	
	Mean	SD	Mean	SD
Hyperspectral analysis	0.948	0.037	0.904	0.052
Inspection shift 1	0.958	0.033	0.918	0.048
Inspection shift 2	0.941	0.038	0.919	0.048

For multispectral classification, fuzzy logic membership functions were built based on the mean and standard deviation values for the 580-nm key waveband from the hyperspectral analysis data subset, and on the mean and standard deviation values for the 580- and 620-nm two-waveband ratio, again from the hyperspectral analysis data subset. Figure 9 shows the structure of the fuzzy logic membership functions. These functions were used to classify each ROI pixel within an image as either wholesome or unwholesome, by using each pixel's 580-nm intensity value and its ratio value using 580 and 620 nm as inputs to

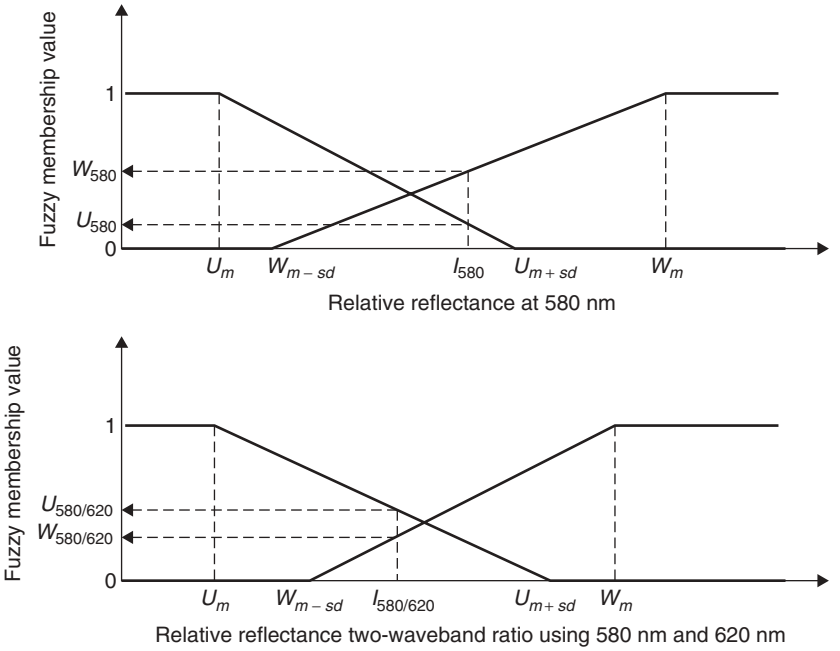

FIGURE 9 Structure of the fuzzy logic membership functions that use the intensity-based input value (I_{580}) and ratio-based input value ($I_{580/620}$) to create pixel-based decision outputs for wholesomeness classification. W_m, wholesome mean; U_m, unwholesome mean; $W_{m-\mathrm{sd}}$, wholesome mean minus 1 standard deviation; $U_{m+\mathrm{sd}}$, wholesome mean plus 1 standard deviation.

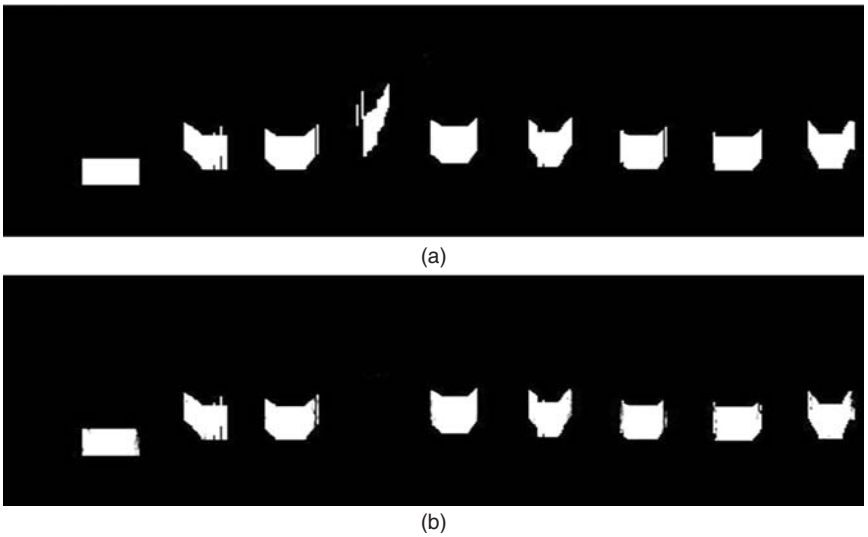

FIGURE 10 (a) Masked image of nine chickens that highlights the ROI pixels to be analyzed for each chicken; (b) the ROI pixels for each chicken that were classified as wholesome.

obtain a decision output value (D_o) between 0 and 1. The average D_o value for a bird was used to determine a wholesome or unwholesome assignment by comparison with a threshold value. Figure 10a shows a masked image of nine chickens with all ROI pixels highlighted for each chicken, and another image highlighting only those ROI pixels that were classified as wholesome pixels is shown in Figure 10b (i.e., D_o values of individual pixels were each compared to the 0.6 threshold value). The fourth chicken from the left is an unwholesome bird, and all of its ROI pixels were identified as unwholesome, consequently not appearing in image (b).

Figures 11 and 12 are scatterplots of the imaging system's decision outputs against the number of ROI pixels for each chicken imaged during inspection shifts 1 and 2. The total numbers of wholesome and unwholesome chickens identified by the system are shown in Table 3, compared with numbers drawn from FSIS tally sheets created by three inspection stations on the same processing line during those two inspection shifts. Although direct bird-to-bird comparison between the imaging inspection system and the inspectors was not possible, the percentages indicated that the relative numbers of wholesome and unwholesome identified by the imaging inspection system and by the processing line inspectors were not significantly different.

A veterinarian also conducted several periods of system verification, each lasting approximately 30 to 40 min. The veterinarian conducted bird-by-bird observation of chicken carcasses immediately before they entered the IFOV of the imaging system. The imaging system output was observed for agreement with

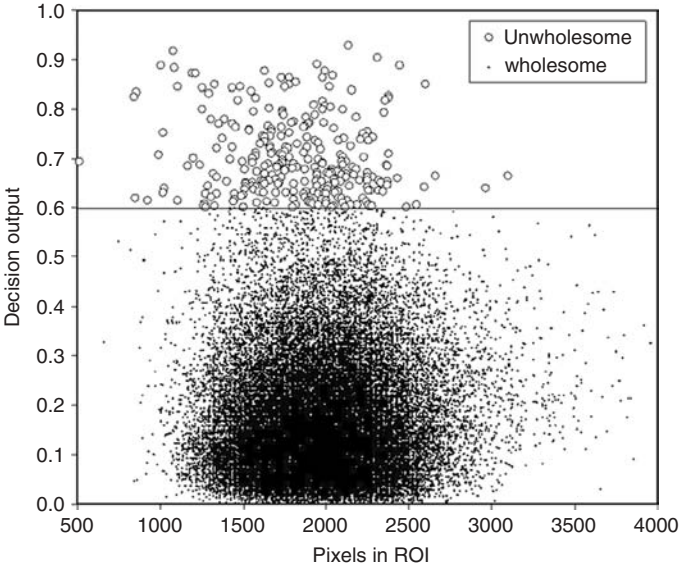

FIGURE 11 Scatterplot graph showing the distribution of chicken carcasses imaged during inspection shift 1, by the number of ROI pixels and the final decision output for each chicken.

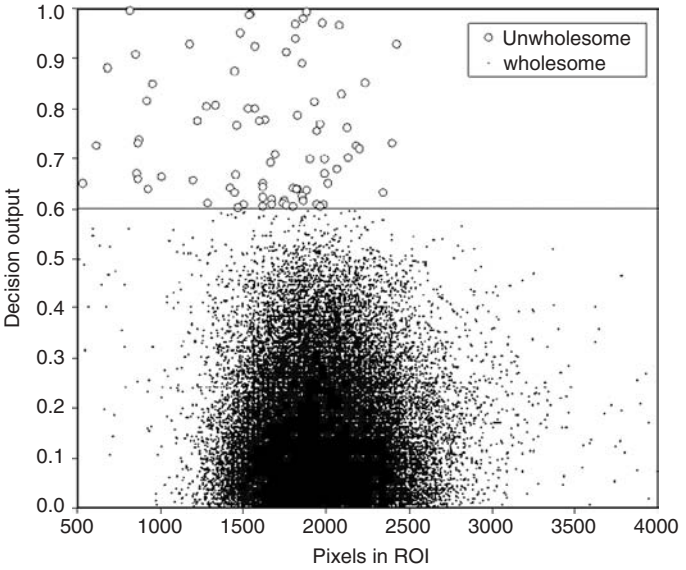

FIGURE 12 Scatterplot graph showing the distribution of chicken carcasses imaged during inspection shift 2, by the number of ROI pixels and the final decision output for each chicken.

TABLE 3 Wholesome and Unwholesome Birds Identified During Inspection Shifts by Processing-Line Inspectors and by the Imaging Inspection System

	Line Inspectors			Imaging Inspection System		
	Wholesome	Unwholesome	Total	Wholesome	Unwholesome	Total
Shift 1	53,563 (99.84%)	84 (0.16%)	53,647 (100%)	45,305 (99.37%)	288 (0.63%)	45,593 (100%)
Shift 2	64,972 (99.89%)	71 (0.11%)	65,043 (100%)	60,922 (99.84%)	98 (0.16%)	61,020 (100%)

the veterinarian's identifications. The veterinarian observed 16,174 wholesome birds and 43 unwholesome birds over four verification periods during inspection shift 1. Of these birds, the imaging system incorrectly identified only 118 wholesome birds (99.27% correct) and 2 unwholesome birds (95.35% correct). The veterinarian observed 27,626 wholesome birds and 35 unwholesome birds over six verification periods during inspection shift 2. Of these birds, the imaging system identified incorrectly only 46 wholesome birds (99.83% correct) and 1 unwholesome bird (97.14% correct). These results, together with the percentages listed in Table 3, strongly suggest that the imaging inspection system can perform successfully on a commercial poultry processing line.

For multispectral inspection conducted on a 140-bpm processing line performed for this study, the imaging system acquired about 30 to 40 line-scan images between the SP and EP for each chicken inspected. Previous testing of the imaging system on a 70-bpm processing line (Chao et al., 2007) demonstrated similar performance in the identification of wholesome and unwholesome birds with an analysis of about 70 to 80 line-scan images for each chicken. Because the unwholesome birds exhibit a systemic unwholesome condition affecting the entire body of the bird, this line-scan imaging system is able to identify such birds at even higher speeds; on a 200-bpm processing line, for example, the system would perform similarly in identifying wholesome and unwholesome birds by analyzing about 20 to 25 line-scan images for each chicken.

CONCLUSIONS

An online line-scan imaging system capable of both hyperspectral and multispectral visible/near-infrared reflectance imaging was developed to inspect freshly slaughtered chickens on a processing line for wholesomeness. In-plant testing results indicated that the imaging inspection system achieved over 99% accuracy in identifying wholesome chickens and over 96% accuracy in identifying unwholesome diseased chickens. With appropriate methods of hyperspectral analysis and algorithms for online image processing, a machine vision system utilizing an EMCCD camera for multispectral inspection can satisfy both the food safety

performance standards and the high-speed production requirements (i.e., at least 140 bpm) of commercial chicken processing. Use of the imaging system may also help to improve product safety by preventing most unwholesome birds from entering the evisceration line, thus lowering the risk of cross-contamination. In addition, use of the system can help reduce the routine workload imposed on FSIS inspectors working in HIMP processing plants, allowing them opportunities to perform more meaningful tasks for ensuring the safety of poultry products and addressing related public health concerns.

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POULTRY-RELATED FOODBORNE DISEASE

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INTRODUCTION

The term *foodborne disease* spans a wide variety of both illness syndromes and causative agents. Although consumers may associate the term with microbial factors, illnesses may also result from poisonous chemicals or toxins such as cleaning compounds or poisonous mushrooms which have entered the food supply either accidentally/incidentally or intentionally. The majority of foodborne diseases, however, are the result of microbiological agents.

Handbook of Poultry Science and Technology, *Volume 1: Primary Processing*, Edited by Isabel Guerrero-Legarreta and Y.H. Hui

Foodborne diseases have been estimated to cause 76 million illnesses with 5000 deaths each year in the United States (Mead et al., 1999). During the period 1998–2002, bacterial pathogens caused 55% of foodborne disease outbreaks as well as 55% of foodborne disease cases in which etiology could be determined (CDC, 2006). Of the 6647 total outbreaks and 128,370 illnesses with known etiology reported in the United States during that time frame, *Salmonella enteritidis* accounted for the greatest number of outbreaks and *Listeria monocytogenes* accounted for the greatest number of deaths. Adak et al. (2005) estimated that 1,724,315 cases of foodborne illness occurred in England and Wales between 1996 and 2000, with 21,997 hospitalizations and 687 deaths associated with the reported illnesses. *Campylobacter* was responsible for the greatest number of primary care visits and hospitalizations, and *Salmonella* caused the greatest number of deaths in those two countries. In the United States, restaurants/delicatessens and private residences were the two locations most commonly associated with foodborne outbreaks, followed by schools, workplace cafeterias, and churches (CDC, 2006).

Foodborne disease surveillance and reporting systems have improved and expanded tremendously over time. In the United States, high levels of morbidity and mortality from typhoid fever and infantile diarrhea led to early surveillance of the role of food, milk, and water in outbreaks of "enteric fever" (CDC, 2006). Consolidation and reporting of data was done through the U.S. Public Health Service until 1961, when the Centers for Disease Control (CDC) took over such duties. Today, the Foodborne Diseases Active Surveillance Network, commonly known as FoodNet, allows local, state, and territorial health authorities, state and federal epidemiologists, and other official investigative agencies to complete an "Investigation of a Foodborne Outbreak" form, which is then submitted to the CDC through the Web-based Electronic Foodborne Outbreak Reporting System (CDC, 2006). Data from pathogen-monitoring systems, such as *Salmonella* and *Escherichia coli* monitoring of meats and poultry now being done as a result of the pathogen reduction-hazard analysis and critical control point systems rule of 1996 (USDA–FSIS, 2000), also contribute to the information flow used to determine the causes of foodborne disease outbreaks. Denmark, the United Kingdom, and many other countries also utilize public health surveillance and microbiological assessment systems to monitor foodborne disease (Batz et al., 2005).

Although surveillance and monitoring have improved substantially, a variety of weaknesses and limitations still exist. Small outbreaks or outbreaks due to pathogens that are rarely associated with foods or are difficult to identify may never be recognized or investigated. Information submitted on foodborne outbreak forms is often incomplete, making it difficult to evaluate accurately such things as etiology, foods associated with outbreaks, or factors contributing to outbreaks (CDC, 2006). Some outbreaks, such as those that occur on cruise ships or those in which transmission from a contaminated food to the infected person(s) is indirect, are not reported on FoodNet. Given these and other limitations of surveillance and monitoring systems in every country, it is generally accepted that foodborne disease is underreported (Batz et al., 2005).

Although recent foodborne illness outbreaks involving spinach, peanut butter, and even dog food have generated more news coverage, poultry continues to be a significant risk factor for illness. Between 1998 and 2002, poultry accounted for an average of 69 foodborne disease outbreaks, with an average of 997 individual cases of foodborne illness (CDC, 2006). In 2002 alone, poultry was associated with 75 outbreaks and 1325 cases of foodborne disease as well as eight deaths—the greatest number of deaths for any food transmission vehicle reported by the CDC in that year (CDC, 2006).

FOODBORNE ILLNESSES ATTRIBUTED TO POULTRY

Campylobacter (Dominguez et al., 2002; Jorgensen et al., 2002; Pezzotti et al., 2003), *Salmonella* (Schlosser et al., 2000; Dominguez et al., 2002; Jorgensen et al., 2002; Altekruse et al., 2006), *Listeria* (Genigeorgis et al., 1990), *E. coli* (Zhao et al., 2001; Northcutt et al., 2003), and other microorganisms have been reported in a variety of poultry products. Microbial contamination loads vary widely, with reported levels ranging from less than $\log_{10}$ 1.0 CFU/cm^2 to more than $\log_{10}$ 7.0 CFU/cm^2. The continuing contamination of poultry products poses a risk for consumers that has often led to foodborne illness.

Chicken consumption has been identified as a risk factor for *S. enteritidis* infections. Kimura et al. (2004) conducted a case–control study in FoodNet sites over a 12-month period in 1996 and 1997. Data were collected from Minnesota, Oregon, and specified counties in California, Connecticut, and Georgia. Over the 12-month study period, 404 cases of *S. enteritidis* were detected. Univariate analysis indicated that international travel and consumption of chicken outside the home were two of the most significant risk factors associated with infection. When all cases were considered in the final multivariate model, 17% of *S. enteritidis* cases were associated with international travel, while 35% were attributed to consumption of chicken outside the home.

An increase in laboratory-confirmed *S. enteritidis* infections in 2000 prompted a reassessment of risk factors for such infections by Marcus et al. (2007). FoodNet data gathered from Connecticut, Minnesota, Tennessee, and selected counties in Colorado and New York was used in this study. Results were similar to those of Kimura et al. (2004), with international travel and consumption of chicken outside the home being significantly associated with illness.

Chittick et al. (2006) summarized foodborne illness outbreaks attributed to *Salmonella heidelberg* between 1973 and 2001. Descriptive data were analyzed separately for the 1973 to 1997 and 1998 to 2000 periods, due to enhancement of the Foodborne Outbreak Reporting Service in 1998, which resulted in increased reports. Overall, 184 of 18,483 outbreaks were attributed to *S. heidelberg*, with 25 of those linked to poultry. Illnesses occurring due to improper handling or storage were not determined.

Foodborne illness data compiled from a variety of sources into a database maintained by the Centers for Science in the Public Interest were analyzed by

Dewaal et al. (2006) for the years 1990 to 2003. Poultry was linked to 476 of the 4486 reported outbreaks. Chicken, turkey, and chicken salad were the foods most commonly associated with illness, while *Campylobacter* spp., *E. coli* and *Salmonella* spp. were the microorganisms most commonly detected in the outbreaks.

The high rates of *Campylobacter jejuni* in Hawaii prompted a study by Effler et al. (2001) to determine potential causes of the foodborne illness. Data from all clinical diagnostic laboratories in Hawaii gathered between May and September 1998 resulted in 199 patients with confirmed *C. jejuni* infections. A case–control study conducted with those patients indicated eating chicken prepared by a commercial food establishment within the 7 days prior to onset of illness was associated significantly with infection. Since data for the study were relatively limited, the authors suggested that additional research was needed to fully determine risk factors for *C. jejuni* infections in Hawaii.

Campylobacter infections were also the focus of a case–control study in Norway by Kapperud et al. (1992). Fifty-two cases of *Campylobacter* infection between May 1989 and November 1990 were included in the study. In contrast to other studies, data indicated that consumption of precooked poultry or poultry prepared at a restaurant was not a significant risk factor. However, consumption of poultry brought into the home in a raw state, particularly frozen poultry, was strongly associated with illness. An increased risk was noted for raw refrigerated poultry, but the association was not significant. Consumption of broiler chickens and poultry produced in Sweden or Denmark were other risk factors associated with illness.

A case–control study to determine risk factors for sporadic cases of campylobacteriosis in Denmark was conducted by Wingstrand et al. (2006). Fifty percent of 272 identified campylobacteriosis patients between October 2000 and September 2001 were included in the study. Three separate models were used to analyze data. Results indicated that eating fresh chicken meat that had not been frozen was the primary domestic risk factor associated with illness. Interactions between fresh turkey and winter, fresh chicken and summer, and chicken cuts and barbecuing were borderline significant risk factors, as was consumption of previously frozen chicken meat.

It is often difficult to determine the exact etiology of a foodborne illness outbreak. Risk assessment is one method used to determine the association between poultry consumption and foodborne illness. Brown et al. (1998) developed a quantitative risk assessment model to determine the risk of salmonellosis from frozen poultry products. Information on the occurrence and distribution of the microbiological agent, the sensitivity of given populations to infection by the agent, and the effect of cooking on contamination levels were included in the model. Although limitations such as an inability to assess the effect of recontamination on risk were noted, the resulting program was said to be useful for demonstrating the effect of a range of variables on the risk of foodborne illness associated with consumption of frozen poultry products containing *Salmonella*. Suggested uses

for the program included providing information useful for risk management and communication.

Bemrah et al. (2003) used risk assessment to evaluate the association between consumption of turkey from catering establishments and salmonellosis. The study, conducted in France, focused on turkey cordon bleu from 21 collective catering establishments and eight retailers. Preparation and cooking practices in the catering establishments were determined and *Salmonella* was enumerated in 325 cordon bleus from 65 different batches. An exposure model was developed and the dose–response relationship, probability of illness, and risk of outbreak were calculated. Although 36 of 95 cordon bleus were *Salmonella*-positive, only two of the 36 contained greater than 2 *Salmonella* per gram. Risk of salmonellosis from cordon bleus cooked in an oven was close to zero, but risk increased substantially when the product was fried, due to insufficient cooking time and a low internal temperature after frying. Investigators also noted a lack of clear preparation instructions on product packaging and confusion between cooked and "precooked" cordon bleus that could contribute to the risk of salmonellosis from the product.

HAND WASHING, CROSS-CONTAMINATION, AND POULTRY-RELATED FOODBORNE DISEASE OUTBREAKS

"Bare-handed contact by handler/worker/preparer" was reported to be the most common contamination factor contributing to foodborne disease outbreaks in the United States during the 1998–2002 surveillance period (CDC, 2006). Washing hands with warm soapy water has been ranked as one of the most important consumer behaviors for reducing risk from foodborne illnesses (Medeiros et al., 2001; Hillers et al., 2003). Infrequent, inadequate, or inappropriate hand washing is often cited as a food-handling error committed by consumers (Worsfold and Griffith, 1997; Jay et al., 1999). Anderson et al. (2004) videotaped consumers in their homes during food preparation. Average hand-washing length was significantly lower than the recommended 20 s and only one-third of the subjects used soap during hand washing. Unwashed hands were also cited by Anderson et al. (2004) as the most common cause of cross-contamination between raw products such as poultry and ready-to-eat foods.

"Raw product/ingredient contaminated by pathogens from animal or environment" was the most common factor associated with outbreaks due to bacterial pathogens during the 1998–2002 surveillance period (CDC, 2006). Poultry and poultry-related products have been implicated in a number of foodborne illness cases attributed to cross-contamination. Although consumers undoubtedly cross-contaminate foods in their own homes, many of the outbreaks reported involve large-group feeding situations.

Cross-contamination and improper handling have resulted in several poultry-related foodborne illness outbreaks in schools. Daniels et al. (2002) reviewed reports of outbreaks in U.S. schools occurring between 1973 through 1997.

Although foods containing poultry were the vehicle most frequently implicated, the authors also noted an eightfold decrease in outbreaks due to turkey. Contamination by a food handler was implicated in 115 of 597 total outbreaks, while contaminated equipment was found to contribute to 165 of the 597 total outbreaks.

Jiménez et al. (2005) reported on an outbreak of *Campylobacter jejuni* enteritis at a school in Madrid, Spain. A cohort study and an investigation of the transportation, storage, and preparation procedures and the brands of raw ingredients used in the school indicated that custard served during the outbreak period was the most likely source of the *C. jejuni*. However, the food preparation areas for raw meats and ready-to-eat foods were not separated in the school kitchen and the authors speculated that cross-contamination of the custard by raw chicken from paella prepared on the day prior to custard preparation was the ultimate source of the outbreak.

Although microbial contamination is the most common reason for foodborne disease, toxic substances have also been linked to foodborne illness outbreaks. Dworkin et al. (2004) reported on an outbreak of ammonia poisoning from chicken tenders served at two Illinois schools. Ninety-one percent of students interviewed after the outbreak reported eating chicken tenders that smelled unusual, while 55% indicated that they had eaten chicken tenders that tasted unusual. Attack rates increased as the number of chicken tenders consumed increased. The unusual sensory properties combined with a very short symptom onset time indicated a chemical agent. Environmental investigation of the schools indicated no critical violations in food handling or preparation, but a traceback investigation found that the chicken tenders had been exposed to a liquid ammonia spill while stored in an Illinois State Board of Education warehouse. Laboratory testing detected ammonia in both uncooked and heated chicken tenders, and all product distributed to Illinois schools was subsequently destroyed.

Improper handling and cross-contamination in restaurants have also been associated with foodborne disease outbreaks due to poultry products. Valenciano et al. (2000) conducted a retrospective cohort study on a concurrent outbreak of gastroenteritis and typhoid fever traced to a floating restaurant in France in 1998. Gastroenteritis was reported by 133 guests at a supper on the floating restaurant, while 27 guests developed typhoid fever. Food attack rates indicated that chicken and/or rice were the most likely transmission vehicles. Poor hygienic conditions, including the absence of a potable water source in the kitchen, common rest room facilities for food preparers and customers, and inadequate hand-washing sinks were reported to be factors contributing to the outbreak.

Lettuce cross-contaminated with raw chicken was determined to be the cause of an outbreak of *C. enteritis* in Oklahoma in 1996 (MMWR, 1998). Fourteen patrons of a restaurant in southwestern Oklahoma met the case definition of three or more loose stools in a 24-h period, or vomiting. A case–control study indicated that lettuce consumption accounted for all cases, while lasagna consumption accounted for 79% of cases. Subsequent investigation of the restaurant indicated

that the preparation area was too small to separate raw products from other foods. Raw chicken for the dinner service was reportedly cut up prior to preparation of salads, lasagna, and other foods for the lunch service. Lettuce for the salads was shredded with a knife, and a towel worn around the cook's waist was used frequently for drying her hands. Although an appropriate bleach solution was available in the kitchen, evidence of proper use was not found. Investigators concluded that the most likely cause of the outbreak was cross-contamination of the lettuce with *C. jejuni* from the chicken, due to inadequately washed or unwashed hands, cooking utensils, or the countertop used for preparation.

Layton et al. (1997) reported on a foodborne outbreak involving both *S. heidelberg* and *C. jejuni* in a New York nursing home. Although six different diet plans were offered at the nursing home, only the puréed diet was strongly associated with infection by one or both of the outbreak microorganisms. Five meat products, including minced chicken, minced turkey, and chopped chicken liver, were highly associated with positive cultures, but many foods were determined to have contributed to the outbreak. Through interviews and environmental investigation it was determined that cooked chopped chicken livers had been placed in a bowl containing juices from raw chicken liver. The bowl of chopped liver salad had then been refrigerated, but a coolant failure in the refrigerator had allowed the temperature of the salad to rise to 50°F prior to serving. Although the blender and grinder used to process the meats were clean at the time of inspection, a meat slicer was crusted with old food material. The investigators speculated that an additional cause of the outbreak was likely cross-contamination between the various foods processed in the blender and grinder.

Cross-contamination by catering establishments has been implicated in several poultry-related foodborne disease outbreaks. Mazick et al. (2006) reported on an outbreak of *C. jejuni* at several companies in Copenhagen in 2005. Employees at four of the five companies serviced by the same catering company developed gastrointestinal illness that met the case definition. Date- and food-specific attack rates indicated that chicken salad was the probable food vehicle. Subsequent telephone interviews with catering personnel indicated that raw chicken had been stored in the refrigerator directly above cooked fried chicken used later to prepare the chicken salad. The investigators speculated that juices from the raw chicken dripped onto the fried chicken. Although no food from the outbreak exposure period remained for testing, raw chicken breast fillets from the same wholesaler and producer tested positive for *Campylobacter*, suggesting that *Campylobacter* was the most likely cause of the outbreak.

An outbreak of *Salmonella typhimurium* was reported by Moffatt et al. (2006) to be linked to a café in Adelaide, South Australia. Attendees at six luncheons catered by the café as well people eating at the café were involved in the outbreak. Sixty-one cases of gastroenteritis were identified, resulting in an attack rate of 60%, with the presence of *S. typhimurium* phage type 64 confirmed in 32 of those cases. Food attack rates indicated that bread rolls, which were common to all catered events as well as the café itself, were the likely transmission vehicle. An experimental roll filled with turkey, lettuce, cucumber, cheese, sprouts, cranberry

sauce, and dressing was positive for *S. typhimurium* phage type 64, as was a 25-g sample of chicken tenderloin taken from the preparation kitchen. Environmental investigation found that general hygiene and food-handling practices at the café were good. However, investigators observed personnel handling raw chicken just prior to seasoning the meat with pinches of salt and pepper taken from containers on the preparation work table. The salt and pepper was then used to season other food items, including the bread rolls. Although food samples from the original outbreak were not available, investigators surmised that bread rolls cross-contaminated by raw chicken via the salt and pepper was the likely cause of the outbreak.

TEMPERATURE AND POULTRY-RELATED FOODBORNE DISEASE OUTBREAKS

Bryan (1980) reported that factors contributing to 88 foodborne illness outbreaks related to meat and poultry between 1968 and 1977 included improper cooling (48%), inadequate cooking or thermal processing (27%), inadequate reheating of cooked foods (20%), and improper storage of cooked foods (19%). Proliferation of microorganisms was most commonly due to "allowing foods to remain at room or warm outdoor temperature for several hours," while survivability of microorganisms was most commonly due to "insufficient time and/or temperature during initial cooking/heat processing" according to surveillance data for the 1998 to 2002 period (CDC, 2006). All of these factors have been associated with poultry-related foodborne diseases.

An outbreak of foodborne illness at a youth camp in Australia was investigated by Hook et al. (1996). The camp site was inspected on the third day of the outbreak and data were collected through a questionnaire mailed to participants. At least 118 camp participants were transported to local hospitals, but only seven stool samples and one vomitus sample were available for analysis; *Clostridium perfringens* was detected at levels greater than 10^6 CFU/mL in four of the samples. *C. perfringens* type A enterotoxin was also detected in four of the samples. Food preparation and handling procedures were found to be inadequate. Deficiencies noted included food and utensils stored both outside and on the floor of a refrigerated shipping container being used for cold storage; cold meats being sliced in the open; flies observed on both the meat slicer and freshly cut meats; a lack of hand-washing facilities in the food preparation area; portable toilets without hand-washing facilities; and a lack of soap and towels in portable toilets. Food attack rates indicated that cold chicken served on the second day of the camp was strongly associated with illness. Subsequent investigation indicated that the chicken had been delivered frozen the day prior to the start of the camp and stored in the refrigerated shipping container. On the first day of the camp, the chicken was thawed at ambient temperatures from 8 to 11 A.M. and then thawed further under running water. At 2 P.M. the chicken was boiled for 1 h, drained, and placed in stainless steel trays in a warmer cabinet. The cooked chicken was

placed in preheated bain maries at 6 P.M. and served to campers at 7 P.M. Leftover chicken was finally refrigerated at 9 P.M. The cold chicken was broken up with gloved hands on the second day of the camp and then served for lunch. *C. perfringens* was detected in the cold chicken. The investigators concluded that the extended time the chicken had been at ambient or warm temperatures resulted in the growth of the *C. perfringens* and led to the outbreak.

Allerberger et al. (2003) reported on a multistate outbreak of *C. jejuni* related to barbecued chicken. The outbreak, which occurred in Austria, Germany, and Liechtenstein during 2001, involved five people who had attended a backyard barbecue. Based on attack rates and relative risk assessment, undercooked chicken fillets were determined to be the probable source of the outbreak. Information on the packaging material allowed the researchers to trace the chicken meat to a specific flock of chickens. Subsequent investigation determined the outbreak *C. jejuni* isolate was cross-contaminating chickens in the slaughterhouse where the poultry was processed.

Undercooking chicken in a "sizzling wok special" was determined to be the cause of a foodborne outbreak of *C. jejuni* in customers of a Hawaiian theme restaurant in Cardiff, Wales (Evans et al., 1998). A number of food safety issues were discovered during investigation of the outbreak, including lack of training of the two main food handlers and storage of both raw poultry and cooked foods in a refrigeration unit. A dome-shaped gas-fired hot plate of sufficient size to cook eight meals simultaneously was used to prepare the specials. Food attack rates indicated that unmarinated chicken was the only food associated with the outbreak. Epidemiological evidence suggested that undercooking as a result of chicken pieces being cut too large, insufficient cooking time, insufficient direct contact between the food and cooking surface, or a combination of these factors, aggravated by a need for prompt preparation for large groups of people was the most likely cause of the outbreak.

A steady increase in campylobacteriosis in New Zealand prompted a study by Eberhart-Phillips et al. (1997) to determine the probable causes. The case–control study, conducted in 1994 and 1995, involved subjects living in Auckland, Hamilton, Wellington, and Christchurch, due to the high rates of infection reported in those areas. Results indicated that consumption of raw or undercooked poultry was strongly associated with infection, particularly when the food was consumed outside the home. Both barbecued and fried chicken were positively associated with campylobacteriosis, whereas consumption of baked or roasted chicken was found to have a protective effect. Evidence collected in the study suggested that thoroughness of cooking was the most likely factor associated with risk of campylobacteriosis.

An outbreak of salmonellosis at a Formula One race track in Hungary in August 2007 was reported by Krisztalovics et al. (2007). Food served at a buffet over a 2-day period was suspected as the cause of the outbreak. The buffet was closed on the third day of the outbreak, and samples of frozen raw and cooked chicken available on site after the buffet was closed were positive for *Salmonella infantis*. Investigators speculated that lukewarm holding temperatures

during transportation of the food from the Budapest restaurant where it was prepared to the race track buffet, combined with undercooking, was the probable cause of the outbreak.

Improper cooking of frozen chicken nuggets has been implicated in several foodborne illness outbreaks (Kenny et al., 1999; MacDougall et al., 2004). Cases in both outbreaks were identified primarily in children under 7 years of age, and food attack rates indicated that chicken nuggets and strips was the only food associated significantly with illness. Chicken nuggets that had been "flash fried" or precooked but were still raw were the focus of both investigations, based on environmental evidence which indicated that incomplete labeling resulted in consumer confusion as to whether the products were fully cooked or raw. Improper heating, particularly the use of a microwave for preparation, was reported in both studies. MacDougall et al. (2004) also reported that one-third of study participants were less likely to wash their hands when handling frozen raw nuggets compared to fresh raw chicken, leading to a potential for cross-contamination. Recommendations included the need for clear, complete instructions on product labels emphasizing the need for complete cooking and that microwave heating was not recommended.

COMMERCIALLY PREPARED POULTRY PRODUCTS AND FOODBORNE DISEASE

Commercially processed raw products have been associated with foodborne illness outbreaks. McPherson et al. (2006) reported on an outbreak of *S. typhimurium* phage type 135 in Australia. More than 80% of cases identified reported purchasing groceries at a specific supermarket chain. Multivariate analysis of data collected in a case–control study indicated a significantly higher risk of infection associated with eating chicken purchased from the supermarket chain or from a fast-food restaurant. Chicken products purchased from different supermarket outlets were positive for several strains of *Salmonella*, including the outbreak strain. No hypothesis could be developed to explain the strong association between illness and the supermarket chain.

Commercially prepared poultry products have also been implicated in foodborne disease outbreaks. Lenglet (2005) reported on an outbreak of *Salmonella hadar* in Spain associated with precooked vacuum-packaged roast chicken. The outbreak resulted in one death. Although the implicated brand of chicken was recalled, results of an environmental inspection of the manufacturing facility were not reported.

An outbreak of *Salmonella bredeney* in Belfast, Northern Ireland was associated with chicken cooked at local butchers and retailed through two local bakeries (Moore et al., 2003). Investigation indicated that inadequate food preparation practices were used in one of the bakeries, and potential problems with cooking and record keeping were found at the butchers. The outbreak strain was isolated from uncooked chicken supplied to one of the butchers, confirming that the chicken was the probable cause of the outbreak.

Olsen et al. (2005) reported on a multistate outbreak of *Listeria monocytogenes* infection in 2000 associated with delicatessen turkey meat. Thirty patients in 11 states were identified as being infected with the identical strain of *L. monocytogenes*, resulting in miscarriages, one stillbirth, and the death of four other patients. A case–control study identified sliced processed deli-style turkey meat as the cause of the outbreak, and 16 million pounds of processed turkey and chicken meat were eventually recalled. Trace-back and environmental investigations identified one manufacturing plant in Arkansas and one in Texas associated with the outbreak; the two plants were also found to be linked through the Texas plant acting as a copacker for the Arkansas plant. Isolates from the outbreak and a 1989 outbreak linked to the plant suggested the *L. monocytogenes* had been present in the facility for at least 12 years.

Deli turkey meat was also linked to a listeriosis outbreak in 2002 (Gottlieb et al., 2006). Eight of the 54 cases identified died, and three fetal deaths were reported as a result of the outbreak. The outbreak strain of *L. monocytogenes* was detected in the environment of one turkey-processing plant and in turkey from a second processing plant, resulting in recall of more than 30 million pounds of product. Postpackaging pathogen-elimination treatments such as pasteurization or irradiation were suggested, and new guidelines for control of and testing for *L. monocytogenes* in ready-to-eat poultry products were issued by the USDA Food Safety and Inspection Service.

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POULTRY-RELATED FOODBORNE DISEASES IN CENTRAL AND SOUTH AMERICA

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Handbook of Poultry Science and Technology, *Volume 1: Primary Processing*, Edited by Isabel Guerrero-Legarreta and Y.H. Hui

INTRODUCTION

Besides being a basic human right, the availability of wholesome food is a so important to people that they get together to develop and have at their disposal specific information on the food they consume and the risks to which they are exposed. Failures in food safety related to contaminated food consumption remain a worldwide problem because of its economic impact as well as the illnesses they cause, creating a serious public health problem. Wholesome food contributes to health and productivity, providing an effective platform for more progress and less poverty. The poultry industry, and products derived from it, are not immune such problems. Ever since the 1960s, important technical improvements in the poultry industry have been introduced in industrialized countries, many of them related to process automation, and as a consequence, there has been improvement in poultry industry performance. The poultry industry is aware of this problem; nonetheless, progress did not translate to improving poultry meat microbial quality; on the contrary, the microbial load in poultry carcasses became a problem. Nowadays, microbial etiology is identified as the principal cause of foodborne outbreaks related to poultry meat consumption. Foodborne outbreak surveillance systems work differently in each country, some being less reliable than others. The real situation thus makes it difficult to compare disease incidence among countries in the same region. Few systems identify exactly the responsible source of an outbreak or a case; on the contrary, in most systems "meat products" in general are identified as being responsible, without specifying the species involved.

In general, it is recognized that a high percentage of recorded cases are not associated with a particular food or an identified pathogen. Yet it is possible to detect a considerable percentage, as poultry meat products, both for home consumption and issuing from catering services for schools, nursing homes, are the and so on, products responsible for most food borne outbreaks, *Salmonella* spp., *Campylobacter* spp., and *Staphylococcus aureus* being the main causal agents. Available information indicates that there is a lack of notification within a region, a situation that most probably arises from a multiplicity of factors. This is a regional problem that should be resolved in the short term because it is through epidemiologic surveillance of such illnesses that it will be possible to obtain the necessary information for quality assurance and food safety through implementation of prevention and control programs. It is necessary to make a multidisciplinary effort, with scientific support, and together to create a compromise with the participation of all countries so that products produced in the region can be accepted in international markets because of their "health harmlessness."

Consumers deeply influence decisions related to the variety of links in the food chain in general and, in particular, of the meat chain. Because of the consumers' position at the very end of the chain and their role as true users of the final product, consumers turned out to be a source of inspiration for organization of the food chain as a whole (Gellynck et al., 2006). Information on food questions available to the population is increasing daily. This situation promotes an interest

in knowing all the details about food that is consumed and the direct and close relationship it has with people's health and with the illnesses that food may cause (Seuß, 1991). Indeed, eating habits are changing, and consumer demands are oriented increasingly by parameters related to health, ethics, environmental problems, food history, and so on. (Grunert, 2006).

The composition of food, especially in terms of the presence or absence of some ingredients, is central to consumption tendencies. Calorie, fat, and salt contents are some of the factors that determine consumer acceptance (Resurrección, 2003). Poultry meat is rich in important amino acids, vitamins (especially B-group), and minerals. Although it has less iron than that in other meats, poultry meat is recognized as a true protein concentrate with high nutritional value. Consumers have become aware of the effect produced by animal fats on serocholesterol (Demos et al., 1994), making poultry meat more attractive, due to its low fat content and because it is possible to lower the saturation of poultry meat lipids through a modification of the animals' diet.

Advances in poultry production arising from the incorporation of technology, made possible by vertical integration of the food chain, have transformed poultry into a meat that has shown a leading consumption increment in recent years: a 10% annual growth rate. In this respect, the adoption of technology and the increased scale of production are acknowledged as the most significant factors in cost reduction and competitive improvement (FAO-SAGPyA, 2007a).

According to the U.S. Department of Agriculture (USDA), the main countries producing poultry meat worldwide are the United States (16 million tons), China (10 million tons), and Brazil (10 million tons). It was expected that poultry production would reach 67 million tons in 2007 and could reach 69 million tons by 2008; consumption for those years was estimated at 66 and 67 million tons, respectively (USDA, 2007). It is expected that poultry will be the most consumed meat worldwide by 2030 (Roppa, 2006).

Both the nutritional value and low price cause most consumers to choose poultry when presented with a variety of meat alternatives. Problems involving alternative meats (e.g., swine flu, mad cow disease) have added to poultry's popularity (Rodriguez Jerez, 2004). However, we should not forget the negative impact that avian influenza occurrence has had on poultry production in general internationally. Although it is recognized that the main door of entry of such illness is the conjunctiva mucus and upper respiratory tract (Wong and Yuen, 2006), we cannot discount its negative impact on the poultry chain, leading to a drop in consumption, restrictions on international trade, and economic loses associated with food safety control measures and eradication of the disease agent (FAO, 2004; Doyle and Erickson, 2006).

Beginning in the 1960s in developed countries, technical advances have been introduced in the poultry sector, allowing automation of the process and, as a consequence, making it possible to achieve higher levels of efficiency. However, these advances in the technology of processing poultry in highly automated plants did not morph into advances in meat microbiological qualities. Conversely, the microbial load in poultry carcasses increased, which may have been influenced

massively by animal management practices during both breeding and slaughtering. Dissemination of microorganisms, in particular enteropathogenic bacteria, in poultry and carcasses is favored by the practices adopted (Moreno Temprado, 2005). Microbiological hazards will continue to be the primary challenge to guaranteed food safety in products manufactured with meats, and strategies to guarantee such safety should be developed by all members in the food chain (Sofos, 2008). As North American accounts for 80% of world exports (USDA, 2007), the association among production rise, hygiene deficiencies, and microbiological contaminants demands study and control of the factors determining the incidence of illnesses transmitted by poultry meat, because of its importance for both public health and the regional economy.

FACTORS CONTRIBUTING TO THE OCCURRENCE OF FOODBORNE OUTBREAKS AND ILLNESSES TRANSMITTED BY POULTRY MEAT

Factors Associated with Production

In food prepared from poultry meat, safety is based on biosafety measures and the implementation of good agricultural practices (GAPs) and good manufacturing practices (GMPs) in the various links in the agrifood chain (Sofos, 2008). In past decades there has been an evolution of animal breeding systems into more intensive and demanding models in which there is higher population density. These new systems give rise to changes in the habits and natural life of animals, exposing them to stressing stimuli that could affect their homeostatic equilibrium and intestinal microbial balance, a situation that would favor the colonization and development of pathogenic microbiota (Rosmini et al., 2004; Rosmini and Signorini, 2006).

Similarly, in some producing regions it is possible to observe a high concentration of poultry farms within too limited an area and too high a poultry density, a situation that demands implementation of preventive sanitary measures for both the farm in particular and the area as a whole. The same animals are a source of contamination on farms, as in the case of the parent stock of chicks that are carriers of pathogenic microorganisms such as *Salmonella* spp. These agents may colonize the reproductive system and digestive tract in poultry, transmitting them to their offspring (direct contamination) or contaminating the incubation area (cross-contamination) (Ponsa i Musarra, 2005). Water and feed given to the animals could also become a source of chemical or microbiological contaminants. In a study done in the year 2000, eight poultry-feed supplements were analyzed and it was confirmed that five of them tested positive for *Salmonella* spp. (Parra et al., 2002).

It is necessary to carry out adequate management of raw material, guaranteeing the use of optimal quality drinking water and feed. There should be strict control of the usual suppliers as well as the raw material the breeders provide, developing safe manufacturing and managing practices in such a way that feed fed to animals is guaranteed to be harmless. A biosafety program should be planned

and developed specifically for each farm, always keeping in mind its particular characteristics. In its design, cleaning and disinfecting procedures, integral management of plagues, and rational management of solid and liquid waste should be considered so that they do not become sources of contamination.

The sanitary plan used for animals during the production stage must guarantee the prevention and control of all illnesses affecting their health and performance; moreover, it must prevent the colonization of those microorganisms that could be pathogenic for the consumer. Correct management of animals selected to be transferred to the abattoir contributes to the continuation of animal comfort, diminishing the stress and, consequently, the disease risks caused by pathogenic microorganisms. Special attention should be given to birds when they are put into crates on the farm, loaded on trucks, and taken to the slaughterhouse. It is important to avoid overcrowding the crates with animals, deficiencies in air circulation, unnecessarily long trips, and delays in downloading.

Factors Associated with Poultry Industrialization

Birds arrive at slaughterhouses with a large external microbial load as a consequence of the activities that take place during the various breeding stages. From the contamination point of view, upon entering the slaughterhouse all the steps are important, but some of them are critical, including scalding, plucking, eviscerating, washing, and chilling (Ricaurte Galindo, 2005), because they determine the control of deaths, or survival, and the multiplication of microorganisms. At the slaughterhouse, the typical rough handling that birds are subjected to, together with the large number of animals that are processed per unit of time, predispose to a multiplicity of factors favoring contamination not only in the birds but also in the environment of the processing line (Ponsa i Musarra, 2005). At the start of the slaughtering process, live birds are taken out of crates and hung upside down by their legs in shackles on a moving chain. This step involves struggling with the animals, and as a result leads to large amounts of airborne microorganisms and dust dispersion in the shackling area environment. The electrical stunning that follows relaxes birds' sphincters, permitting feces with enteric microorganisms to contaminate the birds, thus raising the environmental load. Thus, this area of the slaughterhouse is highly contaminated and should be separated from the rest of the production line.

When stunned birds are dipped and passed through the scalding tank, there is a transfer of microorganisms from the skin, feathers, and intestinal content into the hot water. Water thus becomes a vehicle and means of distribution for microorganisms that are disseminated all over the surfaces of birds and from one animal to another. Plucking machines also contribute to cross-contamination, and the agitation produced by the revolving drums with rubber beaters or disks facilitates the microorganisms' access to the feather follicles (Ricaurte Galindo, 2005). Evisceration is another critical stage in which there is generally cross-contamination, due to injury to the viscera, a situation that could be reduced by having automatic eviscerating machines do the work, as long as it is done

correctly. The washing of carcasses should contribute to eliminating dirt and reducing the number of microorganisms present on surfaces.

During carcass chilling, cold water in the immersion chiller tank also washes away microorganisms accumulated during previous operations. But if the water does not rotate continuously, and if its quality is not guaranteed, water becomes a source of contaminants. The selection, packaging, and storage steps also involve high levels of manipulation, and consequently, operators play a predominant role as a source of contamination.

Good manufacturing practices (GMPs), sanitation standard operating procedures (SSOPs), and hazard analysis and critical control point (HACCP) programs are state-of-the-art approaches used as tools to guarantee control of potential sources of contamination as well as of specific pathogens present during poultry meat processing.

Factors Associated with Merchandising

Contaminant microorganisms on poultry carcasses in commercial facilities are very difficult to avoid, and there exists a high probability that some of them may be pathogenic. Consequently, how these carcasses and their products are handled in the distribution and marketing channels, and even by consumers, determines whether illnesses transmitted by poultry meat can be avoided. Poultry carcasses present a postmortem microbial load that is much higher than it is in other animal species. These values vary with microbiological quality, the grade of hygiene reached during processing, and the efficiency of the cold temperatures used to guarantee an optimal product shelf life (Moreno Temprado, 2005). Assuring continuity of the cold chain in both refrigerated and frozen products is essential to avoid the proliferation of microorganisms. Cross-contamination mediated by tools, equipment, and operators and even by raw or cooked food is a principal factor related to the occurrence of illnesses transmitted by food. Consumer education and the control of environmental contamination are the best tools we have to provide food safety in general and, in particular, with poultry meat (Sofos, 2008).

PRINCIPAL HAZARD FACTORS IN POULTRY MEAT

Failures in food safety related to the consumption of food contaminated with pathogenic microorganisms continue to be a problem worldwide, and efforts to control them have always been oriented toward postmortem sanitation (Callaway et al., 2003). Bacterial contamination is the primary hazard associated with the transmission of foodborne illnesses, particularly as regards chicken meat consumption (Parra et al., 2002; Doyle and Erickson, 2006; Cervantes García and Cravioto, 2007). In addition to the ongoing problems related to pathogens, there are other problems that affect the food industry in general and the poultry meat industry in particular. Clear examples are the continuous pathogen resistance and adaptation to traditional containment systems (low pH, low water activity,

chemicals additives) as well as the environmental problems derived from the rise in poultry populations and, consequently, in contamination, and the massive food production and illnesses derived from animal-to-human relations (Sofos, 2008). However, in contrast to the important number of documents related to the presence of microbial contaminants in poultry meat, little information is available concerning chemical, viral, or parasite contaminants associated with poultry meat that could be responsible for the transmission of foodborne illnesses.

Microbial Hazards

The most important pathogens associated with poultry meat are *Salmonella* spp., *Campylobacter* spp., *Staphylococcus aureus, Clostridium perfringes, Listeria monocytogenes, Yersinia enterocolítica, Bacillus cereus*, and *Pseudomonas* spp. (Moreno Temprado, 2005). The characteristics of *L. monocytogenes*, such as its ubiquitous presence, potential to contaminate products after processing, and ability to multiply even under cold temperatures, make it the principal microorganism associated with poultry product contamination (Tompkin, 2002).

Even though they are not frequently present in poultry meat, there are other pathogens (e.g., *Aeromona hydrophila*) that becomes important because of their capacity to produce exotoxic properties (enterotoxins, hemolysins, and cytotoxins) and to grow at low temperatures (Kirov, 1993; Kelley et al., 1998). Such characteristics, which are manifested in "summer diarrhea," make *A. hydrophila* and other foodborne pathogens associated directly with food safety of emerging importance (Kirov, 1993). Some of the microorganisms associated with poultry meat (e.g., *Salmonella*) have attracted much concern for decades and certainly demand that such attention be retained because they are present in many cases of illness associated with food consumption (Panisello et al., 2000; Sobel et al., 2000; Patrick et al., 2004).

In a study carried out in Bogotá, Colombia, from a total of 410 samples (260 from humans and 150 from birds), *Salmonella enterica* was isolated in 9.6% of human samples and 24% of poultry samples. This study demonstrates the circulation of clones of *S. enterica* in Colombia as well as the presence of a genetic interrelation between strains isolated from both humans and birds (Parra et al., 2002). Both *Salmonella* and *Campylobacter* are know as principal bacterial agents that cause intestinal infectious diseases in people living in developed countries (Pérez-Ciordia et al., 2001).

In recent studies on microbial contamination, in 525 samples taken from poultry carcasses, it was possible to determine that 81% presented *Campylobacter* contamination, 15% *Salmonella*, and 13% both bacteria. Only 17% was pathogen-free (Moreno Temprado, 2005). In the late 1990s, in the city of La Plata, Argentina, 120 samples from carcasses and giblets from poultry bought at commercial centers were evaluated. Forty-two (35%) samples were contaminated with *Campylobacter yeyuni* biotype II, and only 1 (18%) was contaminated with *Campylobacter coli* biotype II (Giacoboni et al., 1999).

In 1970 *C. yeyuni* became the first human pathogen to be identified as causing diarrhea. This bacterium is the most frequently diagnosed as causing

gastroenteritis in human beings, and fowl is the principal source of *Campylobacter* infection in both industrialized and developing countries. Food operators' hygiene and meat thermal treatments are among the best strategies to prevent its presence. Campylobacteriosis is an important cause of travelers' diarrhea (Doyle, 2000; Cervantes García and Cravioto, 2007).

In a study done in Chile, a total of 1524 samples were studied, 1154 (75.7%) from chicken meat and 370 (24.2%) from giblets of the same species. Animal samples were selected from nine commercial firms. Of the 1524 samples analyzed, 144 (9.44%) were contaminated with *Salmonella* spp. Only one of the commercial brands was free of this pathogenic agent. The contamination oscillated between 1 and 15.5%, with a 6.8% mean value per brand. Giblets were contaminated by this pathogen in a higher number of samples. Most of the *Salmonella* isolates that were identified in these poultry meat and giblet samples were *S. enteritidis* (75% of the total) (Alexandre et al., 2000).

In a study done in the Valle de Catamarca, Argentina in the year 2005, 120 chicken carcasses were analyzed; 20.63% were contaminated with *Staphylococcus*, 17.29% with *Acinetobacter*, 15.41% with *Aeromonas*, 14.58% with *Enterobacteria*, 9.58% with *Pseudomonas*, 7.29% with *Micrococcus*, and 6.25% with *Campylobacter* (Soria and Malandrini, 2005).

Chemical Hazards

Many chemical substances are used directly in agricultural production or are generated at some stage of the productive cycle. Several of them are especially important because products or their residues come into direct contact with live animals and thus may be present in poultry meat. Examples include mycotoxins, antimicrobials, and pesticides.

Mycotoxins Mycotoxins are a growing threat for poultry production in particular and for animal production in general. Their presence in animal feed generates important economic problems because they lower animal productivity, diminish animal performance, provoke immunosuppression, and in many cases result in high mortality (Vaamonde, 1995; Resnik, 1997; Williams et al., 2004; Mallmann et al., 2007). Nowadays, hundreds of toxic metabolites of fungal origin are known, but only a few of them are involved in human or animal mycotoxicosis (Resnik, 1997). Moreover, human intoxications due to mycotoxin residues in food of animal origin are unlikely to occur since different animal species have detoxication mechanisms via excretion of the toxic substances of metabolite products consumed (Vaamonde, 1995). Aflatoxins represent a permanent hazard for animal health. In Colombia, in more than 200 raw material and finished feed samples for animals, 29% were positive to AFB1 in levels that oscillated between 1.0 and 66.1 ppb (Céspedes and Diaz, 1997).

Antimicrobials Veterinary pharmaceutical products have been key elements in the increase in animal-derived food production (FAO-OMS, 2002). Modern

agrifood practices, in particular poultry production, include the use of a great variety and wide range of antimicrobial substances, in particular antibiotics, with therapeutic, prophylaxis, and growth-promoting purposes (González Silvano, 1995; Kelley et al., 1998). From the poultry production point of view, the use of antibiotics increases productivity, avoids chicken feed nutritional value losses, contributes to the prevention of subclinical infections, and reduces mortality. The continuous use of antibiotics as a prophylaxis in poultry production is aimed at controlling problems arising from the management of large number of birds per unit of space and from the subsequent stress that animals suffer.

However, excessive use of antibiotics also entails the problematic occurrence of multiple antibiotic resistance (MAR) of potentially pathogenic bacteria, which is of public health concern due to the difficulty in treating infections caused by MAR bacteria. This treatment requires much more expensive antibiotics and long-term therapy, increasing the cost of treatment substantially (Kelley et al., 1998; Cancho Grande et al., 2000). Bacterial resistance studies in poultry done by the Center for Disease Control and Prevention (CDC) in 2004 showed that 18% of *Salmonella* and 53% of *Campylobacter* that had been isolated presented resistance to one or more antibiotics (Ano., 2007).

In an antibiotic resistance study, all nine litter isolates of *A. hydrophila* collected from four broiler houses in the northern Georgia area were resistant to ampicillin, bacitracin, penicillin, tetracycline, and streptomycin and were susceptible to erythromycin, gentamycin, kanamycin, nalidixic acid, neomycin, and sul?soxazole (Kelley et al., 1998). In 2003 and 2004, residues of anticoccidials (maduromicin and nicarbazine), arsenic, nitrofuran, quinolone (enrofloxacine), and sulfanomide were found in slaughtered fowl in Argentina (FAO-SAGPyA, 2007b). In a study carried out in the United States in January 2007, chicken carcasses selected from various stores were analyzed; 162 *Campylobacter* and 80 *Salmonella* isolates were obtained. It was determined that in 31% of the samples the antibiotic inhibited bacterial growth but did not stop it. Table 1 shows the resistance of isolated strains to selected antibiotics (Anon., 2007). The Pan American Health Organization has presented a regional panorama of the pharmaco-resistance to antimicrobials, expressing data organized both by country and by microorganism (OPS, 2008).

Pesticides Poultry may be exposed to pesticides when consuming contaminated feed or water, or when pesticides have been used in chicken pens to control outbreaks. However, in most industrialized countries, little or none trustworthy information is associated with pesticide intoxication cases. Existing records on pesticide-intoxicated people are not exact or trustworthy because adequate administrative mechanisms have not yet been developed. Consequently, data available at present are limited to estimated cases of acute intoxication (García, 1998). Most of the information available is related to pesticide levels in food, found mainly in dairy products, fish, chicken, and vegetables. The pesticides detected most frequently have been dichlorodiphenyltrichloroethane, hexachlorocyclohexane, aldrin, heptachlor and endosulfan. In general, the data reflect a tendency

TABLE 1 Antibiotic Resistance (%) of Bacteria Isolated from Chicken

Antibiotic	*Salmonella*	*Campylobacter*
Nalidixic acid	3	19
Amoxicillin/clavulanic acid	30	—
Ampicillin	30	—
Azithromycin	—	7
Cefoxitin	35	—
Ceftiofur	31	—
Ciprofloxacin	—	20
Clindamycin	—	3
Erythromycin	—	7
Kanamycin	19	—
Streptomycin	38	—
Sulfisoxazole	28	—
Telithromycin	—	4
Tetracycline	70	57
One or more drugs	84	67

Source: Anon (2007).

toward decreasing amounts of pesticides, especially DDT, because its use was prohibited some years ago (PNUMA, 2002). In a study done in the European Community, the number of samples that showed pesticide residues surpassing the maximum limits was around 4.3% (FAO-OMS, 2002).

Chemical Substances in the Environment Some chemical substances may be present in food as a consequence of environmental contamination. Their effects on health could be serious and have been a worrisome issue in recent decades. Such was the case with dioxin-associated intoxication in Seveso, Italy in 1976; and the report on the use of poultry feed adulterated with dioxin-contaminated waste industrial oils in farms in Belgium in 1999 (Rimblas Corredor, 2004).

FOODBORNE DISEASES

Foodborne diseases are a very important public health problem because of their magnitude, growing tendency, emergent and reemergent infectious diseases, occurrence of new epidemiologic scenarios and forms of transmission, rise in antimicrobial resistance, and social and economic impact (Buzby and Frenzen, 1999; Scout, 2003). Food contamination remains a very serious problem. Its magnitude, due to the absence of food protection programs and information systems, is known only partially (Motarjemi and Käferstein, 1999; Scout, 2003). Many explanations have been presented for this lack of data: Many foodborne diarrhetic illnesses are not considered as such; failure of official services to study and make known all foodborne outbreaks; deficiencies in clinical and food analysis laboratories; too few professionals trained to perform analyses

related to foodborne illnesses; and personnel in the sanitary professions with too narrow an understanding of the nature and mechanisms of foodborne illnesses (Sequeira et al., 2000). It may not be easy to detect contaminated food related to foodborne diseases since the investigative process needed to detect it is not fully developed, and many times, patients are taken care of as isolated cases without identifying the etiologic agent causing the illness. Studies of disease outbreaks would develop our ability to recognize the symptoms, agents causing the illness, food involved, places of occurrence, highly exposed population groups, reservoirs, and others factors that, taken together, would make it possible to develop control and prevention methods.

Today, it is estimated that there are approximately 4 billion cases of diarrheaz disease annually worldwide, primarily, but not exclusively, in developing countries (Motarjemi and Käferstein, 1999). The World Health Organization (WHO) estimates that the number of foodborne disease cases could be from 300- to 500-fold above what the statistics indicate, and the most important cause of avoidable death and reducible economic impact. In the United States, 76 million people get ill each year as a consequence of foodborne diseases, 325,000 persons are hospitalized, and 5000 died (Doyle, 2000). According to data from the Pan American Health Association, during the last 9 years in Latin America, close to 250,000 persons became ill due to foodborne diseases, of whom 318 died (WHO, 2005). In the United States, the Centers for Disease Control reported that in 2004, poultry meat was identified as causing 24% of foodborne diseases (CDC, 2006).

FOODBORNE OUTBREAKS TRANSMITTED BY FOOD ASSOCIATED WITH POULTRY MEAT

Foodborne disease surveillance systems operate differently in each country, some of them being less reliable than others. This reality makes it difficult to compare the incidence of foodborne diseases among countries in a region. Moreover, few systems identify accurately the source responsible for the case or outbreak; on the contrary, in most systems "meat products" are held responsible without specifying the pathogen species involved. A high percentage of cases reported cannot be associated to some food in particular or the pathogen responsible can not be identified. This is so since quite frequently the results of bacteriologic analyzes are delayed and the food involved is no longer available to be examined. In view of that, the real-frequency isolation is not always known, and the information available is generally reported in fewer cases than those that really exist.

From 1993 to 2002, Latin American and Caribbean countries reported a total of 6878 foodborne outbreaks, involving 249,197 patients, of which 318 died. From the total of foodborne outbreaks, 292 (4.25%) were related to poultry meat consumption (Table 2); six people died. These data show these illnesses' high morbidity and low mortality (INPPAZ/OPS/OMS, 2008). Etiological agents involved in foodborne outbreaks associated with poultry meat consumption were mainly biological, the most common being associated with *Salmonella* spp.

TABLE 2 Foodborne Outbreaks and Deaths Associated with Poultry Meat in Latin American and Caribbean Countries, 1993–2002

Country	Number of Outbreaks	Number of People Involved	Deaths
Argentina	9	76	0
Brazil	24	470	0
Chile	9	82	0
Costa Rica	1	4	0
Cuba	150	9,686	0
Dominican Republic	2	33	0
Ecuador	4	178	0
El Salvador	2	78	0
Jamaica	1	16	0
Mexico	45	1,641	5
Nicaragua	1	18	0
Panama	7	88	0
Paraguay	8	59	0
Peru	6	744	0
Trinidad and Tobago	7	26	1
Uruguay	9	268	0
Venezuela	7	270	0
Total	292	13,737	6

Source: INPPAZ/OPS/OMS (2008).

(26%), *Clostridium perfringens* (19%), *Stapylococcus aureus* (16%), *Escherichia coli* (9%), and coliforms (2%). In contrast, *Bacillus cereus* and *Shigella* were present in only one foodborne outbreak. In the case of chemical hazards, one foodborne outbreak was associated with potassium dichromate and another with the presence of pesticides. In 27% of foodborne outbreaks it was not possible to identify the causal agent (INPPAZ/OPS/OMS, 2008).

Homes, restaurants, and catering services (schools, nursing, etc.) accounted for 59% of the total of the foodborne outbreaks (Figure 1) (INPPAZ/OPS/OMS, 2008). This situation is similar to that observed by the WHO in Europe, where homes and restaurants accounted for 62% of foodborne outbreaks identified from 1993 to 1998 (FAO-OMS, 2002). In such studies, there is great variability among countries when the association that each place had with the food products consumed was analyzed; for example, foodborne outbreaks are much more common in Hungarian homes than in Swisz homes, a situation that may be associated with health education programs developed by each government.

Evaluating the data available from Latin America and Caribbean countries (INPPAZ/OPS/OMS, 2008) calls attention to the small number of cases reported on food consumption from street vendors. Taking into consideration the sanitary problems that exist in these countries, particularly in relation to street food consumption (Arámbulo et al., 1995), it is probable that the lack of information is associated with a lack of notification.

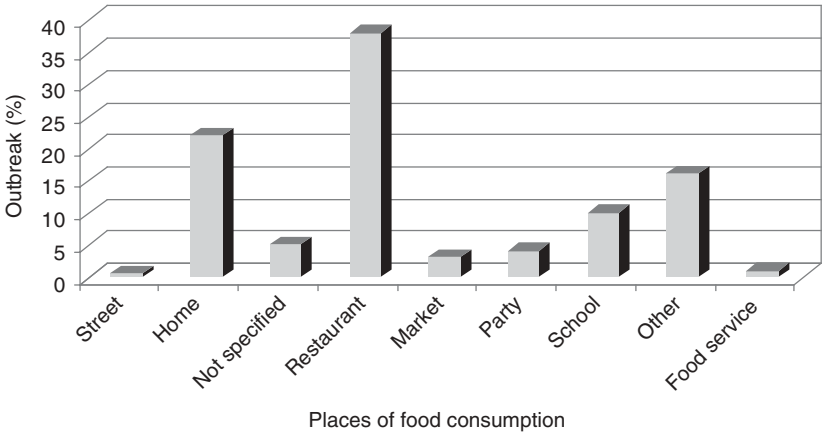

FIGURE 1 Foodborne outbreaks reported in Latin America and the Caribbean from 1993 to 2002. (From INPPAZ/OPS/OMS, 2008.)

From 1993 to 2002, there were 60 foodborne outbreaks of *Salmonella* in Argentina, with 889 ill people and four deaths. Of these outbreaks, 6.7% were caused by *Salmonella enteritidis*, 1.7% by *Salmonella typhimurium*, and 1.7% by *Salmonella arizonae*. In 90% of the cases it was not possible to identify the corresponding serovariety. As regards the food involved in these foodborne outbreaks, 25% corresponded to egg derivatives, mayonnaise, and poultry meat (Velilla et al., 2004). In 1999, in the Department of Antioquia, Colombia, it was found that of 88 informed foodborne outbreaks 32% were connected with poultry meat and 5.7% with egg-based products such as mayonnaise (Uribe and Suárez, 2006). In 2006, the Sistema Nacional de Vigilancia en Salud Pública (SIVIGILA; National System of Public Health Surveillance) in Colombia reported 34 foodborne outbreaks, and in 18 there was an association between poultry and the meals held liable for the outbreak. These outbreaks involved 1107 people (INVIMA, 2006).

In 2002, the WHO established the Global Salmonella Survillance (GSS), a global network of laboratories and people involved in *Salmonella* surveillance, isolation, identification, and tests for antimicrobial resistance. The objective of this network is to strengthen foodborne disease surveillance based on the information reported by the laboratories in different countries (WHO, 2005). Several countries in Latin America and the Caribbean countries are part of this network. Information available from them shows that *S. enteritidis* is the most common *Salmonella* serotype in humans globally, but especially in Europe, where it accounts for 85% of *Salmonella* cases, Asia 38%, and Latin America and the Caribbean countries 31%. In 2002 in Latin America and the Caribbean countries, *S. enteritidis* was the most common serotype among human and nonhuman isolates. *S. typhimurium, S. typhi, S. montevideo*, and *S. paratyphi* B were also commonly observed among human isolates, and *S. typhimurium, S. senftenberg, S. mbandaka*, and *S. agona*, among nonhuman isolates. During the 3-year period of interest, *S. enteritidis, S. typhimurium*, and *S. typhi* were the three most

commonly isolated serotypes among humans in the five countries that reported data every year (Galanis et al., 2006).

In 1999 in Uruguay, of 41 foodborne outbreaks reported, 97.5% were caused by bacteria. In more than half of them (57.5%) *Salmonella* was identified as the agent responsible, and 14 were due to *S. enteritidis*. Coliform bacteria were isolated in 20% of the outbreaks once the etiologic analyses were completed. A total of 729 persons were affected, yet only one death was reported (Acuña et al., 2002).

In 2003 in Cuba, of the 504 foodborne outbreaks reported and studied, 16,888 people were affected, three of whom died. One hundred and twelve of 504 the outbreaks were due to ciguatera poisoning, affecting 487 persons; 320 were caused by other food and involved 13,343 persons; and 72 foodborne outbreaks were associated with water, affecting 3859 persons. From the outbreaks associated with food, 42% were due to meat and meat products, and in 49% of them the etiological agent identified was a *Salmonella* sp. (Ministerio de Salud Pública de Cuba, 2004).

In 2002 in Nicaragua, GSS registered 23 foodborne outbreaks and 12 sporadic cases, resulting in 159 persons affected through consumption of contaminated food, but no deaths were reported. In only one foodborne outbreak, which affected six persons, was it possible to associate poultry meat consumption with the illness, yet it was not possible to isolate the etiological agent involved (Ministerio de Salud de Nicaragua, 2003).

In 1994 the Servicio de Salud Metropolitano del Ambiente (SESMA; Metropolitan Environmental Health Service) in Chile began epidemiologic surveillance of foodborne outbreaks in the Santiago metropolitan area. Reports of outbreaks have increased gradually, from 86 in 1994 to 260 in 2000. The foods most involved were homemade mayonnaise, meringue cake (angel cake), eggs, catering food, and desserts made with milk. *S. enteritidis* associated with these outbreaks has been detected in samples taken from poultry food, mainly meat and giblets. Moreover, its presence was also confirmed as a contaminant in eggs and poultry meat offered for sale at retail stores (Prado et al., 2002).

In 2005 in Costa Rica, 23 foodborne outbreaks affecting 819 people were studied. Thirteen of them (57%) occurred among members of different family groups; 10 cases were associated with *Shigella* spp. serotypes. In only 5 of 23 outbreaks was it possible to demonstrate the presence of *Salmonella* spp. (Bolaños-Acuña et al., 2005).

From the total of foodborne outbreaks reported in Venezuela in 2004, 7.6% corresponded to diseases transmitted by water and food. The main foods involved were cheese (46%), fish (12%), and meat products (5%). The main causal agent identified was *Staphylococcus* spp., and home was the first place of occurrence (Ministerio de Salud y Desarrollo Social de Venezuela, 2008).

From 1980 to 1989 in Mexico, 314 foodborne outbreaks were reported to the Dirección General de Epidemiología (General Epidemiology Directorate), with a total of 12,344 people affected and 348 deaths. Fifty-eight outbreaks were confirmed by laboratory tests; *Staphylococcus aureus* was identified as the

main agent (48.2%), followed by *Salmonella typhimurium* (34.0%). Most of the foodborne outbreaks occurred after a party or social gathering (24%), in schools and kindergartens (24%), in restaurants (10%), and in hospitals (9%). Among the foods involved, cheese and dairy products were in first place (29%), with poultry meat being a less compromized food (Parrilla-Cerrillo et al., 1993).

From 1993 to 2002, sanitary authorities in Mexico reported 633 foodborne outbreaks involving 19,493 people, 107 of whom died; in 398 cases, it was not possible to identify the agent. Chemical agents were detected in 52 cases; 183 different biological agents, including hepatitis A, *Salmonella* spp., *S. aureus*, and *E. coli*, were reported. In 424 of the outbreaks the contaminated food was identified, and in 56 cases poultry meat or poultry products were involved (INPPAZ/OPS/OMS, 2008).

CONCLUSIONS

Quality assurance and food safety is an essential activity of public health authorities to raise average life expectancy of the population and increase the possible food export potentiality, leading to a fake health–commerce dichotomy (OPS/OMS, 2005). Foodborne outbreaks studied in Mexico constitute a minimum part of what is happening in that country, which is why it is necessary to implement and update the techniques used for enteropathogenic diagnosis interrelated with foodborne diseases, to coordinate programs among laboratories, epidemiology services, and preventive medicine and sanitary regulations, with the objective of improving epidemiology surveillance systems (Parrilla-Cerrillo et al., 1993). This situation is present in many of the countries of the region and necessitates multidisciplinary work and joint cooperation efforts to overcome national political barriers and so avert it. In Latin America and the Caribbean, foodborne outbreaks have risen due to population increase, tourism, accelerated urbanization, intense international commerce in food, and regional socioeconomic crises, all factors associated with an increase in vulnerable groups and new forms of chemical and microbial contamination (OPS/OMS, 2005). By means of epidemiologic surveillance of foodborne outbreaks it may be possible to obtain the information necessary to guarantee success of in quality assurance and food safety. Existing data variability makes difficult implementation of an effective strategy that would make it possible reach that objective. SIRVETA (INPPAZ/OPS) and Global *Salmonella* Surveillance (FAO-OMS) are two valuable tools used to collect the needed information. It is also necessary that there be continuity in these programs in every country in the region, with active involvement in sending adequate information as well as participating in activities that have to do with training, coordination, and cooperation.

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OVERVIEW OF POULTRY PROCESSING AND WORKERS' SAFETY

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INTRODUCTION

In a modern society, trade and commercial transactions, when reduced to simplest term, are made by three parties, willingly or unwillingly: government, business and industry, and consumers. A business manufactures a good-quality

Handbook of Poultry Science and Technology, *Volume 1: Primary Processing*, Edited by Isabel Guerrero-Legarreta and Y.H. Hui

products according to the need and preference of consumers. The government monitors the activities of the businesses or firms and incorporates such activities into a database. It uses the information for a variety of reasons, such as taxation, safety of the consumers and workers in the workplace, technology transfers, economic profiles of various industries, and the country's growth in relation to any particular industry. This approach is practiced in most Western countries. The foundation of this government activity or its database is to classify the various manufacturing businesses accordingly, such as car manufacturers, chemical manufacturers, computer manufacturers, and food manufacturers.

Standard Industrial Classification System

The Standard Industrial Classification (SIC) is an establishment–industry classification system that is prepared by the U.S. government for use by all federal agencies, especially those involved in statistics, labor, consumer safety, and so on. Food manufacturing is included in this classification. The SIC is used, among other functions, for the presentation of state and local area estimates of earnings and employment by industry, and records of worker injuries. It is used by the federal government for estimates for the private sector only, although it is designed to cover both public and private economic activities. To understand food manufacturing in the United States, it is important to know the classification of various establishments engaged in food manufacturing in this industry. This is especially important to a food company because state agencies also use the classification system to assist its state officials in monitoring the food manufactured by each company in terms of:

- Compliance with state standards
- Product safety for the consuming public
- Potential economic fraud involving the products

In the SIC, establishments are classified by the primary activity in which they are engaged, and each establishment is assigned an industry code. The information is provided in the *SIC Manual* distributed by the Occupational Safety and Health Administration (OSHA) of the U.S. Department of Labor. The SIC is divided into divisions A to J. Division D, "Manufacturing," is further divided into groups, Major Group 20 being "Food and Kindred Products." This group includes establishments manufacturing or processing foods and beverages for human consumption, and certain related products, such as manufactured ice, chewing gum, vegetable and animal fats and oils, and prepared feeds for animals and fowls. Products described as dietetic are classified in the same manner as nondietetic products (e.g., as candy, canned fruits, cookies). Many other establishments, such as manufacturers of ingredients such as chemical sweeteners, are classified in other major groups within the division.

Division D: Manufacturing Major Group 20: Food and Kindred Products, Industry Group 201: Meat Products

2015: Poultry Slaughtering and Processing Establishments engaged primarily in slaughtering, dressing, packing, freezing, and canning poultry, rabbits, and other small game, or in manufacturing products from such meats, for their own account or on a contract basis for the trade. This industry also includes the drying, freezing, and breaking of eggs. Establishments engaged primarily in cleaning, oil treating, packing, and grading of eggs are classified under Wholesale Trade, Industry 5144; and those engaged in the cutting up and resale of fresh carcasses are classified under Wholesale and Retail Trade.

- *Chickens, processed:* fresh, frozen, canned, or cooked
- *Chickens:* slaughtering and dressing
- *Ducks, processed:* fresh, frozen, canned, or cooked
- *Ducks:* slaughtering and dressing
- *Egg albumen*
- *Egg substitutes made from eggs*
- *Eggs:* canned, dehydrated, desiccated, frozen, and processed
- *Eggs:* drying, freezing, and breaking
- *Frankfurters, poultry*
- *Game, small:* fresh, frozen, canned, or cooked
- *Game, small:* slaughtering and dressing
- *Geese, processed:* fresh, frozen, canned, or cooked
- *Geese:* slaughtering and dressing
- *Ham, poultry*
- *Luncheon meat, poultry*
- *Poultry, processed:* fresh, frozen, canned, or cooked
- *Poultry:* slaughtering and dressing
- *Rabbits, processed:* fresh, frozen, canned, or cooked
- *Rabbits:* slaughtering and dressing
- *Turkeys, processed:* fresh, frozen, canned, or cooked
- *Turkeys:* slaughtering and dressing

North American Industrial Classification System

In February 1999, the statistical agencies of Canada, Mexico, and the United States launched a joint multiphase initiative to develop a comprehensive industrial classification known as the North American Industrial Classification System (NAICS). The foundation of the project was completed basically in 2007. However, permanent revision to refine the system will take place every few years. In basic principles and format, NAICS is essentially the same as SIC, with two major differences:

1. It links three countries in trade: Canada, Mexico, and the United States.
2. The code for each industry is different.

However, it must be emphasized that many other details differentiate NAICS from SIC.

Contents for NACIS Code 3116, Poultry Processing

2007 NAICS	Index Entries for This Industry
311615	Canning poultry (except baby and pet food)
311615	Chickens, processing, fresh, frozen, canned, or cooked (except baby and pet food)
311615	Chickens, slaughtering and dressing
311615	Dressing small game
311615	Ducks, processing, fresh, frozen, canned, or cooked
311615	Ducks, slaughtering and dressing
311615	Geese, processing, fresh, frozen, canned, or cooked
311615	Geese, slaughtering and dressing
311615	Hams, poultry, manufacturing
311615	Hot dogs, poultry, manufacturing
311615	Luncheon meat, poultry, manufacturing
311615	Meat canning, poultry (except baby and pet food), manufacturing
311615	Meat products (e.g., hot dogs, luncheon meats, sausages) made from a combination of poultry and other meats
311615	Poultry (e.g., canned, cooked, fresh, frozen) manufacturing
311615	Poultry (e.g., canned, cooked, fresh, frozen) processing
311615	Poultry canning (except baby, pet food)
311615	Poultry slaughtering, dressing, and packing
311615	Processed poultry, manufacturing
311615	Rabbits processing (i.e., canned, cooked, fresh, frozen)
311615	Rabbits slaughtering and dressing
311615	Small game, processing, fresh, frozen, canned, or cooked
311615	Small game, slaughtering, dressing, and packing
311615	Turkeys, processing, fresh, frozen, canned, or cooked
311615	Turkeys, slaughtering and dressing

Why are both systems, one old and one new, presented here? As far as the United States is concerned, the reasons are simple:

1. For all practical purposes, NACIS is less significant for domestic trading.
2. To change from SIC to NACIS will affect thousands of government documents. The change will be slow. Eventually, the old system will be replaced

by the new system. At present, SIC is preferred by both government and the food industries.
3. For trading between the United States and Canada or Mexico, NACIS will definitely be used.

Although the applications of SIC in the United States are discussed at the beginning of this chapter, the domestic uses of NACIS by Canada or Mexico may be the same or different from those in the United States and are not discussed here.

WORKERS' HEALTH AND SAFETY

In the United States, the safety of workers in a poultry-processing plant is regulated by OSHA. OSHA carries out its responsibility by issuing appropriate regulations and requirements to the industry with SIC code 2015 (poultry processing) affecting the establishments listed earlier (e.g., processed turkey: fresh, frozen, canned, or cooked). Two examples of work safety are:

1. A worker in contact with a turkey carcass may become infected with pathogen.
2. A worker handling the electric saw used in cutting a turkey carcass into parts may lose a finger in the process.

Thus, the processing plant must comply with OSHA regulations governing contact with a carcass and those governing the use of an electric saw in cutting poultry parts. In this chapter and the next we look at the following in a poultry-processing plant:

1. The types of injuries involved
2. The most relevant regulations and their implementation
3. The principles and applications of ergonomics
4. The latest tool made available to operators

In this chapter we discuss two types of potential injuries from biological agents in a poultry-processing plant. In Chapter 38 we describe other physical injuries. The OSHA Web site is a good place to obtain more information.

Psittacosis

The OSHA has provided the following information concerning the hazard of occupational exposure to psittacosis that may be found in pet shops, quarantine facilities, and the poultry-processing industry. Psittacosis is caused by a bacterium, *Chlamydia psittaci*, which is transmitted to humans from birds. Psittacine birds such as parrots and parakeets are classically responsible, although pigeons, chickens, and turkeys may carry the disease as well. An infected bird may appear

to have red, watery eyes, nasal discharge, diarrhea, and a poor appetite. After a bird recovers from infection, the bacteria may remain in its blood, feathers, and droppings for many weeks.

Humans may acquire psittacosis by inhaling infected particles from bird droppings. Symptoms begin 1 to 3 weeks after exposure and usually include headache, fever, and coughing. A "flulike" syndrome of nausea/vomiting, joint aches, and muscle aches is also common. Severe infection may develop into pneumonia that requires hospitalization. Psittacosis is treated with common antibiotics (doxycycline or erythromycin), although recovery may take several weeks. Sustained immunity to infection does not develop; some people have been reported to get the disease more than once. Fewer than 1% of all cases are fatal.

The U.S Department of Agriculture (USDA) regulations require that imported psittacine birds be quarantined for 30 days. The birds may be fed chlortetracycline to prevent transmission of the disease to birds and to humans in quarantine stations; however, the bacteria continue to be found in released birds. Additionally, workers handle many birds that are not imported; rather, they are bred in this country and therefore are not subject to the USDA's medication requirements. OSHA does not have a standard specific to the hazard of psittacosis. However, a number of OSHA standards and good industrial hygiene practices apply. Precautions to protect workers from contracting this disease through inhalation include at a minimum the following:

1. Providing respiratory protection suitable for the purpose intended [high-efficiency particulate air (HEPA) filter] and establishing a respirator program
2. Assuring adequate ventilation in the work area
3. Establishing a psittacosis training and prevention program that includes:
   a. A description of the signs and symptoms associated with psittacosis
   b. Instructions on how to recognize psittacosis in affected avian species
   c. Good housekeeping and work practices procedures
4. Instructing workers to report immediately to the employer any indications that a bird may be infected
5. Instructing workers to report immediately to the employer the development of any adverse signs and symptoms consistent with psittacosis

Caretakers for avian birds should practice the following:

1. When cleaning cages or handling infected birds, caretakers should wear protective clothing, including gloves, a disposable surgical cap, and an appropriately fitted respirator.
2. Cage papers can be lightly misted with a disinfectant to dampen dry stool before removal. This will decrease the amount that becomes airborne.
3. Stool and dirty cage papers placed in a plastic bag should be tied off and placed in another clean garbage bag before disposal.

4. Caretakers should always wash their hands thoroughly with soap and water and remove protective clothing when leaving a contaminated area.

Avian Influenza or Bird Flu

Influenza A viruses can cause three distinct diseases in humans: avian, pandemic, and seasonal influenza. *Avian influenza* in humans is rare; the most common route of infection is via direct or indirect contact with secretions (nasal, oral, or fecal) from infected poultry. Transmission from human to human, if it exists, is extremely rare. However, avian influenza viruses have the potential to mutate or reassort and become pandemic viruses; those that can be transmitted readily between humans and those for which the population has little immunity. If these viruses spread throughout the world, the disease caused by them would be called *pandemic influenza* and the new viruses would be called *pandemic influenza viruses*. Previous pandemic influenza episodes have occurred in two or three waves of 6 to 8-week duration and spanned a 12- to 18-month period. After this period, the population will have built up immunity to the virus, either naturally or through vaccination. If the virus continues to circulate in the population and to cause disease, it would become an influenza virus that causes *seasonal influenza* (more popularly called *human influenza* or the *flu*).

Influenza A viruses are subdivided into numerous subtypes. The subtypes are differentiated by variations in two viral surface proteins, hemagglutinin (H) and neuraminidase (N). Sixteen different H proteins and nine N proteins have been identified. Subtypes are designated by numbering particular combinations of these proteins (e.g., H5N1). Therefore, there are a total of 144 possible subtypes ($16H \times 9N$) of influenza A viruses, and all or most of these have been found in wild waterfowl. Interestingly, only three of the 144 subtypes, H1N1, H2N2, and H3N2, have caused pandemic influenza in the twentieth century. Only strains of H1N1 and H3N2 are currently circulating and causing seasonal influenza. Recently, a number of different subtypes of influenza A viruses have emerged as agents of avian influenza in humans, and these include H5N1, H7N2, H7N3, H7N7, and H9N2.

As of October 2006, H5N1 viruses have killed more than 150 people in 10 different countries since the beginning of 2003. On the other hand, the H7N7 virus has been associated with a single human death but numerous cases of conjunctivitis (eye infection) in the Netherlands. The H7N2, H7N3, and H9N2 viruses have caused only mild disease in humans. While the number of human deaths caused by the H5N1 virus is small in comparison to the annual deaths attributed to human seasonal influenza viruses (ca. 36,000 per year in the United States), it is of particular concern to the public health community because many scientists believe that this virus may continue to mutate or reassort and a strain may ultimately develop the ability to pass readily between humans. If this happens, the virus that emerges may cause the next major influenza pandemic.

Poultry employees among others are likely to become exposed to avian influenza if it reaches the United States. The best sources of information are

OSHA, the CDC (Centers for Disease Control), and the USDA (www.osha.gov, www.cdc.gov, www.usda.gov). The recommendations of OSHA, the CDC, and the USDA include the following procedures: basic infection control, personal protective equipment (PPE), antiviral drug use and seasonal flu vaccination, medical monitoring of employees, and disinfection of contaminated areas. A safety and medical officer should be identified to ensure compliance with procedures. Employees potentially at risk:

- Poultry farmers and their employees
- Service technicians of poultry-processing facilities
- Caretakers at poultry facilities
- Layer barn employees
- Chick movers at egg production facilities
- Employees involved in disease control and eradication activities, including:
  - State
  - Federal
  - Contract
  - Company employees
- Live-bird market employees
- Bird-fighting industry employees

Signs That Poultry May Be Infected Employers should train employees to be alert to poultry that develop one or more of the following signs:

- Sudden death (no apparent symptoms)
- Lack of energy and appetite
- Lack of coordination
- Purple discoloration of the wattles, combs, and legs
- Soft-shelled or misshapen eggs
- Diarrhea
- Swelling of the head, eyelids, comb, wattles, and hocks
- Nasal discharge
- Decreased egg production
- Coughing or sneezing

Transmission to Humans Exposure of the conjunctival membranes of the eyes and/or the oral or nasal mucosa to secretions (oral, nasal, or fecal) from avian influenza (AI)–infected birds is the predominant route of transmission of these viruses to humans. In contrast, seasonal human influenza viruses are transmitted primarily from person to person via nasal or oral secretions only. Direct contact with bird secretions and inhalation of dust contaminated with these secretions should be avoided.

Infection Control Measures

1. Educate employees about the importance of strict adherence to hand hygiene, especially after any of the following activities:
   a. Contact with infected or exposed poultry
   b. Contact with surfaces contaminated with bird feces or respiratory secretions
   c. Removing personal protective equipment of any kind (e.g., gloves, goggles, respirator, etc.).
2. Good hand hygiene should consist of the following:
   a. Washing the hands thoroughly with soap and water for 15 to 20 s; or
   b. If hand-washing facilities are not readily available, use other standard hand-disinfection procedures as specified by state government, industry, or USDA outbreak-response guidelines.
3. Ensure that personnel have access to appropriate personal protective equipment (PPE) and instructions and training in PPE use.
4. Personnel should not eat, drink, or smoke or use bathroom facilities while engaged in activities where contact with contaminated animals or surfaces is possible. PPE should be removed and discarded or disinfected properly. Hands should then be washed thoroughly before eating, drinking, smoking, or bathroom use.

Personal Protective Equipment Do not eat, drink, smoke, or use bathroom facilities while engaged in activities where contact with contaminated animals or surfaces is possible. PPE should be removed and discarded or disinfected properly. Hands should then be washed thoroughly before eating, drinking, smoking, or bathroom use.

Hand Protection

- Wear lightweight nitrile or vinyl disposable gloves, or
- Wear heavy-duty rubber work gloves that can be disinfected.

Important considerations:

- Avoid touching the face and mucous membranes, including the eyes, with gloved hands that have been contaminated.
- Gloves should be changed if torn, punctured, or otherwise damaged.
- Remove gloves promptly after use.
- Gloves used should be appropriate for the activities (e.g., for some activities it may be more appropriate to use thick rather than lightweight gloves).
- Long-term use of gloves can result in dermatitis caused by prolonged exposure to perspiration. This can be alleviated by the use of a thin cotton glove worn inside the external glove.

Body Protection

- Wear disposable outer garments or coveralls with an impermeable apron over them, or
- Wear surgical gowns with long, cuffed sleeves, plus an impermeable apron.
- Wear disposable head or hair cover to keep the hair clean.

Important considerations:

- Because protective clothing can be more insulating than regular work clothing, precautions should be taken to protect employees from the effects of heat stress.

Foot Protection

- Wear disposable protective shoe covers, or
- Wear rubber or polyurethane boots that can be cleaned and disinfected.

Eye Protection

- Wear safety goggles to protect the mucous membranes of the eyes.

Important considerations:

- Properly fitted, indirectly vented safety goggles with a good antifog coating may be a good choice for poultry employees who have lower risks of exposure (e.g., those employees not involved directly in culling poultry). However, such goggles are not airtight, and consequently, they will not prevent exposures to airborne material.
- Employees who wear prescription lenses should wear eye protection that has the correction built into the safety lenses of the protective eyewear, has lens inserts, or can be fitted over regular street-wear prescription glasses without compromising eye or respiratory protection.
- Eye protection should be fitted together with a respirator because some goggles can alter the fit of a half-facepiece respirator. To ensure that the eye protection does not interfere with a facepiece seal, it should be worn when half-facepiece respirators are fit-tested and when employees conduct seal checks each time they put on the respirator.

Respiratory Protection

- NIOSH-approved disposable particulate respirators (e.g., N95, N99, or N100) are the minimum level of respiratory protection that should be worn.

Important considerations:

- This level of respiratory protection or higher may already be in use in poultry operations, due to other hazards that exist in the environment (e.g., vapors, dusts).
- For farms using oils as dust suppressants, use R or P series respirators.
- Employees who are unable to wear a disposable particulate respirator because of facial hair or other fit limitations should wear a loose-fitting

helmeted or hooded powered air-purifying respirator (PAPR) equipped with high-efficiency particulate air (HEPA) filters. A PAPR also provides needed eye and mucous membrane protection.

- For employees with substantial exposure to contaminated materials (e.g., those employees involved directly in mass culling of birds), a PAPR may be a practical alternative in a hot, dirty, and wet environment compared to a disposable particulate respirator.
- Note that the particulate respirators recommended above are not appropriate for protection against decontamination or sanitizing chemicals that may be used in disinfection activities (see the section "Disinfection of Areas Contaminated by AI-Infected Bird").
- Children should not do any work that requires wearing a respirator.
- OSHA requires that respirators must be used in the context of a complete respiratory protection program (RPP). This includes training, fit testing, and user seal checks to ensure appropriate respirator selection and use. To be effective, tight-fitting respirators must have a proper sealing surface on the wearer's face.

Removal of Personal Protective Equipment

- Employees should always remove protective clothing (except for gloves) first and discard or secure the clothing for disinfection before removing their respirators and goggles.
- Remove and discard disposable gloves.
- Wash hands thoroughly with soap and water.
- Keep hands away from the mouth and face until hands are washed thoroughly.
- Remove eye protection and place in a designated receptacle for subsequent cleaning and disinfection.
- Remove the particulate disposable respirator and discard.
- Wash hands thoroughly with soap and water a second time immediately after all PPE has been removed.
- Disposable PPE should be treated as contaminated material and discarded properly.
- Nondisposable PPE should be cleaned and disinfected as specified in state government, industry, or USDA outbreak-response guidelines.

Important considerations:

- All PPE should be removed carefully to avoid dispersal of contaminated material.
- Hand hygiene measures should be performed promptly after removal of PPE.
- If soap and water are not available, use an alcohol-based hand gel.

Vaccination with Seasonal Influenza Vaccine

- The CDC recommends that unvaccinated employees receive the current season's influenza vaccine.

Important considerations:

- The current season's vaccine will reduce the possibility of coinfection with both an AI virus and a human influenza virus. Although there is only a small possibility that coinfection would occur, if it were to happen, there is a potential for the reassortment of the genetic material from the two viruses with the consequent development of a new human flu virus (i.e., one that is transmissible between people). This novel virus would have the potential to cause an influenza pandemic.

Administration of Antiviral Drugs

- The CDC recommends that employees having direct contact with infected poultry or surfaces contaminated with respiratory secretions or feces from infected birds should receive a prophylactic dose of an influenza antiviral drug daily for the entire time that they are in direct contact with infected poultry or contaminated surfaces, as well as for 1 week following their last exposure. Antiviral medications are an important adjunct to vaccination; they are not a substitute for vaccination.

Medical Monitoring of Employees

- Employers should instruct employees to be vigilant for the development of AI symptoms. These symptoms have ranged from typical human influenza-like symptoms (fever, cough, sore throat, and muscle aches) to eye infections (conjunctivitis), pneumonia, severe respiratory diseases (such as acute respiratory distress syndrome), and other severe and life-threatening complications.

Important considerations:

- Human AI infections are manifested in different ways, depending on the health status of the person before the infection and pathogenicity of the AI strain. Although the symptoms are, in general, flulike, they may vary.
  - Persons infected with the H7N7 virus that caused the outbreak in the Netherlands in 2003 most frequently had conjunctivitis only.
  - Hospitalized persons infected with strains of the H5N1 subtype most frequently had fever combined with a cough and also had difficulty breathing and/or diarrhea. Conjunctivitis was rare.
- Employees who become ill after possible exposure to the AI virus should do the following:
  - Seek medical care but prior to arrival notify their health care provider that they may have been exposed to AI.
  - Notify the occupational health and infection control personnel at their facility.

- With the exception of visiting a health care provider, stay home until 24 h after resolution of fever, unless:
  - An alternative diagnosis is established that explains the patient's illness; or
  - Diagnostic tests are negative for influenza A virus.
- While at home, ill persons should practice good respiratory and hand hygiene to lower the risk of transmission of the virus to others. For more information, visit the following CDC Web sites:
  - Cover Your Cough (www.cdc.gov/flu/protect/covercough.htm)
  - Hand Hygiene Guidelines Fact Sheet (www.cdc.gov/od/oc/media/pressrel/fs021025.htm)

Disinfection of Areas Contaminated by AI-Infected Birds After an AI outbreak, it is important that the contaminated areas be disinfected. Depending on temperature and moisture conditions, AI viruses can survive in the environment for long periods, even weeks. However, AI viruses are generally susceptible to the following chemical and physical methods of inactivation:

- Chemical methods
  - Most detergents
  - Specific disinfectants
- Physical methods
  - Heating (the higher the temperature, the more rapid the inactivation)
  - Complete drying

Disinfection in the field is normally done using a chemical method. Viruses associated with organic material such as dust, dirt, litter, and manure may be less susceptible to disinfection because they may be protected from direct contact with the disinfectant.

Certain EPA-registered disinfectants labeled for use against avian influenza viruses are effective for use on hard, nonporous surfaces listed on the label. The label of an EPA-registered disinfectant describes how to use the product safely and effectively and includes measures that persons applying the products should take to protect themselves. The PPE listed on a disinfectant product label is based on the product's toxicity and potential risks associated with use of the product according to the product label. Wearing less protective PPE than specified on the label is considered misuse of the product and a federal violation. However, employees may wear more protective PPE than required on the label.

GUIDANCE FOR FOOD HANDLERS

This guidance is for situations in which highly pathogenic avian influenza (HPAI) H5N1 has been diagnosed or is suspected in poultry or wild birds in your

area. Although there is no direct evidence that any human cases of AI have been acquired by eating poultry products, raw poultry should always be handled hygienically because it can be associated with many infections, including *Salmonella* infections. Therefore, all utensils and surfaces (including hands) that come in contact with raw poultry should be cleaned carefully with water and soap immediately afterward.

Infected poultry stocks should be destroyed before having any possibility of entering the food chain. Ducks can be asymptomatic (with no symptoms) H5N1 carriers, and duck products could be unknowingly contaminated with the virus. In 2001, frozen duck meat imported to South Korea from China was contaminated with HPAI H5N1. Once isolated from the meat, the virus was still infective to mice (mice are used as an animal model for testing the pathogenicity of avian influenza viruses. In a more recent study, an HPAI H5N1 strain was also found in duck meat imported into Japan from China. Eggs from infected poultry could also be contaminated with the virus and therefore care should be taken in handling shell eggs or raw egg products. Fortunately, influenza viruses are destroyed by adequate heat.

Two groups of employees most at risk in poultry food handling are grocery store employees that process raw chicken (butcher it into parts, package parts, etc.) and cooks at restaurants. Grocery store employees should use good hand hygiene routinely when handling raw poultry or poultry products and observe the additional precautions listed below as important considerations after guidance for cooks. During the preparation of poultry, cooks are reminded to follow proper food preparation and handling practices, including the following:

- Separate raw meat from cooked or ready-to-eat foods. Do not use the same chopping board or the same knife for preparing raw meat as is used for cooked or ready-to-eat foods.
- Do not handle either raw or cooked foods without washing your hands and equipment in between.
- Do not return cooked meat to the same plate or surface that it was on before it was cooked or to any surface contaminated with raw poultry.
- Thoroughly cook all poultry products, including eggs and poultry blood. Egg yolks should not be runny or liquid. Poultry meat and eggs should reach a temperature of 165°F (ca. 74°C) throughout to ensure destruction of the virus.
- Do not use raw or soft-boiled eggs in foods that will not be cooked.
- After handling raw poultry or eggs, wash your hands and all surfaces and utensils thoroughly with soap and water or an alcohol-based hand gel (if hands are not visibly soiled).

Important considerations:

- Avoid touching your mouth, nose, or eyes while handling raw poultry products; the virus could be transmitted in this manner.

- Avoid generating aerosols when cutting up poultry; the virus could be transmitted in this manner. For more information on good hand hygiene, consult the CDC's Web site:
  - Hand Hygiene Guidelines Fact Sheet (www.cdc.gov/od/oc/media/pressrel/fs021025.htm)

Precautions

- Avoid all contact with poultry (e.g., chickens, ducks, geese, pigeons, quail) or any wild birds, and avoid areas where H5N1-infected poultry may be present, such as commercial or backyard poultry farms and live poultry markets.
- Do not eat uncooked or undercooked poultry or poultry products, including dishes made with uncooked poultry blood.
- As with other infectious illnesses, one of the most important preventive practices is careful and frequent handwashing. Cleaning your hands often using soap and water (or waterless, alcohol-based hand rubs when soap is not available and hands are not visibly soiled) removes potentially infectious materials from your skin and helps prevent disease transmission.
- The CDC does not recommend the routine use of masks or other personal protective equipment while in public areas.

All employees with potential occupational exposure should be trained on the hazards associated with exposure to influenza A (H5N1) and be familiar with the protocols in place in their facility to isolate and report cases or reduce exposures.

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POULTRY-PROCESSING INDUSTRY AND eTOOL

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INTRODUCTION

Since 1975, workers in this industry have consistently suffered injuries and illnesses at a rate more than twice the national average. The Occupational Safety

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Handbook of Poultry Science and Technology, *Volume 1: Primary Processing*, Edited by Isabel Guerrero-Legarreta and Y.H. Hui

and Health Administration (OSHA) of the U.S. Department of Labor has developed the eTool, which focuses on identifying and controlling major hazards that contributed to the high rates of injuries found in a recent OSHA survey of the industry. Other serious hazards are also discussed. Some manual tasks described may not be applicable to all facilities, due to automation. Examples used here are from chicken processing but may be applicable to other bird processing.

The eTool is a package of relevant information easily digested and cross-referenced at the OSHA Web site or by using an Internet Explorer or a link from any Internet Web site. Let us look at the OSHA Web site of the eTool for poultry processing.

1. The first page shows several major entries, such as hazards, processing, and so on: six entries.
2. If one of these entries is clicked, the content of the entry is displayed.
3. The display provides a one-page discussion of this entry.
4. The discussion contains additional subentries that can be accessed by clicking.
5. The discussion also contains cross-references embedded in other original primary entries.

The information is extensive and cross-referenced more readily than would be information in a printed manual.

The eTool information on poultry processing is organized from the most general to the most specific information.

- *Plant-wide hazards:* describes occupational safety and health hazards that may be found in most areas in poultry-processing facilities.
- *Processing:* describes, for specific tasks within each processing area, hazards that are either specific to the task or especially severe for that task. Some solutions are suggested for the reduction or elimination of hazards. You are encouraged to think of additional ways to reduce hazards.

In keeping with OSHA's policy of using plain language, we describe hazardous situations and possible solutions in words that will be recognized readily by both employers and employees in this industry. OSHA officials and other safety and health professionals may use different terms. For example:

- "Blood on employee" could be referred to as "exposure to contaminants."
- "Standing for a long time" could be referred to as "ergonomic fatigue."
- "Hands/fingers getting caught by rollers" could be referred to as "unguarded machines."
- "Reaching across high and/or wide work surfaces," "repetitive pinch grips," "wrist deflection," and "bending at the waist" could all be referred to as "repetitive ergonomic hazards."

CONTENTS OF eTOOL FOR THE POULTRY-PROCESSING INDUSTRY

The content of OSHA's eTool for poultry processing focuses on the following and can be accessed at www.osha.gov.

1. Follow-up
   (a) Safety and health program
2. Plantwide hazards
   (a) Ergonomics
   (b) Cuts and lacerations
   (c) Struck by, struck against, caught in
   (d) Slips, trips, falls
   (e) Workplace fire safety
   (f) Other OSHA requirements and programs
3. Processing
   (a) Sanitation
   (b) Receiving and killing
      (i) Task 1: Forklift operator
      (ii) Task 2a: Automated dumper operator
      (iii) Task 2b: Manual back dock worker
      (iv) Task 3: Live hanger
      (v) Task 4: Kill room attendant
      (vi) Task 5: Picking room operator
      (vii) Task 6: Paw room grader
   (c) Evisceration
      (i) Task 1: Re-hanger
      (ii) Task 2: Opener
      (iii) Task 3: Neck breaker
      (iv) Task 4: Oil sack cutter
      (v) Task 5: Arranger
      (vi) Task 6: Giblet harvester
      (vii) Task 7: Gizzard harvester
      (viii) Task 8: Gizzard table operator
      (ix) Task 9: Gizzard table peeler operator
      (x) Task 10: Heart and liver cutter/inspector
      (xi) Task 11: Bagger
      (xii) Task 12: Lung vacuumer
      (xiii) Task 13: Backup eviscerator
      (xiv) Support tasks:
         (1) Rework floor person

(2) Ice attendant

(d) Cutting and deboning

(i) Cutting

(1) Task 1: Line loader
(2) Task 2: Tail cutter
(3) Task 3: Saw operator
(4) Task 4: Re-hanger
(5) Task 5: Cone line feeder
(6) Task 6: Wing cutter
(7) Task 7: Leg/thigh cutter
(8) Task 8: Breast/back separator
(9) Task 9: Trimmer/cleanup
(10) Support task:
(a) Knife person

(ii) Deboning

(1) Task 1: Skin puller
(2) Task 2: Line loader
(3) Task 3: Deboner
(4) Task 4: Tender puller
(5) Task 5: Trimmer
(6) Task 6: Quality controller
(7) Support task:
(a) Knife person

(e) Packaging

(i) Option 1: Whole-bird bulk packaging
(ii) Option 2: Whole-bird individual packaging
(iii) Option 3: Bird cut-up (bone In)
(iv) Option 4: Bird cut-up (bone out)

(f) Warehousing

(i) Task 1: Forklift/pallet jack operator
(ii) Task 2: Freezer/cooler worker

4. Standards and compliance
   (a) General
   (b) Personal protective equipment
   (c) Machine guarding
   (d) Ergonomics
   (e) Lockout/tagout
5. Other resources
6. Glossary

EXAMPLE

To illustrate one topic of the eTool for the poultry-processing industry, we describe the contents of "cutting" under "Processing: Cutting and Deboning." You will notice that certain sections are repeated. This repetition will not occur at OSHA's Web site or in an electronic medium because links cannot be implemented in a printed medium.

Processing: Cutting and Deboning

After a chicken has been eviscerated and cleaned, it is prepared for packaging as a whole bird, or it may enter one of two processes: (1) the cutting process for preparation of a bone-in product, or (2) the cutting and deboning process for preparation of bone-out products.

- *Process 1: Cutting*. In the cutting process, the wings and legs/thighs are removed from the carcass and the back is cut away from the breast. Bones are not removed. At this point, parts can be packaged as a consumer product, bulk-packed for delivery to other processors, or shipped to other parts of the plant for further processing.
- *Process 2: Deboning*. Within-plant processing of cut-up parts generally involves creation of a bone-out product. The deboning process involves cutting meat away from the bone using traditional knives or Whizzard knives and trimming and cleaning with traditional bladed knives or scissors. The deboned parts are generally packaged as a fresh or flash-frozen consumer product.

Potential hazards and their prevention are discussed below.

Cutting Removing the legs and wings from a bird is usually the beginning stage for both packaged bone-in and bone-out products. The eviscerated birds are generally impaled on "cones" that pass continually in front of employees. Wings and the legs/thighs are cut away from the main carcass. The breast may also be cut away while on the cone. Wings and legs/thighs are sometimes removed while birds hang on a shackle conveyor similar to that used for evisceration.

This operation includes the following tasks:

- *Task 1: Line loader:* transfers birds from bins to conveyors
- *Task 2: Tail cutter:* removes the tail from a bird
- *Task 3: Saw operator:* uses a saw to cut a chicken into various parts
- *Task 4: Re-hanger:* loads carcasses back onto shackles
- *Task 5: Cone line feeder:* moves a bird from a bin to a cone on a conveyor
- *Task 6: Wing cutter:* cuts a wing from a chicken
- *Task 7: Leg/thigh cutter:* cuts a leg/thigh from a carcass

- *Task 8: Back/breast separator:* uses a saw to separate a breast from a back
- *Task 9: Trimmer/cleanup:* removes fat, skin, and bone debris from a product
- Support tasks:
  —*Knife person:* Collects, sharpens, and replaces knives
- Supplementary data

All illustrations accompanying some discussions are not included here because they are copyrighted proprietary materials, do not belong to OSHA, and therefore are not in the public domain. However, the contents of such illustrations are self-evident in the descriptive parts presented here. Each task listed above is related to common terms or actions. Supplementary data are presented here as a reference source when other tasks are discussed.

Bent Wrist When this posture is used in conjunction with repeated finger activation, the tendons are pulled repeatedly across the bones and ligaments in the wrist. This action is similar to pulling a rope over a ledge or pulley. The tendon and sheath can become inflamed and frayed, and swelling may occur. Swelling may compress the median nerve as it passes through the wrist, causing pain and numbness in the hand and fingers.

Decrease Weight of Loads Lifted Make the box or tote lighter. Cutting the size of the box in half will significantly reduce the weight that must be lifted. Domino Sugar has reduced the weight of its shipping boxes to no more than 40 lb. Other manufacturers have reduced the size of their packaging and thus the weight that must be lifted.

Diverter Bars Diverter bars push materials on a conveyor belt closer to an employee. This reduces the amount of reaching and reduces stress to the shoulder, upper back, and neck.

Finger Contact Using conventional scissors can create a contact trauma to the sides of the fingers. This can damage nerves and lead to tingling in the fingertips and thumb.

Fully Adjustable Palletizing Workstations Developing a fully adjustable workstation will allow employees to lift always at about waist height. This type of station can be lowered to below-floor height for loading the higher tiers of a pallet, and can be raised to waist height for loading the bottom tiers.

Hand Tools That Require Forceful Finger Exertion Tools that require use of repetitive forceful finger exertions can stretch the tendons, and if the wrist is bent can create contact trauma to the tendons and their sheaths as they are pulled across the rigid entities of the wrist. Some tool designs minimize impact to the hand by:

- Bending the tool handle so that the wrist can remain as straight as possible.

- Producing tool handles long enough to run the full length of the hand. This keeps the handle from pressing into the palm and allows all the fingers to provide force when closing the jaw.
- Padding the handles so that there are not sharp edges that will press against the hand, and making them of slip-resistant material.
- Manufacturing tools sized to accommodate both large and small hands. For most people the finger and thumb should touch or slightly overlap (handle span between 2 and 3 in.).

Height-Adjustable Stands Workstations should generally be designed for the tallest employees who are likely to use them, to reduce the need for these employees to bend at the waist while performing their task. Using height-adjustable stands allows employees of shorter body sizes to work at the same workstation without using awkward postures such as reaching above shoulder height. Stands should be easily adjustable at the beginning of a shift without special tools or training.

Knives Working on a flat work surface with a straight-handled knife can force employees to bend (deviate) the wrist. A hazardous situation can develop when this posture is combined with repeated or prolonged exertion of finger force. Employees often use a significant amount of finger force to control the knife during the cutting process, especially if:

- They wear gloves.
- Their hands are cold and they cannot feel the knife in their hands.
- The knife has a slick handle.
- The knife is not sharp.
- The meat is frozen.

The ideal posture when performing hand-intensive tasks is to keep the wrist in a straight (neutral) position. Using bent-handled knives allows the wrist to remain neutral during the cutting task. Providing knives with different-sized handles can also reduce the amount of finger force that is used because a handle that is too big or too small for an employee's hand requires more finger force.

If it is not practical to bend the knife handle, tilting the work surface toward the employee will reduce the bend in the wrist. Glove and knife-handle materials that are rough or slightly sticky will improve the grip that an employee can place on a knife and reduce the amount of force the fingers must exert.

A loop type of handle can sometimes be used that allows an employee to release the handle periodically so that the fingers can rest. Because the hand is placed inside the loop, the knife stays in place without constant exertion or finger force. Encourage employees to put the knife down periodically and to stretch, shake, and flex the fingers. Knife-sharpening programs are important so that knives are always as sharp as possible. A sharp knife requires less finger force to perform a given task.

Narrow Conveyor Conveyors should only be as wide as is necessary to accommodate the product. Using overly wide conveyors forces employees to reach out and away from their bodies, which stresses the shoulder, upper back, and neck.

NIOSH Lifting Recommendations

NIOSH has developed a formula for assessing the hazard of a lifting situation. The formula looks at the elements involved in the lift:

- The distance the load is held in front of the body
- The height the load is lifted from and to
- The height of the load
- The frequency of lifting
- The hand load coupling
- The amount of torso twisting that is involved with the load-lifting motion

Using these parameters, NIOSH has established that for occasional lifting where the load is held close to the body with no twisting and at about waist height, and where the load has good hand holds, the typical industrial worker could lift about 51 lb without a significant increase in risk of injury. As these factors deviate from the ideal, the amount of weight that can safely be lifted is decreased.

A typical box of packed whole chickens or chicken parts can weigh between 40 and 80 lb. It is obvious that even under ideal circumstances, most employees are at increased risk of back injury when lifting a load of 80 lb, since this is about 1.6 times the NIOSH recommended limit of 51 lb. In real life, employees must handle loads that are often held out and away from the body, lowered or lifted to low or elevated locations, involve twisting the torso to access the loading areas, are highly repetitious, and that are in boxes that may not have good handles. These real-life situations reduce the amount that can be lifted safely.

The NIOSH lifting guidelines can factor all of these reductions together and determine a weight that most people should be able to lift when performing a job the way that it is normally performed. A typical recommended weight limit for a task where employees must repeatedly lift loads and place them in low locations where torso twisting may be required is about 8 to 12 lb. The amounts lifted in these typical boxes of chicken are four to eight times this recommended value, and research indicates that many in the workforce will be injured performing these types of lifting tasks. The *Applications Manual for the Revised NIOSH Lifting Equation* will help determine safe load weights.

Positioning

Employees may have to reach behind their bodies or to distant locations to access material for placement into machines or to cut using manual saws. Employees

may need to reach a significant distance in front of their bodies to place chicken sections onto machinery that will process the parts. Employees may need to work with their arms in elevated postures because the saw is placed too high in relation to the employee. Repeated reaching can increase the risk of such chronic injuries as tendinitis and bursitis as the tendons are pulled repeatedly across the bony entities in the shoulder. Lifting a load in the hand or holding the arms in an elevated posture for a prolonged period of time can fatigue the muscles of the shoulder and upper back, increasing the risk of developing acute injuries such as strains, sprains, and tears. Highly repetitive reaches or supporting loads in the hand should be done with the elbows close to the body. Occasional reaches or supporting light loads for a very short period may be done at full arm extension.

Rotation Strategies

Why Rotate? Many stressors cannot be engineered out of a task, short of complete automation. Rotation of assignments can be an effective means of limiting the amount of time during which employees are exposed to these stressors. This will often reduce the chance of injury, because the risk of injury is proportional to the amount of time that one is exposed to a stressor.

Caution Assignments should never be rotated before significant attempts to eliminate the stressors have been investigated. The job should always be modified to expose an employee to the least amount of stress possible. Analysis of the job is essential, because moving an employee between tasks that affect the same part of the body does not provide any periods of rest.

Rotate to Jobs That Affect Different Parts of the Body Many tasks affect primarily a variety of parts of the body:

- Lifting a heavy load
- Repeated bending generally affects the low back
- Reaching to access or to place items in positions that require the elbows to be pulled away from the body often affects the shoulder
- Grabbing, turning, squeezing, or finger strikes can affect the hand, wrist, and elbow
- Looking down or to the side repeatedly for a prolonged time can affect the neck, head, and shoulders
- Tasks that require standing for a long time can affect the legs, feet, and back

Rotation of employees between tasks that affect different parts of the body allows employees to have periods of rest and recuperation while remaining on the job. An example of a possible rotation scheme might be to move an employee who spends most of the day loading and moving boxes to a job where he or she is seated and performs a hand-oriented task such as assembly or trimming. While at the seated task the employee's back and legs can rest if a proper workstation

is provided. While on the lifting task the hands and arms can rest if the loads lifted are not too large and proper handholds are provided.

Rotate to a Job That Has Less Intensity In many operations, materials are fed to a workstation by conveyor belt. Employees at the leading edge of the belt are exposed to a full supply of product that must be processed, whereas employees farther down the belt deal with reduced work demands because some of the product has been processed by the previous employees. Abundance of supply at the beginning of the belt keeps the work intensity high for employees in the lead positions, whereas employees farther down the belt often have periods when there is little or no product to be worked on.

It is difficult to regulate work rates such that all employees work at the same pace. It is often easier to rotate employees through different positions on the belt so that each is exposed to both fast and slower work positions. Usually, this is accomplished by moving the lead person to the end of the line on a regular basis, such as every 15 or 30 min. This type of rotation pattern lessens the chance of a single employee becoming overexerted during the work shift.

Sit/Stand Stools Sit/stand stools are often an appropriate rest option for tasks that are best performed in a standing position. They allow employees to lean and rest but still keep them in a position to perform a task without the workstation modifications that would be necessary to convert to a seated workstation.

Scissors (Pneumatic) A variety of pneumatic scissors are available that greatly reduce the muscle force that must be exerted to close the scissor blades, eliminate the need to open the blades after completing a cutting motion, and completely eliminate the contact trauma to the sides of the finger.

Scissors (Spring Activated) Spring-activated straight-handled hand scissors reduce the hazard to an employee's hand by eliminating the need to open the blades repeatedly and by elongating the handle. By eliminating the finger and thumb loop, all the fingers can participate in closing the blades. Finger force is reduced and contact with the insides of the fingers is greatly reduced.

Telescoping Conveyor A telescoping conveyor capable of reaching into the full length of a transport truck can be used during truck-loading operations. A telescoping conveyor that can be adjusted vertically as well as horizontally may reduce the need for bending and reaching to access low and high locations and elevated reach distances.

Tilter Dumper Using a tilter dumper raises the load so that employees do not need to bend to access product and allows the load to slide forward so that reaching motions can be minimized.

Tilted Work Surface Tilting the work surface toward an employee allows the employee to perform cutting motions using a traditional straight-handled knife while maintaining a more neutral, straight-wrist posture.

Tub Dumper Tub dumpers eliminate most bending and reaching by mechanical emptying of the contents of tubs or barrels.

Vacuum Lifts A mechanical lift uses machinery to provide the force that employees would normally need to exert with their backs. An employee simply directs the load while the lifting mechanism does the work. Employees can lift 80 to 100 lb while exerting only a few pounds of force.

Tasks

Let us look at each task in the cutting category.

Task 1: Line Loader Birds are often transported from the evisceration line to the cone conveyor or line in a tub. Line loaders grasp two or three birds in each hand and lift them from the tub and place them on a conveyor or staging shelf, which is generally at waist to shoulder height. Other personnel usually place the birds on the cone or shackle. Hazards of the task may include bending at the waist to reach into tubs, and forceful gripping.

Bending at the Waist to Reach into Tubs

HAZARDOUS SITUATION Repeatedly bending forward and reaching out away from the body stresses the back even if little is being lifted, because the upper body must be supported. When loads are being lifted, bending over at the waist increases the distance the load is held away from the body and increases the stress placed on the back.

POSSIBLE SOLUTIONS

- Automate movement from the evisceration line to the cone line using conveyors or augers.
- Use a tilter dumper to elevate and tilt so that the contents are continually moved forward toward the employee and are maintained at about waist height at all times.
- Use a tub dumper at the workstation to empty contents onto the conveyor.

Forceful Gripping

HAZARDOUS SITUATION Employees lift multiple birds at one time, usually by the legs. Lifting two or three birds in each hand is not uncommon. Birds are cold and slick, and employees usually wear rubber gloves that are also slick and may not fit well. All these factors increase the finger force that must be exerted. Exerting significant finger force can stretch and fray the tendons of the hand and can create a contact trauma to the tendon and sheath where they come in contact with bone or tendon. These types of actions increase the risk of tendonitis and carpal tunnel syndrome.

POSSIBLE SOLUTIONS

- Automate the movement from the evisceration line to the cone line using conveyors or augers.
- Use a tilter dumper to elevate and tilt so that the contents are continually moved forward toward the employee and are maintained at about waist height at all times.
- Use a tub dumper at the workstation to empty contents onto the conveyor.

Task 2: Tail Cutter The tail is cut from the bird before the bird is placed on the cone. A standard scissors is generally used to perform the operation. Hazards of this task may include ergonomic hazards from the use of scissors, and standing for a long time.

Ergonomic Hazards from the Use of Scissors

HAZARDOUS SITUATION Using traditional scissors forces the fingers to open and close the blade repeatedly, which can stress tendons, increasing the risk of tenosynovitis and carpal tunnel. Contact trauma to sides of fingers can damage nerves, which can cause numbness and tingling in the tips of the fingers and thumb.

POSSIBLE SOLUTIONS

- Provide pneumatic scissors for cutting off the tail; these scissors can be activated by employees with little finger force and with the wrist in a neutral posture.
- Provide spring-activated scissors for cutting off the tail; these scissors open automatically after each cutting motion.
- Rotate to tasks that do not require using scissors.

Standing for a Long Time

HAZARDOUS SITUATION Standing for a long time reduces blood flow to the legs, forces isolated muscles to work for an extended time, and increases the risk of fatigue and varicose veins.

POSSIBLE SOLUTIONS

- Install sit/stand stools, which allow employees to lean and have their weight supported while remaining in an upright posture.
- Rotate employees to tasks that do not require prolonged standing.
- Provide shoe insoles that cushion the feet and spread foot pressure over a larger surface.
- Provide a footrest in front of employees so that they can lift one foot, allowing them to shift their posture continually.

Task 3: Saw Operator Employees may use a saw with a manual feed to cut legs/thighs or wings away from the main carcass, or may load a machine that

performs cuts automatically. Manual-feed saws can be used to remove legs from the back, divide the legs, cut wings away from the breast, and split the breast in two. After being loaded, automated machines perform the same cuts as described above. Hazards of this task may include reaching to access product, saws, or machine load areas; cuts and lacerations; and standing for a long time.

Reaching to Access Product, Saws, or Machine Load Areas
HAZARDOUS SITUATION Employee reaches repeatedly to conveyor or shelf to obtain birds for processing. Reaches are also necessary to place birds into the automatic saw feed mechanism and perform manual cuts. Repetitive reaching stresses the shoulder and upper back.

POSSIBLE SOLUTIONS
- If the feed conveyor is between the saw and the employee, reduce the width of feed conveyors to reduce reaching to the machine.
- Use diverter bars to push the product closer to the employee.
- Reduce the width of the supply conveyor so that the product is presented closer to the employee.
- Position saws and other work fixtures so that all activities of the task can be performed with the elbows close to the torso.

Cuts and Lacerations
HAZARDOUS SITUATION The nature of this task involves employees working with unguarded saws. Cuts, lacerations, and amputations are possible.

POSSIBLE SOLUTIONS
- Wear cut-proof mesh gloves on both hands.
- Keep hands to the side of the blade during feeding of the product.
- Guard all portions of the blade except for an opening large enough to feed the product.

Task 4: Re-hanger Re-hanging is generally not necessary since most cutting is performed on a cone line. If the cutting is to be performed from a shackle conveyor, the bird must be re-hung. Some automated cutters, such as a "multicut" machine, must be loaded, which is technically a re-hanging type of activity. The bird must be lifted from the table or conveyor and the legs placed into a shackle or other device moving in front of the employee. This is a highly repetitive reaching task. Hazards of this task may include reaching up, forward, or to the side to access the shackle; and standing for a long time.

Reaching Up, Forward, or to the Side to Access the Shackle
HAZARDOUS SITUATION Employees may bend to lift chickens from the supply conveyor and then reach out and away, sometimes above shoulder height, to place them on multicut machines or shackle conveyors. Injuries to the shoulder, back,

and neck are common, due to awkward postures and high repetition. Employees at the beginning of the line often work faster than those near the end of the line because there is always a full supply of birds and all positions are open.

Standing for a Long Time

HAZARDOUS SITUATION Standing for a long time reduces blood flow to the legs, forces isolated muscles to work for an extended time, and increases risk of fatigue and varicose veins.

POSSIBLE SOLUTIONS

- Install sit/stand stools, which allow employees to lean and have their weight supported while remaining in an upright posture.
- Rotate employees to tasks that do not require prolonged standing.
- Provide shoe insoles that cushion the feet and spread foot pressure over a larger surface.
- Provide a footrest in front of employees so that they can shift their posture.

POSSIBLE SOLUTIONS

- Minimize forward reaches by moving the shackle conveyor toward the employee.
- Minimize the vertical distance between the shackles and the belt conveyor to minimize bending and elevated reaches.
- Rotate employees up and down the hanging line.
- Install height-adjustable stands so that employees can position themselves properly.

Standing for a Long Time

HAZARDOUS SITUATION Standing for a long time reduces blood flow to the legs, forces isolated muscles to work for an extended time, and increases the risk of fatigue and varicose veins.

POSSIBLE SOLUTIONS

- Install sit/stand stools, which allow employees to lean and have their weight supported while remaining in an upright posture.
- Rotate employees to tasks that do not require prolonged standing.
- Provide shoe insoles that cushion the feet and spread foot pressure over a larger surface.
- Provide a footrest in front of employees so that they can shift their posture.

Task 5: Cone Line Feeder Most plants use a cone line as the main staging area for removing appendages and meat from the body of a bird. The feeder places the eviscerated carcass onto the cone, which is integrated into a conveyor line. This line moves the bird past employees, who remove parts from the carcass. In some plants parts are removed from birds hanging from a shackle conveyor, or

the process may be automated using multicut machinery. In these cases the cone line feeder is replaced by a rehang worker. Hazards of this task may include reaching, or standing for a long time.

Reaching

HAZARDOUS SITUATION Employees repeatedly reach to a conveyor or shelf to obtain birds for processing and reach to place birds on the cone. Repetitive reaching stresses the shoulder and upper back.

POSSIBLE SOLUTIONS

- Use diverter bars to push the product closer to the employee.
- Reduce the width of the supply conveyor so that the product is presented closer to the employee.
- Position cones and other work fixtures so that all activities of the task can be performed with the elbows close to the torso.
- Provide height-adjustable stands, where appropriate, to place the employee in proper orientation to the work surface.

Standing for a Long Time

HAZARDOUS SITUATION Standing for a long time reduces blood flow to the legs, forces isolated muscles to work for an extended time, and increases risk of fatigue and varicose veins.

POSSIBLE SOLUTIONS

- Install sit/stand stools, which allow employees to lean and have their weight supported while remaining in an upright posture.
- Rotate employees to tasks that do not require prolonged standing.
- Provide shoe insoles that cushion the feet and spread foot pressure over a larger surface.
- Provide a footrest in front of employees so that they can shift their posture.

Task 6: Wing Cutter Wing cutters use knives to cut the wings from a bird. This may be a multistep process where several workers along the line each perform one of the necessary cuts, or all cuts can be done by a single operator. Hazards of this task may include ergonomic hazards from the use of knives, cuts and lacerations, reaching, and standing for a long time.

Ergonomic Hazards from the Use of Knives

HAZARDOUS SITUATION Workers use a knife to cut the wings away from the rest of the carcass. The cutting motion may entail some bending of the wrist. Factors such as poorly fitting gloves, slick handles, inappropriately sized handles, or dull knives increase the force that must be used. Finger force and bending of the wrist are recognized risk factors for the development of many hand injuries. Minimize these factors when performing cutting tasks.

POSSIBLE SOLUTIONS

- Keep knives sharp and in good condition.
- Remove damaged knives from service.
- Use knives appropriate for the task.
- Keep the wrist as straight as possible during the cutting task.
- Provide properly sized gloves.

Cuts and Lacerations

HAZARDOUS SITUATION Employees are performing highly repetitive tasks using knives close to other employees. Cuts and lacerations are possible to the employee and those standing nearby because employees are exposed to sharp knife blades. Any cut not treated at once will normally become infected as a result of working with poultry.

POSSIBLE SOLUTIONS

- Allow sufficient room for each employee on the line.
- Use a mesh glove on the noncutting hand.
- Maintain sharp blades.

Reaching

HAZARDOUS SITUATION Employees reach repeatedly to the bird on the cone to perform cutting tasks and may need to reach to a bin or a tub to deposit the item removed. Repetitive reaching stresses the shoulder and upper back.

POSSIBLE SOLUTIONS

- Position cones and other work fixtures so that all activities of the task can be performed in front of the employee with the elbows close to the torso.
- Provide height-adjustable stands so that employees are in proper orientation to their work area.

Standing for a Long Time

HAZARDOUS SITUATION Standing for a long time reduces blood flow to the legs, forces isolated muscles to work for an extended time, and increases risk of fatigue and varicose veins.

POSSIBLE SOLUTIONS

- Install sit/stand stools, which allow employees to lean and have their weight supported while remaining in an upright posture.
- Rotate to tasks that do not require prolonged standing.
- Provide shoe insoles that cushion the feet and spread foot pressure over a larger surface.
- Provide a footrest in front of employees so that they can shift their posture.

Task 7: Leg/Thigh Cutter Cutters use knives to cut the legs/thigh unit from the bird. This may be a multistep process where several workers along the line each perform one of the necessary cuts, or all cuts can be made by a single operator. Hazards of this task may include ergonomic hazards from the use of knives, cuts and lacerations, and reaching.

Ergonomic Hazards from Use of Knives

HAZARDOUS SITUATION Workers use a knife to cut the wings away from the rest of the carcass. The cutting motion may entail some bending of the wrist. Factors such as poorly fitting gloves, slick handles, inappropriately sized handles, or dull knives increase the force that must be used. Finger force and bending of the wrist are recognized risk factors for the development of many hand injuries. Minimize these factors when performing cutting tasks.

POSSIBLE SOLUTIONS

- Keep knives sharp and in good condition.
- Remove damaged knives from service.
- Use knives appropriate for the task.
- Keep the wrist as straight as possible during the cutting task.
- Provide properly sized gloves.

Cuts and Lacerations

HAZARDOUS SITUATION Employees are performing highly repetitive tasks using knives close to other employees. Cuts and lacerations are possible to the employee and those standing nearby because employees are exposed to sharp knife blades. Any cut not treated at once will normally become infected as a result of working with poultry.

POSSIBLE SOLUTIONS

- Allow sufficient room for each employee on the line.
- Use a mesh glove on the noncutting hand.
- Maintain sharp blades.

Reaching

HAZARDOUS SITUATION Employees reach repeatedly to the bird on the cone to perform cutting tasks and may need to reach to a bin or a tub to deposit the item removed. Repetitive reaching stresses the shoulder and upper back.

POSSIBLE SOLUTIONS

- Position cones and other work fixtures so that all activities of the task can be performed in front of the employee with the elbows close to the torso.
- Provide height-adjustable stands so that employees are in proper orientation to their work area.

Task 8: Back/Breast Separator Employees may use a saw with a manual feed to separate the breast section from the back. This manual-feed technique can be used to remove legs from the back, divide the legs, cut wings away from the breast, and split the breast in two. After being loaded, automated multicut machines perform the same cuts as described above. Hazards of this task may include reaching to access product, saws, or machine load areas; cuts and lacerations; and standing for a long time.

Reaching to Access Product, Saws, or Machine Load Areas

HAZARDOUS SITUATION Employee reaches repeatedly to conveyor or shelf to obtain birds for processing. Repetitive reaching stresses the shoulder and upper back.

POSSIBLE SOLUTIONS

- If the feed conveyor is between the saw and the employee, reduce the width of the feed conveyors to reduce reaching to the machine.
- Use diverter bars to push the product closer to the employee.
- Reduce the width of the supply conveyor so that the product is presented closer to the employee.
- Position saws and other work fixtures so that all activities of the task can be performed with the elbows close to the torso.

Cuts and Lacerations

HAZARDOUS SITUATION The nature of this task involves an employee working with an unguarded saw. Cuts, lacerations, and amputations are possible.

POSSIBLE SOLUTIONS

- Wear cut-proof mesh gloves on both hands.
- Keep hands to the side of the blade during feeding of the product.
- Guard all portions of the blade except for an opening large enough to feed product.

Standing for a Long Time

HAZARDOUS SITUATION Standing for a long time reduces blood flow to the legs, forces isolated muscles to work for an extended time, and increases the risk of fatigue and varicose veins.

POSSIBLE SOLUTIONS

- Install sit/stand stools, which allow employees to lean and have their weight supported while remaining in an upright posture.
- Rotate employees to tasks that do not require prolonged standing.
- Provide shoe insoles that cushion the feet and spread foot pressure over a larger surface.
- Provide a foot rest in front of employees so that they can shift their posture.

Task 9: Trimmer/Cleanup Employee obtains separated pieces of poultry from a conveyor and uses scissors to trim excess skin, fat, and pieces of bone. Hazards of this task may include ergonomic hazards from the use of scissors, standing for a long time, and reaching.

Ergonomic Hazards from the Use of Scissors

HAZARDOUS SITUATION Use of traditional scissors forces the fingers to open and close the blade repeatedly, which can stress tendons, increasing the risk of tenosynovitis and carpal tunnel. Contact trauma to the sides of the fingers can damage nerves, which can cause numbness and tingling in the tips of the fingers and thumb.

POSSIBLE SOLUTIONS

- Provide pneumatic scissors; these scissors can be activated by employees with little finger force and with the wrist in a neutral posture.
- Provide spring-activated scissors; these scissors open automatically after each cutting motion.
- Rotate workers to tasks that do not require scissor use.

Standing for a Long Time

HAZARDOUS SITUATION Standing for a long time reduces blood flow to the legs and forces isolated muscles to work for an extended time, and increases the risk of fatigue and varicose veins.

POSSIBLE SOLUTIONS

- Install sit/stand stools, which allow employees to lean and have their weight supported while remaining in an upright posture.
- Rotate employees to tasks that do not require prolonged standing.
- Provide shoe insoles that cushion the feet and spread foot pressure over a larger surface.
- Provide a footrest in front of employees so that they can shift their posture.

Reaching

HAZARDOUS SITUATION Employees reach to a conveyor or shelf repeatedly to obtain parts to be trimmed and reach to place finished parts in tubs or baskets. Repetitive reaching stresses the shoulder and upper back.

POSSIBLE SOLUTIONS

- Use diverter bars to push the product closer to the employee.
- Reduce the width of the supply conveyor so that the product is presented closer to the employee.
- Position product and work fixtures so that all activities of the task can be performed with the elbows close to the torso.
- Tilt the work surface so that the product slides to the employee.

Support Task: Knife Person A knife person collects dull knives from employees along the processing lines and replaces them with sharp ones. This employee may also sharpen knives that have been collected. Hazards of this task may include slips, trips, and falls; and hazards from the use of grinders.

Slips, Trips, and Falls

HAZARDOUS SITUATION Workers walk all over the facility on wet floors that may have bird skin, bird parts, and ice on them, creating a slipping hazard. Metal drain covers on the floor are also very slippery and pose a hazard. A falling worker may contact dangerous equipment or may cut him- or herself on a knife blade.

POSSIBLE SOLUTIONS

- Cover drains with nonslip grating.
- Provide workers with nonslip footwear and require its use.
- Paint floors with slip-resistant paint or install nonslip floor tile.
- Provide guardrails at workstations adjacent to dangerous equipment, to prevent injury.
- Carry knives in sheaths or closed containers.

Hazards from the Use of Grinders

HAZARDOUS SITUATION Employees may suffer cuts, lacerations, skin abrasion, contusions, or eye damage during use of grinders to sharpen knives. Grinding wheels may break up or explode. Bits and pieces of knife blades may be thrown off during sharpening.

POSSIBLE SOLUTIONS

- Use safety goggles or other protective eyewear.
- Use only grinding wheels with an rpm rating that matches the spindle speed of the grinder.
- Use a ring test procedure to check for nonvisible damage to the grinding wheel.
- Follow the manufacturer's recommendations for guarding and use of the grinding wheel.

Personnel managing the safety of workers in a poultry-processing plant should access the OSHA Web site to obtain complete details about the eTool for poultry processing. The information presented in this chapter illustrates the importance and applications of those guidelines.

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