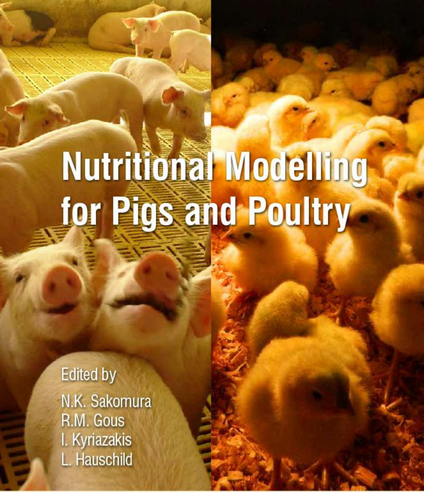


Nutritional Modelling for Pigs and Poultry

Edited by
N.K. Sakomura
R.M. Gous
I. Kyriazakis
L. Hauschild

www.cabi.org

Nutritional Modelling for Pigs and Poultry

FSC
www.fsc.org
MIX
Paper from
responsible sources
FSC® C013604

Nutritional Modelling for Pigs and Poultry

Edited by

N.K. Sakomura

Departamento de Zootecnia, Faculdade de Ciências Agrárias e Veterinárias,
Universidade Estadual Paulista, São Paulo, Brazil

R.M. Gous

University of KwaZulu-Natal, Pietermaritzburg,
South Africa

I. Kyriazakis

School of Agriculture, Food and Rural Development,
University of Newcastle, Newcastle upon Tyne, UK

L. Hauschild

Departamento de Zootecnia, Faculdade de Ciências Agrárias e Veterinárias,
Universidade Estadual Paulista, São Paulo, Brazil

www.cabi.org

CABI is a trading name of CAB International

CABI
Nosworthy Way
Wallingford
Oxfordshire, OX10 8DE
UK

Tel: +44 (0)1491 832111
Fax: +44 (0)1491 833508
E-mail: info@cabi.org
Website: www.cabi.org

CABI
38 Chauncy Street
Suite 1002
Boston, MA 02111
USA

Tel: +1 800 552 3083 (toll free)
E-mail: cabi-nao@cabi.org

A catalogue record for this book is available from the British Library, London, UK.

Library of Congress Cataloging-in-Publication Data

International Symposium of Modelling in Pig and Poultry Production (2013 : São Paulo, Brazil), author.
Nutritional modelling for pigs and poultry / edited by N.K. Sakomura, R.M. Gous, I. Kyriazakis, and L. Hauschild.
p. ; cm.
Includes bibliographical references and index.
ISBN 978-1-78064-411-0 (alk. paper)
I. Sakomura, N. K. (Nilva Kazue), editor. II. Gous, R. (Rob), editor. III. Kyriazakis, I. (Ilias), editor. IV. Hauschild, L. (Luciano), editor. V. C.A.B. International, issuing body. VI. Title.
[DNLM: 1. Animal Nutritional Physiological Phenomena--Congresses. 2. Poultry--physiology--Congresses. 3. Animal Husbandry--methods--Congresses. 4. Models, Biological--Congresses. 5. Swine--physiology--Congresses. SF 494]

SF494
636.5089239--dc23
2014011160

ISBN-13: 978 1 78064 411 0

Commissioning editor: Julia Killick
Editorial assistant: Alexandra Lainsbury
Production editor: Lauren Povey

Typeset by SPi, Pondicherry, India.
Printed and bound in the UK by CPI Group (UK) Ltd, Croydon, CR0 4YY.

Contents

Contributors

I. Andretta, Dairy and Swine Research and Development Centre, Agriculture and Agri-Food Canada, PO Box 90, 2000 Route, 108 East Lennoxville, Quebec, J1M 1Z3, Canada. E-mail: iandretta@gmail.com

I. Bouvarel, Institut Technique de l'Aviculture, 37380 Nouzilly, France. E-mail: bouvarel.itavi@tours.inra.fr

L. Brossard, INRA, UMR PEGASE, 35590 Saint-Gilles, France. E-mail: ludovic.brossard@rennes.inra.fr

L. Cloutier, Département des Sciences Animales, Université Laval, Quebec, Quebec, G1K 7P4, Canada. E-mail: lcloutier@cdpq.ca

J.Y. Dourmad, INRA, UMR PEGASE, 35590 Saint-Gilles, France. E-mail: jean-yves.dourmad@rennes.inra.fr

S. Dubois, INRA, UMR PEGASE, 35590 Saint-Gilles, France. E-mail: serge.dubois@rennes.inra.fr

N.S. Ferguson, Nutreco Canada Agresearch, 150 Research Lane, Guelph, Ontario, N1G 4T2, Canada. E-mail: neil.ferguson@nutreco.ca

A.S. Ferraudo, Departamento de Ciências Exatas, Faculdade de Ciências Agrárias e Veterinárias, Universidade Estadual Paulista, Jaboticabal, São Paulo, Brazil. E-mail: fsajago@gmail.com

C. Fisher, EFG Software, 20 Longstaff Court, Hebden Bridge, HX7 6AB, UK. E-mail: cfisher345@gmail.com

F. Garcia-Launay, INRA, UMR PEGASE, 35590 Saint-Gilles, France. E-mail: florence.garcia@rennes.inra.fr

R.M. Gous, University of KwaZulu-Natal, Pietermaritzburg, South Africa. E-mail: gous@ukzn.ac.za

L. Hauschild, Departamento de Zootecnia, Faculdade de Ciências Agrárias e Veterinárias, Universidade Estadual Paulista, Jaboticabal, São Paulo, Brazil. E-mail: lhauschild@fcav.unesp.br

I. Kyriazakis, School of Agriculture, Food and Rural Development, University of Newcastle, Newcastle upon Tyne, UK. E-mail: ilias.kyriazakis@ncl.ac.uk.

E. Labussière, INRA, UMR PEGASE, 35590 Saint-Gilles, France. E-mail: etienne.labussiere@rennes.inra.fr

P. Lescoat, AgroParisTech, UMR1048 SADAPT, 16 rue Claude Bernard, 75231 Paris Cedex 05, France. E-mail: philippe.lescoat@tours.inra.fr

M.-P. Letourneau-Montminy, Dairy and Swine Research and Development Centre, Agriculture and Agri-Food Canada, PO Box 90, 2000 Route, 108 East Lennoxville, Quebec, J1M 1Z3, Canada. E-mail: marie-pierre.letourneau-montminy.1@ulaval.ca

F. Liebert, Georg-August-University Goettingen, Division of Animal Nutrition Physiology, Kellnerweg 6, 37077, Goettingen, Germany. E-mail: flieber@gwdg.de

E.B. Malheiros, Departamento de Ciências Exatas, Faculdade de Ciências Agrárias e Veterinárias, Universidade Estadual Paulista, Jaboticabal, São Paulo, Brazil. E-mail: euclides@fcav.unesp.br

S.M. Marcato, Departamento de Zootecnia, Universidade Estadual de Maringá, Maringá, Paraná, Brazil. E-mail: smmarcato@uem.br

B. Méda, INRA, UR83, Poultry Research Unit, 37380 Nouzilly, France. E-mail: bertrand.meda@tours.inra.fr

R. Neme, Ilender Pharmaceutical Corporation, Campinas, São Paulo, Brazil. E-mail: rafaneme@hotmail.com

J. Noblet, INRA, UMR PEGASE, 35590 Saint-Gilles, France. E-mail: jean.noblet@rennes.inra.fr

E. Oviedo-Rondón, Prestage Department of Poultry Science, North Carolina State University, Raleigh, North Carolina, 27695, USA. E-mail: eooviedo@ncsu.edu

M. Picard, INRA, UR83, Poultry Research Unit, 37380 Nouzilly, France. E-mail: picard@tours.inra.fr

C. Pomar, Dairy and Swine Research and Development Centre, Agriculture and Agri-Food Canada, PO Box 90, 2000 Route, 108 East Lennoxville, Quebec, J1M 1Z3, Canada. E-mail: candido.pomar@agr.gc.ca

J. Pomar, Department of Agricultural Engineering, Universitat de Lleida, Alcalde Rovira Roure, 191, 25198 Lleida Espagne. E-mail: pomar@eagrof.udl.cat

M. Quentin, Maïsadour, BP 27, 40001 Mont-de-Marsan Cedex, France. E-mail: quentin@maisadour.com

V. Rivera-Torres, Nutreco Canada, 4780 Martineau, Saint-Hyacinthe, Quebec, J4R 1V1, Canada. E-mail: virginie.rivera@gmail.com

J. Rivest, Centre de Développement du Porc du Quebec inc., Sainte-Foy, Quebec, G1V 4M7, Canada. E-mail: jrivest@cdpq.ca

N. St-Pierre, Department of Animal Sciences, The Ohio State University, 2029 Fyffe Rd, Columbus, Ohio, 43210, USA. E-mail: st-pierre.8@osu.edu

A. Sünder, Georg-August-University Goettingen, Division Animal Nutrition Physiology, Kellnerweg 6, 37077, Goettingen, Germany. E-mail: angela.suender@agr.uni-goettingen.de

A. Valancogne, INRA, UMR PEGASE, 35590 Saint-Gilles, France. E-mail: alain.valancogne@rennes.inra.fr

J. van Milgen, INRA, UMR PEGASE, 35590 Saint-Gilles, France. E-mail: jaap.vanmilgen@rennes.inra.fr

C. Wecke, Georg-August-University Goettingen, Division Animal Nutrition Physiology, Kellnerweg 6, 37077, Goettingen, Germany. E-mail: cwecke@uni-goettingen.de

Postgraduate Students of the Universidade Estadual Paulista, Jaboticabal, São Paulo, Brazil

J.A. Araújo – anchietaaraujo@gmail.com
H.C.P. Bendezu – hldplm@gmail.com
M.A. Bonato – melinabonato@ig.com.br
D.C.Z. Donato – dzdonato@gmail.com
J.C.P. Dorigam – dorigam@ig.com.br

J. Sato – joycesato1986@yahoo.com.br
E.P. Silva – euedney@gmail.com
K.S. Venturini – katiani_sv@hotmail.com

Supervisor

N.K. Sakomura, Departamento de Zootecnia, Faculdade de Ciências Agrárias e Veterinárias, Universidade Estadual Paulista, Jaboticabal, São Paulo, Brazil. E-mail: sakomura@fcav.unesp.br

Preface

Modelling is a useful tool for decision making in complex agro-industrial scenarios. One of the first steps required for model development in companies or universities is the training of students and scientists. This book contains the papers presented at the International Symposium of Modelling in Pig and Poultry Production held at Universidade Estadual Paulista – UNESP, Jaboticabal, São Paulo, Brazil, from 18 to 20 June 2013. In this symposium, basic modelling concepts, descriptions and applications of production models and new methods and approaches in modelling were discussed. The objective of the symposium was to encourage greater use of modelling by Brazilian academics and agro-business.

About 200 people attended the symposium including nutritionists, researchers, professors, professionals and students. The organizing committee comprised professors and students from FCAV – UNESP, University of KwaZulu-Natal, Pietermaritzburg, South Africa and Newcastle University, UK. The symposium was a great success and all goals were met.

The symposium also marked the culmination of research started over three decades ago at UNESP – Jaboticabal. In this meeting the main results of the thematic project 'Models to estimate amino acid requirements of broilers and laying pullets' were presented. These results have been used to develop a simulation model known as the 'AVINESP Model'.

This event also recognized and honoured Professor Paulo Alberto Lovatto (*in memoriam*) of Universidade Federal de Santa Maria, Rio Grande do Sul, Brazil and Emeritus Professor Rob Gous of the University of KwaZulu-Natal, Pietermaritzburg, South Africa.

Professor Paulo Lovatto was a pioneer in developing the field of modelling in Brazil. After completing his PhD he realized the limitations of human resources in Brazil. Because of this, Professor Lovatto organized the first research group in modelling, in 2002, to promote the use of models in research, academia and extension. His work was instrumental in developing new leaders in this field. The scientific community recognizes and wishes to thank Professor Lovatto for his contribution. His work will be continued by those that follow.

Professor Rob Gous dedicated his academic life to mechanistic modelling in poultry and swine production. His work has been published in over 170 publications worldwide. These contributions have improved scientific knowledge and have brought new concepts and thinking to monogastric nutrition. An integration of all publications that he developed along with a select group of researchers, Professor Trevor Morris, Dr Colin Fisher, Gerry Emmans and Dr Peter Lewis, was applied in the development of EFG software to optimize the feeding of poultry and pigs. Professor Rob Gous is retired and this tribute is dedicated to his person in recognition and appreciation of his work and contribution to the scientific community and the production sector.

N.K. Sakomura

Acknowledgements

Financial support for this symposium is gratefully acknowledged from:

Fundação de Amparo à Pesquisa do Estado de São Paulo – FAPESP;
Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES);
Evonik Industries;
Ajinomoto Animal Nutrition;
DuPont;
Nutron;
Adisseo;
ABVista Feed Ingredients;
Kemin;
Hubbard; and
Btech.

1 An Overview of Poultry Models

C. Fisher*
EFG Software, Hebden Bridge, UK

Abstract

This overview is concerned with the representation of poultry production systems or their component subsystems in theoretical or numerical terms. Many examples are available of such modelling approaches to problem solving in poultry science. However, the most widely used ‘model’ is still the use of a small group (or pen) of birds in a replicated empirical trial. The relationship between modelling and experimentation in solving practical problems in poultry production is a background theme in this review of poultry models.

Three main approaches to modelling poultry systems have been used, although these are not mutually exclusive and frequently overlap in many ways. They are: (i) the use of mechanistic simulation of some parts of the production system; (ii) methods to extend the value of empirical experiments by statistical or other numerical methods; and (iii) the use of real-time control systems. In addition to these there are a few cases where a theoretical model has been used to extend understanding of basic biological mechanisms and thereby form the basis for further hypothesis testing. Finally, there is an important range of quantitative methods that are applied directly in the management of poultry production. All of these are important and they should not be seen as being in competition with each other. All can be used in different circumstances and all can have practical usefulness.

Recent developments in poultry modelling will be reviewed within this framework giving emphasis to the following points:

1. Identification of the main problems that need to be solved in developing mechanistic simulation models.
2. Making better use of experimental data by statistical modelling.
3. The encouragement of systems methods and modelling in poultry science. Implications for publication and sharing of results, for standardized experimental methods and for commercial application.

Because of the background of the author, the emphasis is on nutritional systems and nutrition research.

Introduction

In its widest sense the term ‘model’ may be used to describe any means of representing the real world. For example it might be a picture, an analogue model or a mathematical equation. The most widely used model in applied poultry science is undoubtedly

---

*E-mail: cfisher345@gmail.com

Nutritional Modelling for Pigs and Poultry (eds N.K. Sakomura *et al.*)

the pen trial, in which the 'real' (commercial) world is modelled by replicated small groups of birds held in pens or cages that, more or less, reflect 'normal' conditions. This familiar procedure is undoubtedly a model used to predict how the real world will behave in different circumstances and some of its characteristics as a model may be noted:

1. This model has formed the main basis of applied poultry science and has clearly been very successful in providing the technical platforms on which a very successful industry has grown. The method is simple, relatively cheap and easy to understand. The results are easily communicated.
2. The limitations of the model are acknowledged in a general way; for example, the extent to which population size or exposure to disease may influence the predictive accuracy of the model. But the question of model validation is not considered in a formal way and receives little attention.
3. The model is clearly empirical, the results applying only to the combination of circumstances that prevailed in the trial. The repetition of similar trials over time and in different places may be justified by the fact that some fixed effects in the 'real' world change over time (e.g. bird genotypes) or to take account of 'local' factors such as country or broad environmental classifications.
4. There is a lot of repetition of similar trials. This is good in the sense that it increases confidence in the results, but is bad insofar as it wastes limited research resources.

Commenting on the effect of applied trials on poultry modelling, Chwalibog and Baldwin (1995) wrote as follows:

> In comparison with nutritionists working with other domesticated species, poultry nutritionists have exploited the specific advantage of being able to run experiments with large numbers of animals economically. It is common to find experiments evaluating responses to numerous treatments which are well replicated and in which up to 10,000 birds were used. This advantage has had several major impacts on the practice of poultry nutrition. One of these has been that most models developed for feeding systems are based on response data. A second impact has been that the model parameters can be updated very quickly, e.g. to accommodate genetic improvements. A third impact has been that poultry nutritionists have been less driven to probe for an understanding of lower level functions such as metabolic regulation, biochemical pathways of nutrient utilization, and energy expenditures in order to describe different metabolic relationships; and further to incorporate such information into mechanistic models that might enable more general application.

These remarks seem very pertinent to the present discussion.

The applications of mathematical modelling in poultry science have been extensive and varied. Conferences like this one, and elsewhere, and several reviews are testament to considerable achievement in many areas of applied poultry science. And yet if we ask two questions about the impact of modelling on poultry science there still seems to be a lot to do. First we may ask whether modelling is an integral part of applied poultry science methodology. Second, whether modelling is fulfilling its potential to improve commercial decision making. At the present time it is suggested that the answer to both of these questions has to be no.

In this overview of poultry modelling the literature on modelling is reviewed using these two questions as a background agenda.

Types of Poultry Models

France and Thornley (1984) have suggested a useful 2 × 2 × 2 classification of models: empirical or mechanistic, deterministic or stochastic, dynamic or static. While these are important qualities of the models of interest, a different grouping is used in the present discussion:

1. Models of scientific theories.
2. Models to extend and increase the value of pen trials.
3. Growth curves.
4. Empirical models of poultry production systems.
5. Mechanistic models of poultry production systems.
6. Real-time control models.

Models of scientific theories

Explicit statements of theoretical ideas have not played a very prominent part in poultry research, perhaps because of the availability and cost-effectiveness of empirical trials. One notable exception is the hypothesis proposed by Fraps (1955) to explain the ovulatory cycle of the laying hen. The model of this theory was presented diagrammatically and described in the accompanying text. Etches and Schoch (1984) formulated the theory in mathematical terms, work which was later extended by Johnston and Gous (2006). This theory or model underpinned decades of experimental and physiological studies, work that was summarized by Etches (1996).

The other theory that has had a profound effect on nutritional modelling in both poultry and pigs was promulgated by Emmans (1981); this is the idea that animals have a definable purpose and that they try to eat enough food to fulfil that purpose. This leads eventually to a quantifiable theory of food intake (Emmans, 1997) and has formed the basis of several models for monogastric animals (Emmans, 1981; Ferguson *et al.*, 1994).

These two theories have been brought together in work by R.M. Gous to model the productivity of laying hens and broiler breeders (Johnston and Gous, 2006; Gous and Nonis, 2010).

Models to extend and increase the value of pen trials

Possibly the earliest method used to combine the results of repeated experiments was to use a committee of experts to review the experiments and to reduce the multiple findings to simple (and ostensibly useful) summaries. This method was extensively used in nutrition to resolve the issue of nutrient requirements (Agricultural Research Council, 1975; National Research Council, 1994). A further extension was to fit regression models simultaneously to the results of several experiments, both to summarize findings and to identify those factors that systematically influenced the results of the experiments. In poultry science this approach was pioneered especially by G.D. Rosen and was explained by him in promoting the term holo- rather than meta-analysis (Rosen, 2006) for this type of modelling. In this paper Rosen eloquently summarizes the objectives and applications of holo- (or meta-) analysis as follows:

> (i) prediction of responses with confidence limits; (ii) provision of software to quantify responses to pronutrients and nutrients unique in time, place, and economics; (iii) translation of research conditions to praxis (field) conditions, as in processed vs mash feed, as-hatched vs sexed birds, floor pen vs cage housing, presence vs absence of diagnosed or endemic disease, practical vs purified diet, and optimal vs suboptimal dosages; (iv) exposure of key missing variables, e.g. temperature and nutrient contents; (v) discovery of theoretically unpredictable independent variables and interactions; and (vi) definition of topics and priorities for future research.

The methods and applications of meta-analyses in animal nutrition are described and discussed by Sauvant *et al.* (2008) and will not be discussed further here.

The following list demonstrates several significant contributions that the application of meta- or holo-analysis has made to applied poultry science.

- Morris (1968) combined the results of 34 experiments showing the relationship between feed intake in laying hens and dietary energy level. A general rule for predicting food intake was derived for birds of different body size (characteristic food intake). This analysis has not been updated using more recent data.
- Fisher and Wilson (1974) combined the results of 160 estimates of broiler response to dietary nutrient density (energy level at constant nutrient:energy ratios). Linear regressions were derived to summarize the effects of sex, age, breed type, energy:protein ratio and feed form on growth and feed intake responses. This analysis has not been updated using more recent data.

- Lee *et al*. (1971) combined the results of a large number of experiments to illustrate the effects of feed restriction on growing pullets. Restriction of feed, dietary energy and dietary protein levels were considered along with their effects on growth, sexual maturity, egg production and egg weight. This analysis has not been updated using more recent data.
- Lewis *et al*. (1998) combined the results from 15 experiments to produce a general model describing the effects of constant photoperiods on sexual maturity of pullets. Further developments of a similar type consider the effects of changes in photoperiod on sexual maturity in laying pullets (Lewis *et al*., 2002; Lewis and Morris, 2004, 2008) and in broiler breeder pullets (Lewis *et al*., 2007). These models have been used in system models of laying birds (see Gous, Chapter 3, this volume).

An increasing number of empirical pen trials have, in recent years, been concerned with evaluating different types of feed additive. The banning of antibiotic growth promoters and the development of feed enzyme technology have stimulated this type of trial work. G.D. Rosen has led the way in using combined analyses of such trials: a process he calls holo-analysis as described above. Summaries of the application of these techniques to antimicrobials (Rosen, 1995) and enzymes (Rosen, 2010) are available. The application of these techniques to the evaluation of single substances is illustrated by Rosen (2007a,b). From a database of 1717 publications describing 7001 tests of the response of broilers to 'pronutrients', Rosen (2004) calculates that about 100 such tests are required to determine a statistical model for predictive purposes. It thus appears that meta-analysis is a tool to make more effective use of empirical trials but not to reduce the need for them.

Many experiments were reported that compared DL-methionine and the hydroxyl analogue of methionine. Competing meta-analyses have been reported by Vázquez-Añón *et al*. (2006) and Sauer *et al*. (2008). This important commercial dispute was not fully resolved by the application of meta-analysis, but this topic illustrates very well the advantages of modelling existing data rather than repeating experiments. Discussion about the analytical methods used has been contributed by Kratzer and Littell (2006), Piepho (2006) and Rosen (2007c).

A large number of pen trials are concerned with the question of nutrient requirements, and many arguments and mathematical procedures have been proposed and used in the interpretation of such trials. The trial data typically lead to a description of the response of an output characteristic to dietary nutrient levels or to nutrient intake. The purpose of the model is to identify one point on this input–output curve which is designated a 'requirement'.

Although these procedures have been widely used in applied poultry science it can be argued that they are not very logical. The idea that populations of birds have characteristic requirements for nutrients is hard to defend and the logical way to determine nutrient feeding levels for commercial use is to interpret the experimentally observed response in economic terms. Although this idea has been frequently expressed over a long period of time (Morris, 1983; Mack *et al*., 2000) the conclusions of many response trials are still expressed in terms of a numerical statement of a 'requirement'. This is one area of poultry science where the early adoption of a systems approach and the use of modelling would have led to a better use of resources and to better practical decision making. These ideas were discussed by Pesti and Miller (1997) and have been updated by Gous (see Gous, Chapter 13, this volume).

Growth curves

The description of growth by mathematical equations has been a backbone topic for animal modelling over many years. This is a huge topic still best approached by the student of poultry modelling through the work of Parks (1982). A central issue that is too often ignored is the distinction between potential and observed growth. Observed growth is the outcome of interactions between the animal's genotype and both the internal and external environment in which it is kept. Potential growth, expressed in a non-limiting environment, is a concept that can reasonably be assumed to reflect the genotype of the animal and nothing else. There can be no general rule about the nature of observed growth and hence no reason why observed growth data should conform to any particular mathematical form. Those many studies in which different growth equations are compared to observed data sets seem to the present writer to not enhance our understanding of growth. Parks (1982) raised this issue in a different way by considering the mathematical properties that a growth function may have. He lists several cases, one of which that growth is continuous and possesses continuous rates of change of all orders leading to justification of a growth function widely accepted by most people writing in this field. Parks argued that this case should be accepted because (i) there appears to be no evidence to the contrary, and (ii) it is intuitively the most promising of the cases considered. However, Parks' assumption that these properties of growth curves could be used to study the effects of environmental and non-environmental factors on growth seems to the present writer to not be justified. Alternative approaches to modelling irregular growth patterns are suggested by the work of Roush *et al*. (1994), who explored an analytical approach to periodicity or chaos in broiler growth data, and Talpaz *et al*. (1991) who modelled growth following a period of feed restriction.

The weakness of arguing for the study of potential growth is that non-limiting environmental conditions are difficult to define and to confirm in any particular experimental circumstances. It is easy to say that 'non-limiting' environments must be used, but difficult to ensure that they apply to all birds at all times in an experiment. These problems cannot be solved completely, although several experiments of this kind have been reported and they seem to be based on reasonable assumptions for practical modelling. Once a growth function has been selected, then deviations from the smooth function can be used to identify periods in which growth might not have been unrestricted (Ferguson and Gous, 1993).

Studies of growth parameters under assumed non-limiting conditions have been reported for broilers by Stilborn *et al*. (1994), Hancock *et al*. (1995), Gous *et al*. (1996, 1999), Hruby *et al*. (1996), Wang and Zuidhof (2004) and Sakomura *et al*. (2005, 2006). Similar experiments have not been reported for turkeys, although Emmans (1989) considers the problem. Additional information on turkeys is available from Hurwitz *et al*. (1991) and Porter *et al*. (2010).

Empirical models of poultry production systems

A wide range of approaches to the empirical modelling of biological systems is described by Roush (2006) and their application to the poultry industry is discussed by Roush (2001). Amongst the tools listed by Roush (2006) are: (i) stochastic and fuzzy logic models; (ii) non-linear dynamics (chaos); (iii) regression analysis and response surface methodology; (iv) artificial neural networks; (v) genetic algorithms; (vi) Kalman filter; and (vii) linear, chance constrained, goal, and quadratic programming. Elegant examples of each of these procedures have been demonstrated by Roush and his colleagues but their application to the solution of poultry science problems or for commercial decision making remains elusive. Ad hoc application of single analytical techniques to single problems (e.g. Faridi *et al*., 2013) seems to the present author to emphasize the limitations rather than the usefulness of these methods.

Empirical models are typically based on commercial data or on experimental data from pen trials, but can be distinguished from the methods discussed above by the fact that they consider part or all of a poultry production system and are aimed at improved commercial decision making. The distinction between these models and, for example, meta-analysis is not absolute and, as usual, the distinction between empirical and mechanistic models of animal systems is at best blurred. Table 1.1 lists some empirical models that have been published to assist with decisions about flock structure and replacement, nutrition, the environment, management and processing. This is not a comprehensive list but has been chosen to illustrate the many possibilities of using this type of model.

Mechanistic models of poultry production systems

In 1941 Heuser published a review of protein requirements of poultry. In the discussion of the paper he wrote as follows:

> the requirement is for the various amino acids... In practice it is necessary to meet the requirements of as many of the individuals as we can economically... The actual need is probably on the basis of certain amounts of amino acids per unit weight of maintenance plus definite additional quantities for productive increases such as units of growth and quantity of eggs. Meeting these minimum needs will be materially influenced by food consumption.

This elegant conceptual theory provides, at one level, a virtually complete model of the system being described. It contains mechanistic ideas that can be tested independently of the whole model, it makes the important distinction between biological systems described at the level of the individual animal and the behaviour of populations, and it refers to marginal economic analysis. The same ideas were later used by Fisher *et al.* (1973) in proposing a model to describe the response of laying hens to amino acid intake; a model that became widely known as the 'Reading model'. This was a more formal (and independent) statement of Heuser's ideas and allowed a

Table 1.1. Empirical models of poultry management systems.

Ref[a]	System modelled	Type of model	Notes
	Flock planning and replacement		
1	Flock replacement in egg production	Dynamic programming	
2	Broiler production; killing age according to price	Econometric analysis	
3	Optimum slaughter age turkeys	Polynomials	
	Nutrition		
4a,b	Response to dietary lysine	Exponential equation	Model for economic feeding levels
5	Optimizing dietary lysine and energy level	Quadratic response surface	Model for economic feeding levels
6	Optimizing protein and energy levels in broiler feeds	Quadratic programming	
7	Production responses to dietary energy and protein	Multiple regression	IGM™ Growth Model
	Environment		
8	Operational characteristics; broilers	Many empirical	Mainly concerned with energy transactions
9	Operational characteristics; turkeys	Many empirical	Mainly concerned with energy transactions
	Enterprise		
10	Integrated production – decision model for profit maximisation	Multiple regression	
11	Profit maximisation	Multiple regression	Turkish industry data

[a]References: 1 Low and Brookhouse (1967); 2 Hochman and Lee (1972); 3 Case *et al.* (2010); 4a Eits *et al.* (2005a); 4b Eits *et al.* (2005b); 5 De Beer (2009); Talpaz *et al.* (2013); 6 Pesti *et al.* (1986); 7 Harlow and Ivey (1994); 8 Teter *et al.* (1973); 9 Teter *et al.* (1976); 10 Costa *et al.* (2002); 11 Cevger and Yalçin (2003).

statistical description of the model to be developed later (Curnow, 1973).

Thus mechanistic ideas have played a part in applied poultry science for a long time and yet the main thrust of both the experimental approach used and of thinking has remained rooted in empiricism and in trials with small groups of birds. Why this has happened is outside the scope of this overview, but a consideration of the issue must be central to the further development of modelling in support of the poultry industry. As a simple example of how ideas have been developed, some of the follow-up to Heuser's statements can be reviewed.

The statement that 'the requirement (for protein) is for the various amino acids' is not at all controversial and is fully embedded in future developments. After a long controversial period of trying to deal with individual amino acids and interactions between them (e.g. D'Mello, 1994) it is interesting that the emphasis for practical nutrition is now being given to the idea of the profile of amino acid requirements and the response to 'balanced' protein (Lemme, 2003). In a general sense this is a return to a systems approach after the failure to resolve practical issues using a reductionist approach.

Heuser's recognition that 'in practice it is necessary to meet the requirements of as many of the individuals as we can economically' draws attention to the need to consider stochastic elements in nutritional modelling and also to the idea that nutritional requirements are economic concepts. In modelling, biological determinants or mechanisms must be conceived and defined at the level of the individual animal, while the observed population response is simply the mean of the responses of contributing individuals.

The statement 'the actual need is probably on the basis of certain amounts of amino acids per unit weight of maintenance plus definite additional quantities for productive increases such as units of growth and quantity of eggs' reflects the development and use of the factorial approach in nutrition. This was well established at the time of Heuser's work and has continued to play a large part in nutritional science. The idea of nutrient requirements being seen as rates of nutrient utilization for different biological functions has been at the root of mechanistic nutritional modelling and this seems likely to continue.

In the 1960s several authors were proposing simple factorial equations as a guide to feeding chicks (e.g. Combs, 1967) and laying hens (e.g. Combs, 1960). Thus Combs (1960) proposed that the methionine requirement of a hen could be represented by the equation: $MET = 5.0E + 0.05W \pm 6.2\Delta W$. Where MET = requirement for methionine (mg/day), E = egg output (g/day), W = body weight (g), ΔW = change in body weight (g/day).

The linear nature of such expressions was obviously at variance with the observation of diminishing response curves seen in experiments and elsewhere. Combs introduced some iterative procedures to deal with this problem. Fisher *et al.* (1973) proposed that such expressions of nutrient utilization could only be applied at the level of the individual animal and that the non-linear population response was a reflection of the variation in output characteristics (E, W and ΔW) amongst individual animals. The work of Curnow (1973) in formalizing this idea makes it possible to estimate the coefficients of the assumed underlying linear model from non-linear observations of populations (e.g. Morris and Blackburn, 1982) given assumptions about the variance–covariance structure of the underlying population (Curnow and Torenbeek, 1996).

Continuing work has concentrated on both of the issues raised by such factorial equations; first, on the definition of suitable output characteristics, and second, on the determination of nutrient utilization coefficients. A third question about how the equation elements should be scaled has received less attention although it is important, especially for maintenance. The description of growth has been discussed briefly above and also concerns the level of biological organization that is used in the system being modelled. Mathematical models of growing birds have used growth of the whole body (King, 2001), growth of feather-free body protein (Emmans, 1981) and protein and lipid turnover (Rivera-Torres *et al.*, 2011) as descriptors of growth. In egg layers the weight of egg output is normally used, although separate prediction of yolk, albumen and shell weight is possible (Johnston and Gous, 2006). The growth of feathers in particular is a difficult problem and one that remains significantly unresolved (see discussion in Gous *et al.*, 1999).

Studies on nutrient utilization have used a variety of techniques but still remain rather inconclusive especially in growing birds. Work concerning energy and protein in laying hens has been reviewed by Chwalibog and Baldwin (1995), and that concerning amino acids by Fisher (1994). A series of experiments from the laboratory of the late Professor D.H. Baker provide the best direct experimental evidence about the utilization of amino acids in growing chickens (Baker *et al.*, 1996; Edwards *et al.*, 1997; Edwards and Baker, 1999; Edwards *et al.*, 1999). Information on the utilization of amino acids for maintenance is very inconclusive and this is an area that may need a better theoretical and experimental basis. Maintenance requirements have variously been scaled to body weight (Fisher, 1994), to metabolic body weight (Hurwitz *et al.*, 1978; King, 2001 and many others) and to feather-free body protein weight scaled to mature body protein (Emmans and Fisher, 1986). A paper by Nonis and Gous (2008) concerned with lysine and threonine in broiler breeder hens illustrates these various points and also presents what is probably the best experimental approach available at this time.

The factorial approach to energy utilization has led to a huge literature in all classes of stock. Again, earlier work was reviewed by Chwalibog and Baldwin (1995). More recently an extensive series of papers have been published covering broilers, layers and broiler breeders (see Sakomura, 2004 for a summary of this work).

'Meeting these minimum needs will be materially influenced by food consumption'. In this final statement Heuser recognizes one of the great challenges for nutritional research and one that has not been fully solved today. The ability to predict food intake is an essential feature of nutritional models and one for which a lot more development is required.

For growing monogastric animals a major stimulation to model development was the pioneering work of Whittemore and Fawcett (1974). Their description of the simulation of protein and lipid deposition in the growing pig (Whittemore and Fawcett, 1976) was really the start of modern developments in this field. Table 1.2 lists the models of poultry production systems that have reflected, in a general way, the idioms and, in particular, the levels of analysis

Table 1.2. Mechanistic poultry production models.

Ref[a]	System modelled	Notes
1	Broiler/turkey growth	Basis of EFG Software (1995) models
2	Broiler growth	With corrections for light:dark cycles
3	Rearing pullets	With corrections for seasonal light effects
4	Broiler growth	Not reviewed here
5	Broiler growth and production	SONCHES simulation system for growth and production of whole birds
6	Broiler growth	Full description of model in unpublished thesis. Not reviewed here
7	Broiler growth	
8	Broiler growth	Native Taiwan breeds and feed optimization
9	Broiler growth	
10	Broiler growth	French breeds and production systems
11	Turkey growth	
12	Broiler breeder hens	See Gous, Chapter 3, this volume

[a] References: 1 Emmans (1981); 2 Isariyodom *et al.* (1988); 3 Muramatsu *et al.* (1989); 4 Burlacu *et al.* (1990); 5 Grosskopf and Matthäus (1990); 6 Dänicke (1995); 7 Novák (1996); 8 Roan and Wang (1996); 9 King (2001); 10 Quentin (2004); 11 Rivera-Torres *et al.* (2011); 12 Gous and Nonis (2010).

proposed by Whittemore and Fawcett (1974). It is difficult to summarize the main features of these different models in a comparative way, but some points may be noted. In particular it is interesting to note the driving element in each model.

The theory of growth and food intake first proposed by Emmans (1981) has been extensively described and discussed in the literature. It forms the basis of the software developed by EFG Software (1995) and has also been followed fairly directly by Roan and Wang (1996). The same ideas have been applied more widely in pig modelling, and Emmans (1989) discusses their application to the turkey. Gous and Brand (2008) demonstrate the application of this theory to ostriches.

In this theory growth is driven by the idea that animals have a purpose; that is to achieve their potential growth of the feather-free body protein, and that they will continue to eat food to achieve this purpose unless prevented from doing so by other factors. The amount of a given food that will meet the nutrient requirements of potential growth is expressed as a 'desired' food intake that the bird is seeking to fulfil. This idea is wrongly seen by some commentators as a theory of feed intake driven by energy transactions, but this is not so; the theory is held to apply whichever nutrient is limiting, although in practice only energy and amino acids are considered. A second important element is that animal characteristics (genotypic values) are seen as only being meaningful if they are defined under non-limiting conditions, i.e. the animal's potential is defined by its genotype, as discussed above.

The approach proposed by Emmans is the only one used in poultry modelling that contains a true theory of food intake. The ideas are challenging but they have the advantage of being open-ended and being capable of further development. A limitation is that the method of describing the growth of body components other than protein, which uses allometry, restricts the basic growth curve (for potential feather-free body protein against time) to the Gompertz curve.

Isariyodom *et al.* (1988) describe the main framework of their model as being based on Whittemore and Fawcett (1974). The essential driver of growth is metabolizable energy (ME) intake, which is predicted from body weight and corrected for various factors. Energy and protein partition and utilization closely follow the pig models, but a correction of ME intake for photoperiod shows an interesting combination of empirical and mechanistic modelling. The equations used were:

$$MEI = C_2((1165 - 4.73\mathrm{T})\,(W/1000)^{0.75})) + C_1 \tag{1.1}$$

and

$$\begin{aligned} C_2 = (&96.54035767 + 1.44628213TH \\ &- 0.0512548TH^2 - 1.36290206LH \\ &+ 0.00114968LH^4 \\ &- 0.00004401LH^5)/100 \end{aligned} \tag{1.2}$$

Where MEI = ME intake (kJ/day); T = temperature, °C; W = body weight, g; C_1 = correction for birds less than 500 g ($C_1 = (60 - 0.12W)$; TH = total hours in one light:dark cycle; and LH = the photoperiod (light hours) in one light:dark cycle.

This second equation is described as 'based on 14 literature sources', but no evaluation of such a complex function is provided. For 24-h values of TH, C_2 varies between 0.93 when $LH = 8$ h and 1.16 when $LH = 20$ h. It is difficult to see how such an approach can be developed further.

Finally Isariyodom *et al.* (1988) provide some comparisons of predicted growth and feed intake to 56 days of age with published data from the literature. These involved fully fed birds and the ability to distinguish between different conditions was not reported. The authors allude to further developments but these have not been found.

Similar mechanistic elements were used by Muramatsu *et al.* (1989) in a model for growth prediction in replacement pullets. Again the driving element is the prediction of energy intake from body weight and weight gain. In this model more empirical elements were introduced to deal with a slower growing animal and a production system in which some controlled feeding is used. First, the equations for energy intake were derived empirically from a set of production data described by the National Research Council (1994). Second, a large set of field data was used to calibrate the model for seasonal temperature effects and to calculate lag periods between a change in temperature and the response in feed intake and growth. Again some complex empirical relationships were introduced; for example, in birds less than 90 days of age the efficiency of protein retention was described by the equation:

$$Z = 0.78 \times \exp(0.1851 - 0.01681A + 0.0000962A^2 - 0.0000001A^3) \quad (1.3)$$

Where Z is the conversion of available protein to body protein above maintenance and A = age in days. The source of this equation, and therefore the opportunity to evaluate it, is not described. The model was evaluated by comparison with a large set of commercial data. The authors describe the model in the context of restricted feeding in both egg laying and breeding stock. However, it is difficult to see how fully controlled feeding would be considered since the model is driven by energy intake calculated from growth. Also in breeding birds the most important economic responses to restricted feeding are in reproductive performance and these are not considered in this work.

The extensive works of Burlacu (G. and R.) on modelling poultry and pig systems have not been reviewed in the preparation of this chapter. A broiler model for energy and protein balance simulation is described by Burlacu *et al.* (1990).

Grosskopf and Matthäus (1990) describe a mathematical simulation of a complete broiler production system with economic evaluation on a live weight basis. A broiler compartment calculates the growth of a single animal, the poultry house compartment includes climate factors and mortality and corrects feed intake for temperature and stocking density effects, while the economy compartment places the results in a financial framework. The model contains a series of mechanistic functions but the source of the parameterization is not revealed. The model is driven by the assumption that birds fed *ad libitum* aim to eat enough feed to achieve their genetic potential. This is then adjusted for the intake capacity of the digestive tract and for ‘passage ability’ making the model similar to the one described by Emmans (1981). The model considers mortality, stocking density effects and a description of an environmental control system to provide a complete description of the production process. There are many interesting ideas in this paper and the authors state that ‘efforts for further qualification of the model are aimed at using it for economic off-line process control and in future as a software solution for a computer-aided operative on-line process control in practice’. No evidence of such further developments has been found in the literature.

The models described by Dänicke (1995 – available only in summary form) and Roan and Wang (1996) have not been reviewed in detail in the preparation of this chapter but are included for completeness. Novák, L. (1996) describes a self-regulating growth model in homeothermic animals that has been applied to the description of broiler growth (Novák and Zeman, 1997; Novák *et al.*, 2004). Inputs to the model include initial body mass, genetically limited (mature) body mass and daily food intake. Daily growth is then calculated mainly in terms of energy transactions. Novák (2003) describes the idea that the effects of various stressors on growth can be represented by increased maintenance energy requirements. These effects may be calibrated for known energy transactions, for example, for a cold environment, but in general it appears they can be determined only by empirical adjustment.

It is difficult to give a summary of the broiler growth model described by King (2001); this work illustrates very well the problems of describing a model in the literature. The calculations of growth appear to be driven by either user-provided feed intake data or empirical feed intake data based on polynomial analysis of two pens of birds. Intake data at 7-day intervals are expressed as ‘Repletion Units’ (*RU*), which take account of the energy and protein content of the feed as follows:

$$RU\ (\text{per g diet}) = 2 \times TME + (1.65 \times 5.739 \times CP) \times Q \quad (1.4)$$

Where TME = true ME content of feed (kcal/g); CP = crude protein (g/100 g); and Q is a calibration coefficient of default value = 1. The units of the number 5.739 are kcal/g protein.

From the bird data two polynomial equations were calculated for live weight (LWF) more or less than 640 g. For the smaller birds the relationship derived was:

$$RU\,(\text{per bird day}) = -7.110241 + 2.549947\,(LWF) - 4.267 \times 10^{-3}\,(LWF)^2 + 4.0 \times 10^{-6}(LWF)^3 \quad (n = 11,\ R^2 = 1.00) \tag{1.5}$$

Food intake is calculated as $FI = (RU/\text{bird day})/(RU/\text{g diet}) \times F$ g/bird day, where F is a calibration coefficient of default value = 1.

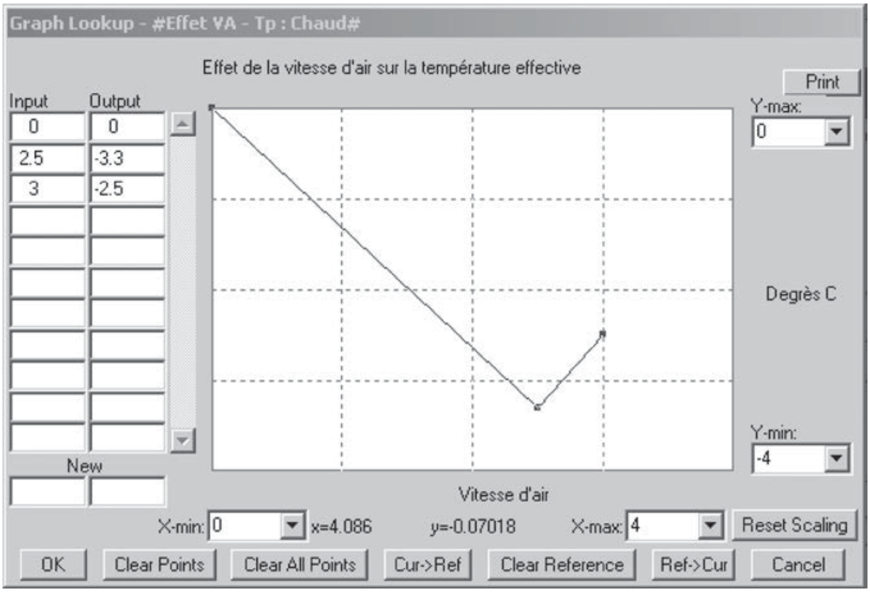
Apart from repeating all the observations and calculations it is difficult to see how such an approach can accommodate genetic change or the subtle differences between broiler strains which are a feature of the modern industry.

The two remaining models listed in Table 1.2 are discussed elsewhere in this volume but a brief mention is included here to compare the approaches used. The model INAVI developed and described by Quentin (2004; see also Méda *et al.*, Chapter 9, this volume) represents a significant recent development in the field of poultry modelling. The program was developed using the Vensim® modelling software in combination with Microsoft Excel spreadsheets. Vensim® provides a useful facility for the user to adjust some of the more difficult functions in the model using a graphical 'look-up' facility. This facilitates the use of 'local' data and also allows for these aspects of the model to be continuously updated. INAVI is specifically aimed at commercial practice in the French market and the authors include a wide range of genotypes and environments that cover the main systems of production in France; commercial broiler, Label and the intermediate 'Certified' production.

INAVI is essentially driven by feed intake. For this, and for a range of other model elements, reference levels of bird performance are used to initiate the simulation. It is the user's responsibility to ensure that the reference data for different inputs are related in a meaningful way. A device called the 'bilan thermique' (thermostat) adjusts feed intake relative to the reference level following calculation of the energy balance. The reference data are also used to adjust two parameters in the model prior to modelling; this adjustment makes the reference simulation and the reference data coincide and, the authors claim, allows the model to operate over the very wide range of environments and differences in bird activity reflected in the French production sectors. The parameters adjusted are called 'l'indice d'entretien' (the index of maintenance) and the 'facteur d'activité' (factor of activity) and the adjusted values are used in the subsequent simulations. The model then considers inputs for diet composition, feed form and pellet quality, physical activity and effective temperature as influenced by ambient temperature, humidity, air speed, stocking density and sun radiation. Both constant and cyclic temperatures are considered and a lighting module distinguishes between light and dark periods. The model cycles on a period of 1 h of the bird's life.

The look-up facilities of Vensim® offer the user graphical control of some 19 components of the model. Figure 1.1 illustrates one of these for adjusting the influence of air speed on effective temperature in hot conditions. While some of these adjustments are quite complex they undoubtedly offer a very valuable facility for use of this model and for its further development.

The turkey growth model described by Rivera-Torres *et al.* (2011; see also Rivera-Torres, Chapter 8, this volume) is included in Table 1.2 even though this work draws on a different strand of modelling theory and technique. This started with a general paper by Sauvant (1992) developed initially for application to ruminants (Sauvant, 1994 and elsewhere), but also applied to pigs (Lovatto and Sauvant, 2003) and in this case to turkeys. The model works at an 'operational' level, which is roughly comparable to the models described above, but also includes a 'regulatory' subsystem (called the 'decisional' system by Rivera-Torres), which is described at a lower level of metabolic organization within the animal. The two systems interact so that



Input	Output
0	0
2.5	-3.3
3	-2.5

Y-max: 0

Y-min: -4

X-min: 0

x=4.086

y=-0.07018

X-max: 4

Fig. 1.1. An example of the look-up facility in INAVI. Allows modification of the coefficient of adjustment of the effective temperature (Output data) as a function of air velocity (Input data) for temperatures higher than 26°C. (The underlying relationships were based on the results of Yahav *et al.* (2001); taken from Quentin (2004).)

‘homeorhetic regulations in the decisional system constitute <pull> driving forces that define the genetic potential of the animal as a dynamic balanced state controlled by both protein and lipid retention in the body compartments of the operational system’. Protein and lipid retention in carcass, viscera and feathers are controlled by defined fractional rates of synthesis and degradation. Deviations from the desired (balanced) body weight gain of the genetic potential are controlled by homeostatic regulations that act to limit the difference between actual growth and the balanced state (as defined by the homeorhetic regulations) and the flows of nutrients (fatty acids, amino acids, glucose and ‘energy’ as acetyl-CoA) among the compartments of the operational system. The development of the model is discussed by Rivera-Torres *et al.* (2010).

This model appears to be driven by the ‘genetic’ parameters governing the rates of protein and lipid turnover. These are inputs to the model and the turkey is assumed to eat food to achieve this potential growth. To that extent the model derives from the theory proposed by Emmans (1981). The calculation of turnover also leads to the determination of feed intake in energetic terms and these parameters also control the <pull> driving forces of the ‘decisional’ compartment of the model. Experiments to determine these important ‘genetic’ parameters are not described and the authors state that ‘model calibration was mostly performed manually’. This seems to have been done to give model outputs that correspond to experimental data. Although this was done separately for male and female turkeys, it is not clear how the parameters would be adjusted for different genotypes or to allow for genetic changes in the future. Of the 42 parameters used in the model, 22 were assumed to be constant and derived from a variety of sources, 15 were estimated manually from the data as above and 5, which describe the diet, are user-defined. The determination of the tissue turnover parameters is very critical since the sensitivity of model outputs to changes in parameter values is quite high. Thus a ±5% change in the two parameters of carcass protein anabolism changed estimated body weight gain at 77 days of age by +120.1, –76.7, –94.5 and +60.9 g/day. At this age daily gain is about 200 g/day so these are significant levels of sensitivity. Given these issues of estimation and sensitivity, it needs to be clearly shown that model performance is significantly improved by describing growth at the level of protein turnover rather than considering just protein growth.

Finally the model of egg production and nutrient response in broiler breeders described by Gous and Nonis (2010) is included in Table 1.2. This is written at a similar level of organization and uses similar principles to the broiler models listed although, of course, additional issues are raised in modelling egg production. This model is discussed by Gous (see Gous, Chapter 3, this volume).

The considerable level of accomplishment and research revealed by these mechanistic approaches to modelling poultry systems is self-evident. The application of two of these models (see Méda *et al.*, Chapter 9, this volume; Gous, Chapter 13, this volume) was discussed at the 2013 International Symposium of Modelling in Pig and Poultry Production, but in general the uptake of modelling in commercial decision making in the poultry industry remains at a low level. The commercial development of models is useful in that it provides stimulus and funding but it is not helpful if the models are less open, or in some cases, not open at all. There is a commercial need to defend the model and to prove it 'right', which contrasts with the scientific need to criticize it and to prove it 'wrong' so that it may be improved.

The scientific development of modelling concepts might be advanced more effectively by concentrating on the nature of the problems that need to be resolved if successful mechanistic models of poultry systems are to be developed. Such an approach, rather than model development, might also join together related work using empirical trials, empirical modelling and the elaboration of mechanistic ideas.

The poultry systems that we seek to simulate vary quite widely but have a general quality of being biologically complex. The housing in one place of many, often thousands, of animals creates a system of great complexity that is difficult to describe. Doing this in sufficient detail, so that different commercial situations can be differentiated but also in a way that can be reflected in the principles of a model, is a first, and very considerable, problem to be solved. The model itself needs to be quite comprehensive if it is to be of use in practice. The questions that need to be considered, for example, for a broiler growth model, can be grouped under three headings: the bird, the environment and feed resources.

The description of the bird in terms of its genetically determined potential performance seems to be a powerful idea. For broilers, and following Emmans (1981), in EFG Software (1995) we use parameters for potential feather-free body protein growth and for a desired level of fatness. These parameters can be determined in independent trials and, in principle at least, can be adjusted to reflect genetic progress from year to year. In addition, feathering must be described and this presents a considerable problem. Total feather growth (weight and composition) can be incorporated in the genotype description (e.g. see Gous *et al.*, 1999) but the description of feather cover, which may be very uneven, is a problem that still has to be solved. Similar approaches seem to be appropriate for turkeys but the parameters for modern genotypes remain to be determined. The description of potential egg production is discussed by Gous (see Gous, Chapter 3, this volume).

If models are to predict economic performance they need to consider all those components of the body that generate revenue in different markets (Fisher and Gous, 2008). These will range from whole birds, dressed carcasses and portions to dissected meat. Offal and feet, for example may be significant in some markets and 'waste' components such as excess fat, may have negative money value. The relationships governing the growth of these many body components will vary between breeds and may be the subject of specific genetic manipulation as in the development of high-yield broilers.

The description of the physical environment is superficially a simple problem, and records of the main parameters are readily available both from meteorological data and from poultry houses. However, a description of the 'effective' environment, as experienced by the bird, is much more complex and is a problem that has not been completely solved despite the best efforts of the environmental physiologists. Interactions with feathering in particular, and to a lesser extent with stocking density, are important. Modelling the physiological and behavioural adaptations to high environmental temperatures and other stresses is likely to be very difficult. Our experience (EFG Software) is that the balance between heat production and heat loss to the environment in broilers is the major limiting factor governing response to diet under practical conditions, so this is a very critical area for modelling. Other aspects of the physical environment that need to be resolved include diurnal variation, light:dark patterns and stocking density.

Most of the parameters describing the availability of energy and amino acids from the feed are likely to be model inputs. For practical use these need to draw on the extensive data and experimentation that are used in the industry. For energy, metabolizable energy is a convenient input, although energy transactions in the model will have to be expressed in terms of a net energy scale if heat production is to be calculated. For the same reason dietary fat will have to be considered as a resource. For amino acids the scale that is used needs to be compatible with the assumptions that are made about their rates of utilization. This topic has been critically discussed by Moughan (2003).

For modelling growing birds consideration of nutrients other than energy and amino acids seems to be unnecessary. In the laying hen where calcium and phosphorus absorption is one of the control mechanisms governing shell quality, then these additional nutrients and absorption processes may be important (Kebreab *et al.*, 2009). Modelling mineral utilization may also be useful in designing anti-pollution strategies. Although gut function and digestion play a major role in practical broiler nutrition, to date, ways of handling this in a mechanistic model have not been suggested. If such work is undertaken, some early work on digestion in the pig may be useful (Bastianelli *et al.*, 1996; Rivest *et al.*, 2000). In addition, a huge amount of effort has gone into the simulation of digestion in ruminants.

The prediction of feed intake is a central necessity in any mechanistic model of animal production systems. Models in which feed intake is a direct or indirect input to the model are unlikely to be flexible enough for practical use. A possible exception to this is the idea of an adjusted reference feed intake as used by Quentin (2004). Feed intake will be influenced by factors in the bird description, in the environment and in the feed. This remains one of the most challenging areas requiring further development in mechanistic modelling. Once the basic problem of prediction is solved, characteristics of the feed such as 'palatability' and bulk (limiting gut fill) will need to be considered.

Existing mechanistic models of broiler growth simulate the performance of a single animal, which is assumed to be at the mean of a population. If the parameters used to describe genetic potential growth are from known correlated distributions, then populations of birds can be generated and simulations of population response carried out (Gous and Berhe, 2006). Whether other model elements, for example, the efficiencies with which nutrients are utilized, should be seen as stochastic, remains an open question for lack of any hard information. If this is considered, then the covariance amongst different model components needs to be included. Simply introducing stochasticity as a statistical device to all elements in a model probably has little value. If one of the model outputs is to reflect some sort of grading scheme such as percentage rejects, then the question of non-normal distributions may need to be considered.

The other issues that arise in creating a model of broiler production include mortality (usually considered as an input), calibration or adjustment for known stressors or for disease and economic modules. The assembling of all these elements into a single program is a significant enterprise emphasizing the need for research in these areas to be integrated as far as possible.

Real-time control models

Recursive control algorithms are well developed for control of physical processes and environments, and interest in applying these ideas to broiler production seems to have been stimulated by two developments: the use of two feeds, usually involving a whole cereal; and the need to control feeding in some circumstances. In the first case the problem is to control the mixture of the two feeds presented to the birds taking account of their performance, and in the second case to control the feed supply to achieve a given growth trajectory. Real-time measurements of feed intake, water intake, body weight and environmental variables can be used to provide the control.

Filmer (2001) and Stacey *et al.* (2004) describe the application of a commercial automatic growth and nutrition control system for broiler production. This was conceived as part of an integrated management system (IMS) for broiler production (Frost *et al.*, 2003). Published research in this area has come from the Catholic University of Leuven, Belgium. Aerts *et al.* (2003a,b) demonstrated the control of growth trajectory through both quantitative and qualitative dietary control. Similar approaches have been used to model heat production under various temperature and light intensity regimes (Aerts *et al.*, 2000).

This seems to be an area where the modelling is ahead of the implementation. The IMS described by Frost *et al.* (2003) has not developed further because of the difficulty of maintaining a high level of day-by-day management input and also maintaining sensitive equipment in a broiler farm environment. A scale-up of the control system devised by Aerts *et al.* (2003b) from the laboratory to pens of 1500 birds led to a deterioration in accuracy of control (Cangar *et al.*, 2007). If such engineering and management problems can be overcome then a rapid implementation of the modelling seems to be possible.

Discussion

If modelling techniques are to make a lasting contribution to poultry science and to the poultry industry, then communication amongst the participants in this field of endeavour is essential. This will of course take many forms but publication in refereed journals and the sharing of models may create special requirements for this area of research. In the age of the internet it should be possible to develop these.

Most journals now accept modelling papers and editors are responsible for setting the standards required. However, if the aim is to enable modellers to benefit from each other's work, then the quality of the paper's content becomes very important. Refereeing of modelling papers requires a high level of technical knowledge and the commitment of a great deal of time. If the general criterion for a paper describing experimental work is that the reader should be able to repeat the experiment, an analogous criterion for a paper describing a model is that it should be possible to recreate the model from the information given. Because of technical issues of computer programming this may not be literally possible but the information content should be at this level. To date this has rarely been achieved.

Ideally a paper describing a model should explicitly present the theories and assumptions on which the model rests, the detailed flow of information through the model, individual mathematical forms and equations, the logic and process of parameterization and the parameter values. Additional information about sensitivity and model validation may also be available. The emphasis should be on the process and not on the end result.

In many cases modelling will require that previously published experimental data are available for re-calculation or re-use. Rosen (2006) has emphasized the need for additional reporting of conditions and results in trials which might be useful in a future holo- or meta-analysis. In developing his effective energy scale, which has been widely used in modelling, Emmans (1994) was able to re-use data on individual cow experiments dating back nearly 100 years. Data on growth and body composition of individual broilers (Håkansson *et al.*, 1978a,b) were also used by Emmans (1994) and for many other useful developments in modelling. Some system of posting detailed information as appendices to papers or as spreadsheets on the internet could make a considerable contribution to the development of poultry models.

The exchange of models or parts of models could also play an important part in encouraging research with shared goals. The technicalities of programming and support on different platforms may limit such exchange but it remains a worthwhile objective. In overviewing the work that has been published it is apparent that much that has been achieved has probably been lost to future developers and users.

References

Aerts, J.M., Berckmans, D., Saevels, P., Decuypere, E. and Buyse, J. (2000) Modelling the static and dynamic responses of total heat production of broiler chickens to step changes in air temperature and light intensity. *British Poultry Science* 41, 651–659.

Aerts, J.M., Van Buggenhout, S., Vranken, E., Lippens, G., Buyse, J., Decuypere, E. and Berckmans, D. (2003a) Active control of the growth trajectory of broiler chickens based on online animal responses. *Poultry Science* 82, 1853–1862.

Aerts, J.M., Lippens, G., de Groote, G., Buyse, J., Decuypere, E., Vranken, E. and Berckmans, D. (2003b) Recursive prediction of broiler growth response to feed intake by using a time-variant parameter estimation method. *Poultry Science* 82, 40–49.

Agricultural Research Council (1975) *Nutrient Requirements of Farm Livestock: No. 1, Poultry.* Agricultural Research Council, London.

Baker, D.H., Fernandez, S.R., Parsons, C.M., Edwards, H.M., Emmert, J.L. and Webel, D.M. (1996) Maintenance requirement for valine and efficiency of its use above maintenance for accretion of whole body valine and protein in young chicks. *Journal of Nutrition* 126, 1844–1851.

Bastianelli, D., Sauvant, D. and Rérat, A. (1996) Mathematical modelling of digestion and nutrient absorption. *Journal of Animal Science* 74, 1873–1887.

Burlacu, G., Burlacu, R., Columbeanu, I. and Alexandru, G. (1990) Mathematical model for energy and protein balance simulation in broilers. *Archive of Animal Nutrition, Berlin* 40, 469–484.

Cangar, Ö., Aerts, J.M., Vranken, E. and Berkmans, D. (2007) Online growth control as an advance in broiler farm management. *Poultry Science* 86, 439–443.

Case, L.A., Miller, S.P. and Wood, B.J. (2010) Determination of the optimum slaughter weight to maximize gross profit in a turkey production system. *Canadian Journal of Animal Science* 90, 345–356.

Cevger, Y. and Yalçin, C. (2003) A quantitative model to determine factors affecting profits of broiler enterprises. *Turkish Journal of Veterinary and Animal Science* 27, 1201–1205.

Chwalibog, A. and Baldwin, R.L. (1995) Systems to predict the energy and protein requirements of laying fowl. *World Poultry Science Journal* 51, 187–196.

Combs, G.F. (1960) Protein and energy requirements of laying hens. In: *Proceedings of the Maryland Nutrition Conference*, pp. 28–45.

Combs, G.F. (1967) Amino acid allowances for growing chicks including broilers. In: Morton, R.A. and Amoroso, E.C. (eds) *Protein Utilization by Poultry*. Oliver and Boyd, Edinburgh, UK, pp. 119–136.

Costa, E.F. Houston, J.E., Gunter, L. and Pesti, G.M. (2002) Incorporating consumer demand in broiler profit maximization modelling. *Journal of Food Distribution Research* 33, 1–10.

Curnow, R.N. (1973) A smooth population curve based on an abrupt threshold and plateau model for individuals. *Biometrics* 29, 1–10.

Curnow, R.N. and Torenbeek, R.V. (1996) Optimal diets for egg production. *British Poultry Science* 37, 373–382.

Dänicke, S. (1995) Prediction of growth responses of male broilers using a simulation model. *Archiv für Geflügelkunde* 59, 58–60.

De Beer, M. (2009) Adjusting nutrient density when faced with volatile markets. In: *Proceedings Arkansas Nutrition Conference, 2009*. The Poultry Federation, Little Rock, Arkansas. Available at: www.thepoultryfederation.com/public/userfiles/files/DeBeer%20-%20Adjusting%20Nutrient%20Density%20when%20Faced%20with%20Volatile.pdf (accessed 20 May 2013).

D'Mello, J.P.F. (1994) Responses of growing poultry to amino acids. In: D'Mello, J.P.F. (ed.) *Amino Acids in Farm Animal Nutrition*. CAB International, Wallingford, UK, pp. 205–243.

Edwards, H.M. Jr and Baker, D.H. (1999) Maintenance sulfur amino acid requirements of young chicks and efficiency of their use for accretion of whole-body sulfur amino acids and protein. *Poultry Science* 78, 1418–1423.

Edwards, H.M. Jr, Baker, D.H., Fernandez, S.R. and Parsons, D.G. (1997) Maintenance threonine requirement and efficiency of its use for accretion of whole-body threonine and protein in young chicks. *British Journal of Nutrition* 78, 111–119.

Edwards, H.M. Jr., Fernandez, S.R. and Baker, D.H. (1999) Maintenance lysine requirement and efficiency of using lysine for accretion of whole-body lysine and protein in young chicks. *Poultry Science* 78, 1412–1417.

EFG Software (1995) EFG software. Available at: www.efgsoftware.net (accessed 28 May 2014)

Eits, R.M., Kwakkel, R.P., Verstegen, M.W.A. and den Hartog, L.A. (2005a) Dietary balanced protein in broiler chickens. 1. A flexible and practical tool to predict dose-response curves. *British Poultry Science* 46, 300–309.

Eits, R.M., Giesen, G.W.J., Kwakkel, R.P., Verstegen, M.W.A. and den Hartog, L.A. (2005b) Dietary balanced protein in broiler chicks. 2. An economic analysis. *British Poultry Science* 46, 310–317.

Emmans, G.C. (1981) A model of the growth and feed intake of *ad libitum* fed animals, particularly poultry. In: Hillyer, G.M., Whittemore, C.T. and Gunn, R.G. (eds) *Computers in Animal Production.* Occasional Publication No 5., British Society of Animal Production, Thames Ditton, UK, pp. 103–110.

Emmans, G.C. (1989) The growth of turkeys. In: Nixey, C. and Grey, T.C. (eds) *Recent Advances in Turkey Science*. Butterworths, London, pp. 135–166.

Emmans, G.C. (1994) Effective energy: a concept of energy utilisation applied across species. *British Journal of Nutrition* 71, 801–821.

Emmans, G.C. (1997) A method to predict the food intake of domestic animals from birth to maturity as a function of time. *Journal of Theoretical Biology* 186, 189–199.

Emmans, G.C. and Fisher, C. (1986) Problems in nutritional theory. In: Fisher, C. and Boorman, K.N. (eds) *Nutrient Requirements of Poultry and Nutritional Research*. Butterworths, London, pp. 9–39.

Etches, R.J. (1996) *Reproduction in Poultry*. CAB International, Wallingford, UK.

Etches, R.J. and Schoch, J.P. (1984) A mathematical representation of the ovulatory cycle of the domestic hen. *British Poultry Science* 25, 65–76.

Faridi, A., France, J. and Golian, A. (2013) Neural network models for predicting early egg weight in broiler breeder hens. *Journal of Applied Poultry Research* 22, 1–8.

Ferguson, N.S. and Gous, R.M. (1993) Evaluation of pig genotypes. 1. Theoretical aspects of measuring genetic parameters. *Animal Production* 56, 233–243.

Ferguson, N.S., Gous, R.M. and Emmans, G.C. (1994) Preferred components for the construction of a new simulation model of growth, feed intake and nutrient requirements of growing pigs. *South African Journal of Animal Science* 24, 10–17.

Filmer, D.G. (2001) Nutritional management of meat poultry. In: Wathes, C.M., Frost, A.R., Gordon, F. and Wood, J.D. (eds) *Integrated Management Systems for Livestock*. Occasional Publication No. 28., British Society of Animal Production, Edinburgh, UK, pp. 133–146.

Fisher, C. (1994) Responses of laying hens to amino acids. In: D'Mello, J.P.F. (ed.) *Amino Acids in Farm Animal Nutrition*. CAB International, Wallingford, UK, pp. 245–279.

Fisher, C. and Gous, R.M. (2008) Modelling the growth of body components in broilers. In: *Proceedings XXIII World's Poultry Congress 2008*. WPSA, Brisbane, Australia.

Fisher, C. and Wilson, B.J. (1974) Response to dietary energy concentration by growing chickens. In: Morris, T.R. and Freeman, B.M. (eds) *Energy Requirements of Poultry*, British Poultry Science Ltd, Edinburgh, UK, pp. 151–184.

Fisher, C., Morris, T.R. and Jennings, R.C. (1973). A model for the description and prediction of the response of laying hens to amino acid intake. *British Poultry Science* 14, 469–484.

France, J. and Thornley, J.H.M. (1984) *Mathematical Models in Agriculture*. Butterworths, London.

Fraps, R.M. (1955) Egg production and fertility in poultry. In: Hammond, J. (ed.) *Progress in the Physiology of Farm Animals, Vol.* 2. Butterworths, London, pp. 671–740.

Frost, A.R., Parsons, D.J., Stacey, K.F., Robertson, A.P., Welch, S.K., Filmer, D.G. and Fothergill, A. (2003) Progress towards the development of an integrated management system for broiler chicken production. *Computers and Electronics in Agriculture* 39, 227–240.

Gous, R.M. and Berhe, E.T. (2006) Modelling populations for purposes of optimization. In: Gous, R.M., Morris, T.R., Fisher, C. (eds) *Mechanistic Modelling in Pig and Poultry Production*. CAB International, Wallingford, UK, pp. 76–96.

Gous, R.M. and Brand, T.S. (2008) Simulation models used for determining food intake and growth of ostriches: an overview. *Australian Journal of Experimental Agriculture* 48, 1266–1269.

Gous, R.M. and Nonis, M.K. (2010) Modelling egg production and nutrient response in broiler breeder hens. *Journal of Agricultural Science* 148, 287–301.

Gous, R.M., Pym, R.A.E., Mannion, P.F. and Wu, J.X. (1996) An evaluation of the parameters of the Gompertz growth equation that describe the growth of eight strains of broiler. In: *Proceedings Australian Poultry Science Symposium 1996*, University of Sydney, Sydney, Australia, pp. 174–177.

Gous, R.M., Moran, E.T., Stilborn, H.L., Bradford, G.D. and Emmans, G.C. (1999) Evaluation of the parameters needed to describe the overall growth, the chemical growth and the growth of feathers and breast muscles of broilers. *Poultry Science* 78, 812–821.

Grosskopf, K. and Matthäus, E. (1990) Mathematical simulation of the broiler production process. *Systems Analysis Modelling and Simulation* 7, 473–491.

Håkansson, J., Eriksson, S. and Svensson, S.A. (1978a) The influence of feed energy level on feed consumption, growth and development of different organs of chickens. *Swedish University of Agricultural Science, Department of Animal Husbandry, Report no. 57*. Sveriges Lautbruksuniversitel, Uppsala, Sweden.

Håkansson, J., Eriksson, S. and Svensson, S.A. (1978b). The influence of feed energy level on chemical composition of tissues and on the energy and protein utilisation of broiler chicks. *Swedish University of Agricultural Sciences, Department of Animal Husbandry, Report no. 59*. Sveriges Lautbruksuniversitel, Uppsala, Sweden.

Hancock, C.E., Bradford, G.D., Emmans, G.C. and Gous, R.M. (1995) The evaluation of the growth parameters of six strains of commercial broiler chickens. *British Poultry Science* 36, 247–264.

Harlow, H.B. and Ivey, F.J. (1994) Accuracy, precision and commercial benefits of growth modelling for broilers. *Journal of Applied Poultry Research* 3, 391–402.

Heuser, G.F. (1941) Protein in poultry nutrition – a review. *Poultry Science* 20, 362–368.

Hochman, E. and Lee, I.M. (1972) Optimal decision in the broiler producing firm: a problem of growing inventory. *Giannini Foundation Monograph* 29, 1–49. Available at: http://giannini.ucop.edu/Monographs/29-BroilerProduction.pdf (accessed 22 May 2013).

Hruby, M., Hamre, M.L. and Coon, C. (1996) Non-linear and linear functions in body protein growth. *Journal of Applied Poultry Research* 5, 109–115.

Hurwitz, S., Sklan, D. and Bartov, I. (1978) New formal approaches to the determination of energy and amino acid requirements of chicks. *Poultry Science* 57, 197–205.

Hurwitz, S., Talpaz, H., Bartov, I. and Plavnik, I. (1991) Characterization of growth and development of male British United turkeys. *Poultry Science* 70, 2419–2424.

Isariyodom, S., Tasaki, I., Okumura, J.-I. and Muramatsu, T. (1988). Construction of a mathematical model for predicting broiler performance. *Japanese Poultry Science* 25, 191–200.

Johnston, S.A. and Gous, R.M. (2006). Modelling egg production in laying hens. In: Gous, R.M., Morris, T.R., Fisher, C. (eds) *Mechanistic Modelling in Pig and Poultry Production*. CAB International, Wallingford, UK, pp. 229–259.

Kebreab, E., France, J., Kwakkel, R.P., Leeson, S., Kuhi, H.D. and Dijkstra, J. (2009) Development and evaluation of a dynamic model of calcium and phosphorus flows in layers. *Poultry Science* 88, 680–689.

King, R.D. (2001) Description of a growth simulation model for predicting the effect of diet on broiler composition and growth. *Poultry Science* 80, 245–253.

Kratzer, D.D. and Littell, R.C. (2006) Appropriate statistical methods to compare dose responses of methionine sources. *Poultry Science* 85, 947–954.

Lee, P.J.W., Gulliver, A.L. and Morris, T.R. (1971) A quantitative analysis of the literature concerning the restricted feeding of growing pullets. *British Poultry Science* 12, 413–437.

Lemme, A. (2003) The 'Ideal Protein Concept' in broiler nutrition 1. Methodological aspects – opportunities and limitations. *Degussa AG Amino News* 4–1, 7–14.

Lewis, P.D. and Morris, T.R. (2004) Research note: amendments to the model for predicting age at sexual maturity for growing pullets of layer strains following changes in photoperiod. *Journal of Agricultural Science* 142, 613–614.

Lewis, P.D. and Morris, T.R. (2008) Research note: an amendment to the model for predicting age at sexual maturity for growing pullets of layer strains given two opposing changes in photoperiod. *Journal of Agricultural Science* 146, 591–594.

Lewis, P.D., Morris, T.R. and Perry, G.C. (1998) A model for the effect of constant photoperiods on the rate of sexual maturation in pullets. *British Poultry Science* 39, 147–151.

Lewis, P.D., Morris, T.R. and Perry, G.C. (2002) A model for predicting the age at sexual maturity for growing pullets of layer strains given a single change of photoperiod. *Journal of Agricultural Science* 138, 441–458.

Lewis, P.D., Gous, R.M. and Morris, T.R. (2007) A model to predict age at sexual maturity in broiler breeders given a single increment in photoperiod. *British Poultry Science* 48, 625–634.

Lovatto, P.A. and Sauvant, D. (2003) Modelling homeorhetic and homeostatic controls of pig growth. *Journal of Animal Science* 81, 683–696.

Low, E.M. and Brookhouse, J.K. (1967) Dynamic programming and the selection of replacement policies in commercial egg production. *Journal of Agricultural Economics* 18, 339–350.

Mack, S., Hohler, D. and Pack, M. (2000) Evaluation of dose-response data and implications for commercial formulation of broiler diets. In: *Proceedings Australian Poultry Science Symposium 2000*, University of Sydney, Sydney, Australia, pp. 82–87.

Morris, T.R. (1968) The effect of dietary energy level on the voluntary calorie intake of laying hens. *British Poultry Science* 9, 285–295.

Morris, T.R. (1983) The interpretation of response data from animal feeding trials. In: Haresign, W. (ed.) *Recent Developments in Poultry Nutrition*. Butterworths, London, pp. 13–24.

Morris, T.R. and Blackburn, H.A. (1982) The shape of the response curve relating protein intake to egg output for flocks of laying hens. *British Poultry Science* 23, 405–424.

Moughan, P.J. (2003) Simulating the partitioning of dietary amino acids: new directions. *Journal of Animal Science* 81 (E. Suppl. 2), E60–E67.

Muramatsu, T., Isariyodom, S., Umeda, I. and Okumura, J.-I. (1989) Computer-simulated growth prediction of replacement pullets with special reference to seasonal changes in feed intake. *Poultry Science* 68, 771–780.

National Research Council (1994) *Nutrient Requirements of Poultry*. National Academy Press, Washington, DC.

Nonis, M.K. and Gous, R.M. (2008) Threonine and lysine requirements for maintenance in chickens. *South African Journal of Animal Science* 38, 75–82.

Novák, L. (1996) Self-regulating model in homeotherms (SGM). *Acta Veterinaria Brno* 65, 107–114.

Novák, L. (2003) The growth of farm animals simulated by the biological model of growth. In: Windisch, W. (ed.) *Proceedings Boku – Symposium Tierernährung*, Institut für Wissenschaften, Wien, Austria, pp. 84–89.

Novák, L. and Zeman, L. (1997) The broiler growth calculated from the intake of metabolisable feed energy by means of self-regulating growth model. In: *Proceedings 11th European Symposium on Poultry Nutrition*, WPSA Danish Branch, Faaborg, Denmark, pp. 397–399.

Novák, P., Zeman, L., Kosar, K. and Novák, L. (2004) Modelling of body mass increase and feed conversion ratio in chickens ROSS 208. *Acta Veterinaria Brno* 73, 17–22.

Parks, J.R. (1982) *A Theory of Feeding and Growth of Animals*. Springer, Berlin.

Pesti, G.M. and Miller, B.R. (1997) Modelling for precision nutrition. *Journal of Applied Poultry Research* 6, 483–494.

Pesti, G.M., Arraes, A. and Miller, B.R. (1986) Use of the quadratic growth response to dietary protein and energy concentrations in least-cost feed formulation. *Poultry Science* 65, 1040–1051.

Piepho, H.-P. (2006) A cautionary note on appropriate statistical methods to compare dose responses of methionine sources. *Poultry Science* 85, 1511–1512.

Porter, T., Kebreab, E., Darmani Kuhi, H., Lopez, S., Strathe, A.B. and France, J. (2010) Flexible alternatives to the Gompertz equation for describing growth with age in turkey hens. *Poultry Science* 89, 371– 378.

Quentin, M. (2004) A dynamic model of broiler growth for practical utilisation: INAVI. PhD Thesis. L'École Nationale Supérieure Agronomique de Rennes, Rennes, France.

Rivera-Torres, V., Ferket, P.R. and Sauvant, D. (2010) Model development of nutrient utilisation to represent poultry growth dynamics: application to the turkey. In: Sauvant, D., van Milgen, J., Faverdin, P. and Friggens, N. (eds) *Modelling Nutrient Digestion and Utilisation in Farm Animals*. Wageningen Academic Publishers, Wageningen, The Netherlands, pp. 289–296.

Rivera-Torres, V., Ferket, P.R. and Sauvant, D. (2011) Mechanistic modelling of turkey growth response to genotype and nutrition. *Journal of Animal Science* 89, 3170–3188.

Rivest, J., Bernier, J.F. and Pomar, C. (2000) A dynamic model of protein digestion in the small intestine of pigs. *Journal of Animal Science* 78, 328–340.

Roan, S.W. and Wang, B.Y. (1996) Computer simulation model of broiler growth. *Chinese Society of Animal Science* 25, 75–96.

Rosen, G.D. (1995) Antibacterials in poultry and pig nutrition. In: Wallace, R.J. and Chesson, A. (eds) *Biotechnology in Animal Feeds and Animals Feeding*. V C H, Weinheim, Germany, pp. 143–172.

Rosen, G.D. (2004) How many broiler feeding tests are required to elaborate working models for the prediction of nutritional effects of pronutrients in praxis? *British Poultry Science* 45 (suppl. 1), 58–59.

Rosen, G.D. (2006) Holo-analysis. *Poultry Science* 85, 957–959.

Rosen, G.D. (2007a) Holo-analysis of the efficacy of Bio-Mos® in broiler nutrition. *British Poultry Science* 48, 21–26.

Rosen, G.D. (2007b) Holo-analysis of the efficacy of Bio-Mos® in turkey nutrition. *British Poultry Science* 48, 27–32.

Rosen, G.D. (2007c) Nutritive value of methionine sources. *Poultry Science* 86, 209–210.

Rosen, G.D. (2010) Holo-analysis of the efficiency of exogenous enzyme performance in farm animal nutrition. In: Bedford, M.R. and Partridge, G.G. (eds) *Enzymes in Farm Animal Nutrition*. CAB International, Wallingford, UK, pp. 272–303.

Roush, W.B. (2001) An operations research approach to leveraging new technology opportunities. *Journal of Applied Poultry Research* 10, 293–302.

Roush, W.B. (2006) Advancements in empirical models for prediction and prescription. In: Gous, R.M., Morris, T.R. and Fisher, C. (eds) *Mechanistic Modelling in Pig and Poultry Production*. CAB International, Wallingford, UK, pp. 97–116.

Roush, W.B., Barbato, G.F. and Cravener, T.L. (1994) A nonlinear dynamical (chaos) approach to the analysis of broiler growth. *Poultry Science* 73, 1183–1195.

Sakomura, N.K. (2004) Modelling energy utilisation in broiler breeders, laying hens and broilers. *Brazilian Journal of Poultry Science* 6, 1–11.

Sakomura, N.K., Longo, F.A., Oviedo-Rondón, E.O., Boa-Viagem, C. and Ferraudo, A. (2005) Modelling energy utilisation and growth parameter description for broiler chickens. *Poultry Science* 84, 1363–1369.

Sakomura, N.K., Marcato, S.M., Munari, D.P., Freitas, E.C. and Fernandez, J.B.K. (2006) Growth curves and body nutrients deposition on two broiler chicken strains. In: *Proceedings XII European Poultry Conference*. WPSA, Verona, Italy. Available at: http://www.cabi.org/animalscience/Uploads/File/AnimalScience/additionalFiles/wpsaverona.htm (accessed 22 May 2013).

Sauer, N., Emrich, K., Piepho, H.-P., Lemme, A., Redshaw, M.R. and Mosenthin, R. (2008) Meta-analysis of the relative efficiency of methionine-hydroxy-analogue-free-acid compared with DL-methionine in broilers using nonlinear mixed models. *Poultry Science* 87, 2023–2031.

Sauvant, D. (1992) La modélisation systémique en nutrition. *Reproduction Nutrition Development* 32, 217–230.

Sauvant, D. (1994) Modelling homeostatic and homeorhetic regulations in lactating animals. *Livestock Production Science* 39, 105–113.

Sauvant, D., Schmidely, P., Daudin, J.J., St-Pierre, N.R. (2008) Meta-analyses of experimental data in animal nutrition. *Animal* 2, 1203–1214.

Stacey, K.F., Parsons, D.J., Frost, A.R., Fisher, C., Filmer, D.G. and Fothergill, A. (2004) An automatic growth and nutrition control system for broiler production. *Biosystems Engineering* 89, 363–371.

Stilborn, H.L., Moran, E.T., Gous, R.M. and Harrison, M.D. (1994) Experimental data for evaluating broiler models. *Journal of Applied Poultry Research* 3, 379–390.

Talpaz, H., Sharpe, P.J.H., Wu, H.I., Plavnik, I. and Hurwitz, S. (1991) Modelling of the dynamics of accelerated growth following feed restriction in chicks. *Agricultural Systems* 36, 125–135.

Talpaz, H., Cohen, M., Fancher, B. and Halley, J. (2013) Applying complex models to poultry production in the future – Economics and biology. *Poultry Science* 92, 2541–2549.

Teter, N.C., DeShazer, J.A. and Thompson, T.L. (1973) Operational characteristics of meat animals. Part III: Broilers. *Transactions of the ASAE* 16, 1165–1167.

Teter, N.C., DeShazer, J.A. and Thompson, T.L. (1976) Operational characteristics of meat animals. Part IV: Turkeys, Large White and Bronze. *Transactions of the ASAE* 19, 724–727.

Vázquez-Añón, M., Kratzer, D., González-Esquerra, R., Yi, I.G. and Knight, C.D. (2006) A multiple regression model approach to contrast the performance of 2-hydroxy-4-methylthio butanoic acid and DL-methionine supplementation tested in broiler experiments and reported in the literature. *Poultry Science* 85, 693–705.

Wang, Z. and Zuidhof, M.J. (2004) Estimation of growth parameters using a non-linear mixed Gompertz model. *Poultry Science* 83, 847–852.

Whittemore, C.T. and Fawcett, R.H. (1974) Model responses of the growing pig to the dietary intake of energy and protein. *Animal Production* 19, 221–231.

Whittemore, C.T. and Fawcett, R.H. (1976) Theoretical aspects of a flexible model to simulate protein and lipid growth in pigs. *Animal Production* 22, 87–96.

Yahav, S., Straschnow, A., Razpakovski, V. and Shinder, D. (2001) Air velocity alters broiler performance under harsh environmental conditions. *Poultry Science* 80, 724–726.

2 InraPorc: Where Do We Come From and Where Do We Want to Go?

J. van Milgen,* J.Y. Dourmad, J. Noblet, E. Labussière, F. Garcia-Launay, S. Dubois, A. Valancogne and L. Brossard
INRA, Saint-Gilles, France

Abstract

The first nutritional models for pig growth were published in the mid-1970s. Although modelling has been seen for a long time as a very promising approach in animal nutrition, widespread use of models has been limited. We hold the opinion that models should be user-friendly to ensure that they will be adopted by users other than the model developers. It is with this in mind that we started the development of the InraPorc model and software tool. One of the main challenges we encountered was to capture the phenotypic variation among pigs in a limited number of user-accessible model inputs. Feed intake, protein deposition and energy expenditure are model inputs, while lipid deposition is an energy sink. An inappropriate description of the feed intake, protein deposition or energy expenditure will therefore result in a very fat or very lean pig when the simulation is carried out for a long period of time. We included a function in the model where feed intake is described as a Gamma function of the maintenance energy expenditure. This function ensures that, as the pig matures, feed intake attains the maintenance energy expenditure so that energy retention and growth cease. Deterministic growth models such as InraPorc simulate the performance of a single 'average' pig. However, nutritional recommendations for the average pig should not be applied to a population of pigs because the performance of the population would then be less than that of the average pig. To include variation among pigs in simulation models, the variance–covariance structure of model parameters should be taken into account because variation among animals is only partly random. For example, a pig that eats more than average will probably also grow faster than average. Including stochastic aspects in simulation models is currently a research topic in our group, and results of this will be included in a future release of the InraPorc software tool.

Introduction

The InraPorc project started in 1998 with the goal of developing a nutritional model for growing pigs and sows that could be accessed through a user-friendly interface. InraPorc is a model and a software tool that allows users to work with the model. Development of the model and the tool was intended to be a 3-year project with an anticipated delivery in 2001. However, the first software version was released in 2006 and the model description was published in 2008 (Dourmad *et al.*, 2008; van Milgen *et al.*, 2008). What went wrong? Not much in terms of model development. This is not too surprising because the InraPorc model (at least the growing pig model) is a rather

---

*E-mail: jaap.vanmilgen@rennes.inra.fr

classical model. The main challenge and an extremely time-consuming task has been the development of the software tool. This involved identifying the most relevant and accessible inputs to run the model under a variety of conditions and providing outputs that allow the user to analyse and understand the responses predicted by the model. Since its initial release, various minor and major software upgrades have been published, most of which concerned improving the user-friendliness of the tool. The software can be downloaded from www.rennes.inra.fr/inraporc/ and is free for educational purposes.

The InraPorc model is structurally very similar to that developed 40 years ago by Whittemore and Fawcett (1974), where body weight gain is modelled as a function of protein and lipid weight gain. Under nutritionally non-limiting conditions, feed intake and protein deposition are modelled independently and are user inputs required to run the model. Feed intake is represented as a function of body weight, while protein deposition is defined as a Gompertz function, both of which have to be parameterized by the user. The main reason that we chose to use feed intake and protein deposition as user inputs is that these can be determined relatively easily by the user. Through its relationship with body water, there is a strong relationship between protein deposition and body weight gain. Likewise, feed or energy intake can be measured directly by the user. Energy not used for protein deposition and maintenance will be available for lipid deposition, and lipid deposition is thus considered an energy sink. The consequence of this approach is that errors will accumulate in lipid deposition. Because it is very difficult to estimate lipid deposition accurately during growth (and even at slaughter), it is thus very difficult to evaluate the accuracy of the predicted lipid deposition (or related traits). This is a generic problem in growth models and not specific for the InraPorc model. Feed restriction, amino acid deficiencies and changes in the maintenance energy requirement can affect protein deposition, energy partitioning and thus growth.

In the next sections, we will describe how these responses are modelled and how this has been incorporated into the software tool. In doing so, we had to decide how model parameters can be determined. In certain cases (e.g. defining the phenotypic feed intake and growth potential of the animal) the user has to provide the corresponding model parameters. In other cases, default model parameters are provided that can be changed by the user if sufficient information is available to justify a change. We also decided to hard-code certain parameters in the software tool because we felt that changing these parameters would require information inaccessible to most users, or that it may affect model predictions beyond our control.

Using the InraPorc Software Tool

To run a simulation for growing pigs, InraPorc combines information from three different modules: the animal profile, a feed sequence plan and a feed rationing plan. The animal profile describes the phenotypic *ad libitum* feed intake and growth potential of the animal. To account for differences among animals, the user has to provide a minimum of five parameters: the initial body weight, two parameters to describe the feed intake curve and two parameters to describe the protein deposition curve. In the first version of the software, the user had to obtain these model parameters by trial and error by confronting experimental data with model predictions. Since 2009, we have included an algorithm that allows the estimation of model parameters directly from experimental observations through a statistical procedure. Because both feed intake and growth are dynamic, the user has to provide feed intake and growth data for at least two different periods to estimate the parameters for the feed intake and growth curves. A feed sequence plan defines the different diets that will be used during a simulation. The diet composition can be calculated from the composition of feed ingredients (Sauvant *et al.*, 2004), or can be provided by the user based on the analysed diet composition. A feed rationing plan is used to indicate how much feed is provided to the animal. This can be based on fixed quantities or as a percentage of the *ad libitum* feed intake.

In a single simulation, the information from the animal profile, the feed sequence plan and the feed rationing plan are combined and the user can evaluate the response in various ways (see the figures used later in the text). It is beyond the scope of this chapter to depict all the graphs and reports that can be produced; however, we are of the view that InraPorc is a very appropriate tool for professional nutritionists and to teach swine nutrition. It deals with practical aspects such as the dynamics of feed intake, growth and nutrient requirements. It can be used to study nutrient partitioning and to illustrate the different concepts used in energy and amino acid nutrition (e.g. explaining the difference between GE, DE, ME and NE). Apart from running a single simulation, comparisons of simulations can be performed by combining different modules. For example, two different feed rationing plans can be used to evaluate the consequence of applying a feed restriction during the finisher phase. Also, sensitivity analyses can be performed to evaluate the sensitivity of model predictions to parameters of the animal profile or to the supply of the most important nutrients.

Our Love–Hate Relationship with Maintenance

The concept of maintenance is widely used in animal nutrition. Virtually all nutritionists have some feeling as to what maintenance is. However, there has been quite some debate on how maintenance should be interpreted for growing animals. The maintenance energy requirement corresponds to the situation where energy intake equals energy expenditure. For a growing animal, it is clear that this situation is not attained because energy intake exceeds energy expenditure, which consequently results in energy gain and growth. Lister and McCance (1967) offered feed to piglets so that they would maintain a body weight of 5 kg for 1 year. In these restricted pigs, the oxygen consumption reflects the maintenance energy requirement and was, as anticipated, considerably lower in the restricted pigs compared to the normally fed pigs of a similar body weight during the first months of the experiment (McCance and Mount, 1960). However, it increased during the course of the feed restriction to attain values similar to that of the control group after 12 months of feed restriction. This indicates that it is very difficult to measure the maintenance energy requirement in growing animals and to give it a biological meaning. As van Milgen and Noblet (1999) wrote: ‘The concept of maintenance may not be appropriate for growing animals. However, no suitable alternatives are currently available, and it may be better to fully adhere to the concept of maintenance and accept its constraints.’

In InraPorc, many concepts are expressed relative to maintenance. Apart from the lack of suitable alternatives, we also felt that maintenance (or homeostasis) is a fundamental concept in biology. In non-producing, mature animals energy intake equals energy production. If this were not the case, energy would be gained or lost. Non-producing animals regulate energy intake, energy production or both to maintain energy equilibrium. Even in obese humans, energy intake is only slightly greater than the energy expenditure. The difference is typically less than 0.5% but if maintained for a long period of time it results eventually in obesity. In an experimental setting, we would consider the 0.5% difference as a ‘margin of error’, but it clearly indicates that energy intake and energy expenditure are highly regulated, even in the case of obesity.

Feed Intake

In the first version of the InraPorc software tool, we proposed three equations to express *ad libitum* feeding or energy intake relative to body weight. These included a linear function ($Y = a + b \times BW$), an asymptotic function ($Y = a \times (1 - \exp(-b \times BW))$), and a power function ($Y = a \times BW^b$). We had a personal preference for the power function because it enables comparison with the maintenance energy requirement, which is expressed relative to $BW^{0.60}$. When the parameter 'b' for the power function is less than 0.60, the difference between feed intake and maintenance declines with increasing body weight.

The functions we proposed initially have the limitation that there is no explicit control of feed intake relative to the energy expenditure, so the animal would become excessively lean or fat if the simulation were to be carried out for a long period of time. This is why we included a new function in InraPorc where feed intake is expressed as a Gamma function of the maintenance energy expenditure (i.e. $Y = (a \times (b \times BW \times \exp(-b \times BW)) + 1) \times c \times BW^{0.60}$). The parameters '$a$' and '$b$' are user inputs, while 'c' is a constant, which depends on whether intake is expressed on a quantity basis or on an energy basis (e.g. it is 0.75 MJ/(kg $BW^{0.60}$)/day when intake is expressed on a net energy basis). With increasing body weight, feed or energy intake will approach the maintenance energy requirement so that the animal stops growing and attains maturity. The Gamma function contrasts with the other three functions because it allows for a reduction in feed intake when body weight increases. Compared to the other functions, it also provided the most accurate fit to observed data on feed intake (Vautier *et al.*, 2011a,b). Because protein deposition is described by a Gompertz function (which also becomes zero when the animal attains the mature protein mass), lipid deposition will be controlled. This approach contrasts with that of Ferguson *et al.* (1994), who explicitly modelled genetically determined protein and lipid depositions using Gompertz functions to predict feed intake. These fundamentally different approaches can be summarized as 'do animals grow because they eat or do they eat because they want to grow?' Even though we feel that the second approach may be biologically more appropriate, we opted for the first approach because feed intake is easier to measure and control than lipid deposition.

The Gamma function also predicts that feed intake equals the maintenance energy requirement at zero body weight (i.e. around conception), which is, of course, debatable. Alternatively, an exponentially declining function of maintenance could be used ($Y = ((a \times \exp(-b \times BW) + 1) \times c \times BW^{0.60})$) so that energy intake would be highest at conception. Although we tested this function, we did not include it in the InraPorc software tool because its fit to experimental data was not as good as that of the Gamma function.

In the InraPorc software tool, it is left to the user to decide whether voluntary feed intake is determined by quantity (dry matter) or energy (DE, ME or NE). This has of course an impact on how the animal responds to diets with different energy densities. If the user decides to define voluntary feed intake on a dry matter basis, feeding a high energy diet (e.g. with a high fat content) results in a greater energy supply and growth rate than feeding a low energy diet. However, if energy intake is assumed to be regulated on an NE basis, there will be no difference in growth rate between both diets. As discussed before concerning energy homeostasis in mature animals, it is likely that the regulation of feed intake is described best on an NE basis. However, there may be situations where the physical feed intake capacity of the animal is limited (especially in younger pigs fed high fibre diets), and expressing intake on a DE or dry matter basis (or on a bulk basis) may then be more appropriate. We realize that leaving the choice to the user has an important impact on the model response.

Potential Protein Deposition

A Gompertz function was used to describe the potential protein mass. The Gompertz function is a sigmoidal function so that pigs will attain a constant protein mass at maturity. The first derivative of the Gompertz function describes the potential protein deposition. This first derivative can be expressed relative to time or as a function of current protein mass. This choice for either expression has an important (theoretical) meaning because it implies that either time (or age) or state (current protein mass) is considered the driving force for protein deposition. This also has practical consequences in the way compensatory growth is predicted. When protein deposition is described as a function of time, the pig may lose (part of) its growth potential because of ageing. This is not the case when protein deposition is described as a function of current protein mass. The study of Lister and McCance (1967) is inconclusive because refeeding the pigs after 1 year of severe feed restriction resulted in growth rates similar to that of the control group. However, the restricted pigs stopped growing at a lower body weight, suggesting that both time and current state play a role in protein deposition. In InraPorc, we chose to describe the potential protein deposition as a function of the current protein mass. Initial simulations indicated that this allowed for a better prediction of compensatory growth after a period of feed restriction using the data of Bikker *et al.* (1994, 1996).

Different approaches have been taken for the empirical modelling of protein deposition or body weight gain (Black *et al.*, 1986; Emmans and Kyriazakis, 1997; Schulin-Zeuthen *et al.*, 2008). We felt most comfortable with a function that would account for the concept of maturity (i.e. protein deposition should tend to zero) but without attributing a specific biological meaning to the Gompertz function or to its parameters. When written as a differential equation, the Gompertz function is often parameterized to include the initial protein mass, the protein mass at maturity and a shape parameter. The mature protein mass of pigs is around 30 kg, but the protein mass at slaughter is much lower. When data up to a normal slaughter weight are fitted to a function like the Gompertz, it is not uncommon to obtain estimates of the mature body weight that are biologically unrealistic. This is a problem of fitting partial data to a function that describes growth throughout life. Rather than restraining mature protein mass within biologically reasonable limits, we preferred to parameterize the Gompertz function with parameters that have a practical meaning and that best describe the protein deposition during the productive life of the animal. The Gompertz function for protein deposition was parameterized in InraPorc by the initial protein mass, the mean protein deposition during the productive life and a precocity parameter. By default, the initial protein mass is calculated from the initial body weight. Because we used a fixed relationship to estimate body weight from protein and lipid mass, the user will have the possibility of adjusting (within reasonable limits) the initial protein mass for a given initial body weight. The mean protein deposition determines the difference between the initial and final protein mass at the end of a simulation. For a given feed intake, changing the mean protein deposition will therefore change the body weight gain and body composition. The precocity parameter represents the shape of the Gompertz function. For a given initial protein mass and mean protein deposition, the protein mass at slaughter will be known, but not the trajectory to get there. A high value for the precocity parameter results in an early maturing animal, while a low value results in a late maturing animal.

Maintenance Energy Requirement

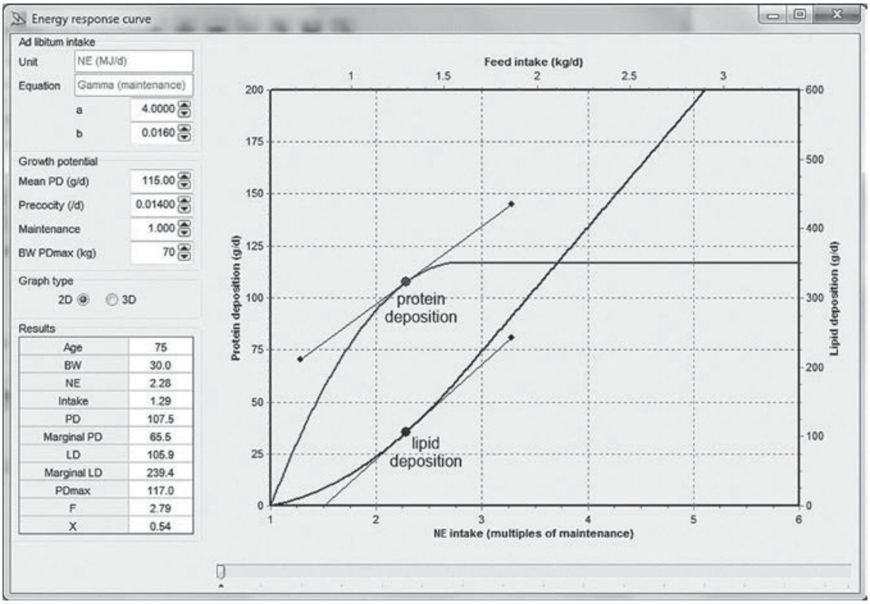
As explained before, maintenance is a fundamental concept in biology but difficult to measure in growing animals. We feel that the fasting heat production is the best measurable indicator for the maintenance energy requirement in growing animals. There is strong evidence that the fasting heat production in growing pigs varies with body weight raised to the power 0.60 (Noblet *et al.*, 1999) and not to the frequently used scalar of 0.75. The latter is derived from comparing maintenance in different mature, non-producing species (e.g. from mice to elephants) and it is not surprising that other values are found for growing animals of different body weights within a species. The choice of an appropriate scalar has important consequences for the change in maintenance energy during growth and thus for the available energy for protein and lipid deposition. For the same energy expenditure at 60 kg body weight, using 0.75 as a scalar underestimates the energy expenditure by 15% at 20 kg (relative to using 0.60 as a scalar) and overestimates it by 11% at 120 kg.

In InraPorc, the maintenance energy requirement is determined based on the fasting heat production and 'normal' physical activity. The fasting heat production is a function of body weight raised to the power 0.60 and feed intake before fasting. There are several studies showing that the fasting heat production is affected by the feeding level before fasting (Koong *et al.*, 1982; de Lange *et al.*, 2006).This relationship is somewhat in contradiction with the classical separation of requirements for maintenance and growth, because it implies that the maintenance requirement depends on the level of feed intake and thus on growth.

The change in the maintenance energy requirement during growth (as a function of feed intake and body weight) is converted to a default value of 100% in InraPorc. We opted for this approach because it is virtually impossible for users to appreciate quantitatively the different components of maintenance (e.g. changes in physical activity, breed differences and immune function). As lipid deposition is considered an energy sink, a change in the maintenance energy requirement will affect predictions for lipid deposition and traits related to lipid deposition such as backfat thickness. We do not recommend that the user changes the maintenance energy requirement based on predictions and measurements of backfat thickness. Lipids in backfat account for not more than 18% of the total body lipids (Kloareg *et al.*, 2006) and only the thickness of this tissue is determined during growth or at slaughter. In InraPorc, backfat thickness is predicted from the lipid mass (the equation is given in the configuration window and can be changed by the user). Because of the difficulty in actually measuring whole-body lipid deposition, we recommend that the user changes the prediction equation for backfat thickness if a systematic bias in the prediction of backfat thickness is observed, rather than adjusting the maintenance energy requirement for the animal.

Response to a Feed Restriction

As indicated by Whittemore and Fawcett (1976), a restriction in energy intake may not only affect lipid deposition, but can also affect protein deposition. A linear-plateau model has often been used to model the relationship between energy intake and protein deposition. With increasing energy intake, protein deposition increases up to a maximum (referred to as PDmax). An increase in energy intake beyond that required to attain PDmax will not affect protein deposition and the additional energy will be used for lipid deposition only. In InraPorc, we used a curvilinear plateau function to describe the response of protein deposition to energy intake. Also here, we used maintenance as a reference criterion and we expressed the NE intake as multiples of maintenance. The reason for this is that we felt that a 1-MJ change in energy intake has a different meaning for a very young pig than a 1-MJ change in an older pig. Consequently, energy itself is not used as the 'currency', but it is scaled relative to maintenance. Figure 2.1 is a screenshot from the InraPorc software and illustrates how we represent the response of the animal to the energy intake. In Fig. 2.1, the response of the pig at 75 days of age is represented (the cursor below the graph allows the changing of the age of the pig). At 75 days of age, this pig eats 2.28 times the NE requirement for maintenance, resulting in a protein deposition of 107.5 g/day and a lipid deposition of 105.9 g/day. It is clear that at 75 days of age, the animal is in the energy-dependent phase of the response, as a change in energy intake would affect both protein deposition and lipid deposition. The pigs would need to eat 2.79 times the NE requirement for maintenance to attain PDmax (indicated by 'F' in Fig. 2.1), which is beyond the feed intake capacity of the animal at this stage. With increasing body weight, the feed intake capacity of the pig



Ad libitum intake

Unit: NE (MJ/d)

Equation: Gamma (maintenance)

a: 4.0000

b: 0.0160

Growth potential

Mean PD (g/d): 115.00

Precocity (/d): 0.01400

Maintenance: 1.000

BW PDmax (kg): 70

Graph type

2D ● ○ 3D

Results

Age	75
BW	30.0
NE	2.28
Intake	1.29
PD	107.5
Marginal PD	65.5
LD	105.9
Marginal LD	239.4
PDmax	117.0
F	2.79
X	0.54

Fig. 2.1. Screenshot of InraPorc illustrating the response of the pig to the energy supply at 75 days of age. The solid dots indicate the protein and lipid deposition at this age. The protein and lipid deposition response curves are also given as well as the marginal response to a change in energy intake at 75 days of age.

increases and there will be a point in time where protein deposition is no longer determined by feed intake capacity but by PDmax. In InraPorc, we assume that at 70 kg of body weight, the feed intake capacity of the pig is sufficient to attain PDmax (as indicated by the parameter '*BW PDmax*'), but this value can be modified by the user. The concepts depicted in Fig. 2.1 are mostly important in situations where feed restrictions are imposed. For body weights before '*BW PDmax*', there may be an interest in maximizing feed intake because a feed restriction would adversely affect both protein and lipid deposition. For body weights greater than '*BW PDmax*', a (small) feed restriction only adversely affects lipid deposition, resulting in leaner animals. This feeding strategy is often applied in France (with liquid feeding systems) to control carcass fatness during the finisher phase.

It is important to mention that InraPorc only predicts the response to farmer-imposed feed restrictions. Acute changes in feed intake (e.g. due to a sanitary challenge or to heat or cold stress) are not accounted for and these changes may affect protein deposition differently from a farmer-imposed feed restriction. For example, Le Bellego *et al.* (2002) showed that a heat-induced feed restriction affected protein and lipid deposition differently from an experimentally induced feed restriction.

Response to the Amino Acid Supply

In InraPorc, the response to the amino acid supply is modelled in a rather classical way by separating the basal endogenous losses, the maintenance requirement (due to losses of integuments and minimum protein turnover), the amino acid composition of whole-body protein and the maximum efficiency with which available amino acids can be used for protein deposition (Table 2.1).

The supply of digestible amino acids can be expressed on an apparent ileal digestible (AID) or on a standardized ileal digestible (SID) basis. The difference between both modes of expression is the way the basal

Table 2.1. Traits used in InraPorc to determine the protein deposition possible by the amino acid supply.[a]

	Basal endogenous losses (g/kg DM intake)	Maintenance (mg/kg BW$^{0.75}$/day)	Maximum efficiency of amino acid utilization (%)	Amino acid composition of body protein (%)
Lysine	0.313	28.4	72	6.96
Methionine	0.087	8.0	64	1.88
Cystine	0.140	9.4	37	1.03
Threonine	0.330	17.1	61	3.70
Tryptophan	0.117	4.4	57	0.95
Isoleucine	0.257	14.9	67	3.46
Leucine	0.427	32.4	76	7.17
Valine	0.357	20.2	71	4.67
Phenylalanine	0.273	16.7	82	3.78
Tyrosine	0.223	10.9	67	2.86
Histidine	0.130	11.5	93	2.79
Arginine	0.280	0	154	6.26
Protein	8.517	465.5	85	–

[a]The requirements for basal endogenous losses and maintenance are subtracted from the supply of SID amino acids. The resulting supply of available amino acids is then multiplied by the maximum efficiency and divided by the amino acid composition of body protein to determine the protein deposition that would be possible from the amino acid supply.

endogenous losses are accounted for. On an AID basis, the basal endogenous losses are part of the feed value. These losses, due to endogenous secretions and sloughing of intestinal cells, are of animal origin and contribute to the ileal amino acid flow. On an SID basis, the basal endogenous losses are considered to be part of the requirement of the animal. Because of the way basal endogenous losses are accounted for, the supply and the requirement of amino acids are higher on an SID basis than on an AID basis.

In InraPorc, the basal endogenous losses (when expressed on an SID basis) are assumed to be proportional to the dry matter intake and these losses are directly subtracted from the SID amino acid supply. Consequently, the composition of endogenous losses secretions and the efficiency with which the basal endogenous secretions are synthesized by the animal are summarized in a single value for each amino acid. Although this certainly is an approximation, we felt that the contribution of basal endogenous losses is relatively minor (compared to other losses) and that there is insufficient information to justify a different approach. We used values from the INRA and the Association Française de Zootechnie (AFZ) tables to characterize the amino acid profile for the basal endogenous losses (Sauvant *et al.*, 2004). These tables are also the basis for the AID and SID amino acid digestibility of feed ingredients available in InraPorc, which warrants a consistent approach when changing from an AID to an SID system.

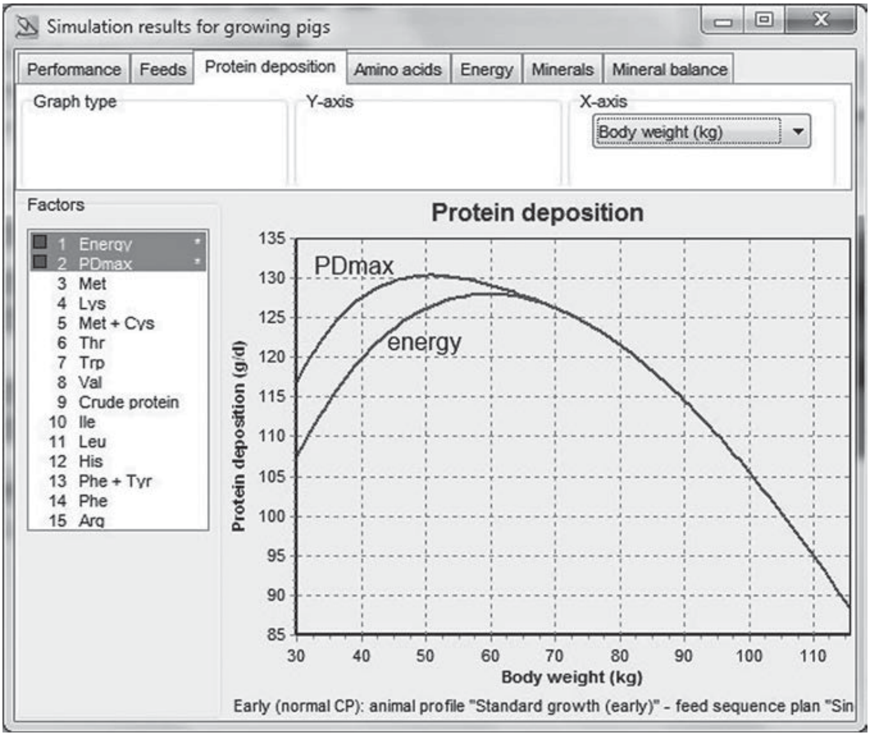
The maintenance amino acid requirements used in InraPorc are those proposed by Moughan (1998), and are expressed relative to BW$^{0.75}$. These requirements are also directly subtracted from the digestible amino acid supply, thereby ignoring that differences in metabolism (efficiency of post-absorptive utilization for maintenance) may exist among amino acids. Again, the maintenance amino acid requirements are relatively small and this approximation has little impact on amino acid utilization.

The available amino acid supply is the supply of digestible amino acids minus the basal endogenous losses (for SID) and the maintenance amino acid requirement. This supply is then multiplied by maximum efficiency and divided by the amino acid composition of whole-body protein to determine the protein deposition that would be possible for the supply of each of the amino acids. If the protein deposition for all of these is greater than the protein deposition determined by the Gompertz function or by the energy supply, the amino acid supply would not be limiting for protein deposition. However, if one (or more) of these values were lower than the protein deposition determined by the Gompertz function or by the energy supply, the amino acid supply will be a limiting factor for protein deposition. This approach also allows us to determine the order of limitation for the different amino acids (Fig. 2.2).

Amino acids that are not used for actual protein deposition will be deaminated and there are different reasons for this deamination. If the amino acid itself is the first-limiting factor for protein deposition, there will be a minimum oxidation due to the fact the amino acid is used with a maximum efficiency lower than 100% (i.e. the minimum oxidation is the complement of the maximum efficiency). If the supply of the amino acid exceeds the protein deposition potential of the animal, the excess supply of amino acids will be deaminated, in addition to the minimum oxidation. A third situation occurs when the supply of an amino acid is the determining factor for protein deposition. Part of the supply of the other amino acids will then be deaminated because the supply of one amino acid is limiting and it is the imbalance in amino acid supply that provokes the deamination. Increasing the supply of the limiting amino acid would improve the balance and improve the efficiency of the utilization of the non-limiting amino acids. The way amino acids are used can be shown in a dynamic way in InraPorc (Fig. 2.3).

Modelling Amino Acid Utilization vs an Ideal Amino Acid Profile

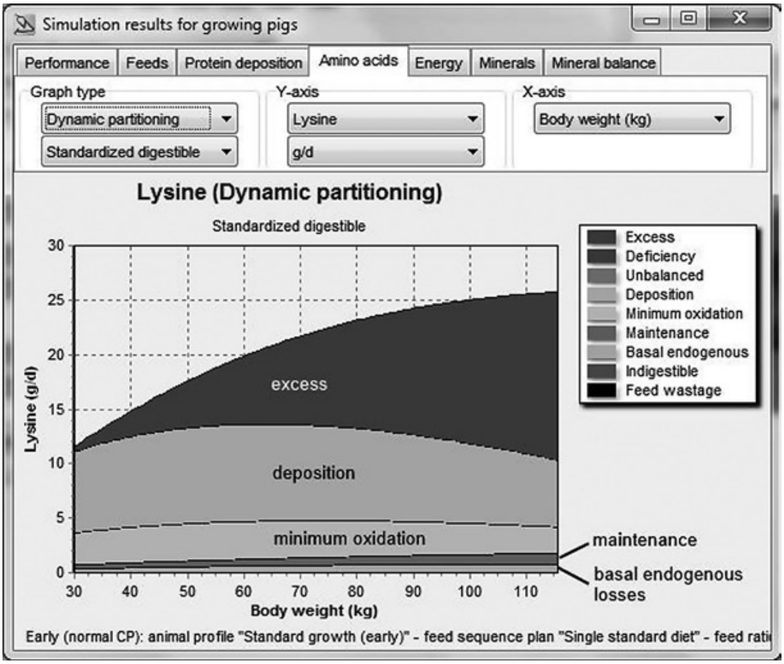
The approach of separating basal endogenous losses, maintenance requirements and



X-axis
Body weight (kg)

Early (normal CP): animal profile "Standard growth (early)" - feed sequence plan "Sin

Fig. 2.2. Screenshot of InraPorc illustrating the order in which different factors can be limiting for protein deposition. From 30 to 70 kg of body weight, energy intake is limiting protein deposition. After 70 kg of body weight, protein deposition is determined by PDmax. In this simulation, the supply of amino acids does not limit protein deposition.



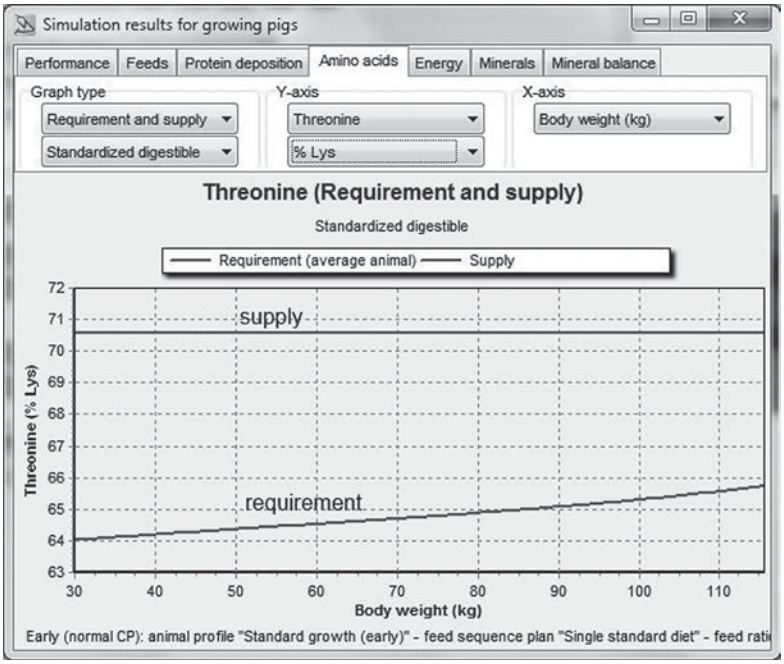
Graph type: Dynamic partitioning; Standardized digestible
Y-axis: Lysine; g/d
X-axis: Body weight (kg)

Early (normal CP): animal profile "Standard growth (early)" - feed sequence plan "Single standard diet" - feed rati

Fig. 2.3. Screenshot of InraPorc illustrating the utilization of SID lysine by the growing pig between 30 and 115 kg of body weight.

the efficiency of amino acid utilization differs from the concept of a fixed ideal amino acid profile with which most nutritionists are accustomed to work. The ideal amino acid profile corresponds to a profile where all amino acids are equally limiting for performance, independent of their utilization (i.e. for maintenance or for growth). Because the maintenance requirements and potential protein deposition evolve independently (as a function of $BW^{0.75}$ or as a Gompertz function in InraPorc, respectively), the ideal amino acid profile will change during growth. InraPorc can display how the requirement of an amino acid changes relative to Lys, thereby allowing the user to evaluate the ideal amino acid supply. As shown in Fig. 2.4, these changes are relatively minor during growth. For example, it is known that Thr is an important contributor to endogenous secretions (through mucins), but the change in the relative contribution of basal endogenous secretions has little impact on the SID Thr:Lys requirement ratio during growth.

If an amino acid can be used with the same maximum efficiency as Lys, the requirement for that amino acid (relative to Lys) is essentially reflected by the amino acid composition of whole-body protein. In InraPorc, the maximum efficiency of Lys utilization is fixed at 72% (Table 2.1). The maximum efficiencies of the other amino acids were determined by reverse-calculation of an ideal amino acid profile for a standard situation (van Milgen *et al.*, 2008). The result of this calculation was that the maximum efficiencies are higher for Leu, Phe, His, and Arg than for Lys (Table 2.1). The efficiency for Arg exceeds 100% because Arg can be synthesized by the pig, but the synthesis capacity may be insufficient to sustain maximum growth. For the other amino acids, the maximum efficiencies were lower than that of Lys. As can be seen from Table 2.1, there is quite a range in the maximum efficiencies, although the reasons for these differences are not fully clear. They are, of course, determined by the amino acid composition of whole-body protein, which is assumed to be



Graph type: Requirement and supply; Standardized digestible

Y-axis: Threonine; % Lys

X-axis: Body weight (kg)

Early (normal CP): animal profile "Standard growth (early)" - feed sequence plan "Single standard diet" - feed rati

Fig. 2.4. Screenshot of InraPorc illustrating the change in the SID threonine to lysine requirement ratio in the growing pig between 30 and 115 kg of body weight.

constant. However, there are indications that this is not the case and that amino acid composition of whole-body protein can be affected by various conditions, including the amino acid supply (Conde-Aguilera *et al.*, 2010). In the first version of InraPorc, we determined a much lower efficiency for Ile than for Val and Leu (i.e. 0.60, 0.76 and 0.71, respectively) even though the three branched-chain amino acids are catabolized by the same enzyme complex. Subsequent experimental work in our group indicated the SID Ile:Lys requirement ratio was overestimated resulting in an underestimation of the maximum efficiency. We thus changed the maximum efficiency of Ile utilization from 0.60 to 0.67 in a more recent version of the software. It is striking that the maximum efficiencies of Trp and Met+Cys are low compared with that of Lys. As for Ile, it is possible that the SID Trp:Lys and (Met+Cys):Lys requirement ratios have been overestimated. However, differences in the efficiency of amino acid utilization cannot be excluded and the reasons for these differences need further research.

The concept of using a fixed value for the maximum efficiency of amino acid utilization results in the relationship between the deposition and the supply of a limiting amino acid (above maintenance) being described by a linear-plateau function, which intersects the origin, and where the slope of the linear line segment corresponds to the maximum efficiency. This differs from the way we described the relationship between protein deposition and energy intake (i.e. curvilinear-plateau function). The linear-plateau function for this type of response has been criticized because the animal may adapt its efficiency depending on the supply of a limiting nutrient. Also, even if the linear-plateau function were to be accurate for a single animal, a curvilinear-response would be observed for a group of animals (Pomar *et al.*, 2003). In the future, we may change the way we describe the response to the amino acid supply. A curvilinear-plateau function may have appealing properties, although the efficiency with which essential amino acids can be used for amino acid deposition cannot exceed 100%.

Another aspect that is not represented appropriately in the current version of InraPorc is the fact that animals have different mechanisms to cope with an amino acid deficiency. Currently, an amino acid deficiency results in a lower supply of available amino acids, but feed intake will not be affected. It is known that feed intake can be reduced when pigs are offered a diet with a limiting amino acid content. This has been observed for certain amino acids (e.g. Trp, Val, Ile and Met) but not for others (e.g. Lys and Thr). This may be an explanation for the lower maximum efficiencies of these amino acids relative to Lys. In a series of experiments, Gloaguen *et al*. (2011, 2013) observed that the growth response of piglets to a limiting amino supply varied among amino acids. A deficiency in Val or Ile resulted in a strong reduction in growth, whereas a deficiency in His or Leu resulted in more moderate reductions in performance. The response to an amino acid deficiency may thus be driven by a reduction in feed intake, changes in amino acid composition of body protein, differences in maximum efficiency of amino acid utilization or by a combination of these factors.

Accounting for Variation Among Animals

InraPorc is a (somewhat) mechanistic and deterministic model and thus does not account for variation among animals. The consequence of this is that certain predictions have to be used with caution. For example, one could use InraPorc and define an animal profile based on the average animal in the herd. However, feeding the herd based on the nutritional requirements of the average animal would result in nutrient supplies that would be sufficient for 50% of the pigs in the herd, and deficient for the other 50%. Preliminary studies indicated that providing nutrients at a level of 110% of the requirement of the average pig covered the requirement for a majority of animals in the herd (Brossard *et al*., 2009) and this level is given as a rough estimate of the requirement of the herd in the current version of InraPorc. However, the optimum nutrient supply relative to the requirement of the average animal depends on the economic context. When nutrients are expensive, a level greater than 110% may be economically more beneficial (Quiniou *et al*., 2013).

To answer the question of ‘which animal in the herd do we want to feed?’, we have to know how animals within a herd differ. During the past few years, we have studied the variation in the five main model parameters because they do not vary in an independent way. An animal that eats a lot probably also grows faster (or the other way around, if you prefer). It is important to consider the covariance among model parameters because ignoring it results in an overestimation of the observed variation. Relatively little is known about the covariance structure among model parameters and this problem is not specific to InraPorc and, indeed, concerns all simulation models (Knap, 1996).

Vautier (2013) obtained data on feed intake and body weight for 1288 individual pigs originating from different cross-breeds, and sexes (barrows and gilts), which were raised in different batches for a total of 40 subpopulations. Feed intake was determined daily using an automatic feed dispenser and animals were weighed every 2–3 weeks. With these data, each of the individual pigs could be characterized so that the covariance structure of model parameters could be determined, with possible effect of cross-breed, sex and batch. Figure 2.5 shows the correlation structure of the five main model parameters indicated by the solid lines and calculated traits indicated by the dashed lines. Overall, more than 50% of the variation was shared among the 40 subpopulations. The two parameters describing the feed intake curve on an NE basis (DFI50 and DFI100) were correlated and, as anticipated, average daily feed intake (ADFI) was positioned in-between. Likewise, the parameter describing the mean protein deposition (Pm) was correlated with average daily gain and, to a lesser extent, with the parameters describing the

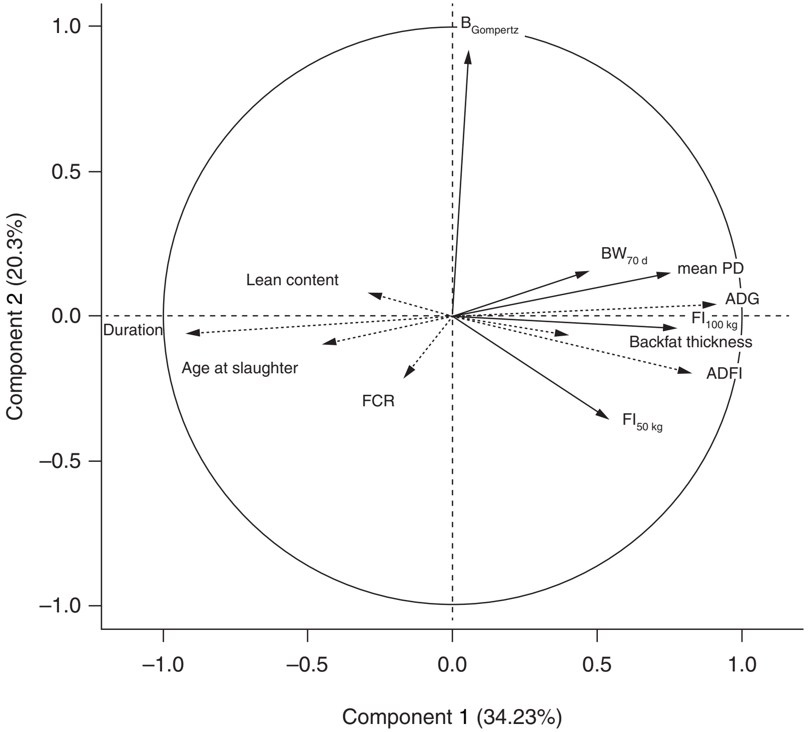


Fig. 2.5. Correlation among model parameters that describe feed intake and growth in InraPorc. The main model parameters are indicated by solid lines and derived traits by dashed lines. (From Vautier, 2013.)

feed intake curve. The shape parameter of the Gompertz function for protein deposition was positioned perpendicular to 'Pm', indicating that there are different trajectories by which pigs can attain a final protein mass. Information about how fast an animal grows therefore provides little information about how it grows. The covariance structure of the 40 subpopulations was affected by cross-breed, sex and batch (Vautier, 2013), and meant that not only the absolute value of model parameters will vary for each population, but also the covariance structure. This was a rather surprising observation because it meant that each situation is unique. It has been our experience that users already have difficulties obtaining data for the dynamics of feed intake and growth for the average pig in the herd, but quantifying the variation within a herd would probably be beyond reach for most users of InraPorc. Vautier (2013) determined a median covariance matrix as the next-best (and feasible) solution to account for variation among individuals. This median covariance matrix can be used to generate a virtual population of pigs while respecting the covariance structure of the parameters. The algorithms used in InraPorc and the ever-increasing computing speeds make it possible to run a simulation for thousands of pigs within a few seconds. Vautier (2013) evaluated whether the prediction of the variation in a simulated population of 2000 pigs (using the median covariance matrix) corresponded to that actually observed in a real population. The *in vivo* and *in silico* pigs were offered feed *ad libitum* or at a restricted level with a maximum of 2.4 (gilts) or 2.7 (barrows) kg/day. Two experiments were conducted in which the pigs were either group-housed (by sex) or housed individually. In both experiments, the coefficient of variation was similar for the *in vivo* and *in silico* pigs. These results are promising and suggest that a generic structure of the covariance matrix of model parameters can be used to account for variation among pigs in simulation modelling. This approach is in line with that of Knap (1995), who stated that 'Variation should be introduced as deep in the model as possible: when basic model variables are varied, all variables that depend on them will automatically display covariance'. A future version of InraPorc could generate a virtual population of pigs to evaluate how the population responds to different management practices (e.g. change of diets, slaughtering of animals, carcass payment grids). Because many of these practices are based on discrete events, our view is that this can be addressed best by repeated simulations of a deterministic model while accounting for the variation among individuals.

Conclusions

We have attempted to develop a model and user-friendly tool that allows the evaluation of the response of the pig to nutrient supply. One of the main challenges during model development was the identification of the most important model parameters for which model users could provide relevant information. This meant that certain model parameters were made constant in the software because we felt that the required information was not readily available to the user. Our goal was to capture the maximum information (across animals) using a minimum of model parameters to ensure that the model would be robust. Allowing users to change parameters that are now hard-coded in the model would certainly make the model more flexible; however, it would also place an additional challenge or burden on users to provide that information.

Variation among individuals is inherent to living systems. However, most nutritional growth models are deterministic and thus ignore this variation. There are two approaches to dealing with variation among animals in the practical application of growth models. Our approach was to account for variation among animals and to identify optimum management strategies for the population. Another approach is that of precision feeding, which is discussed by Candido Pomar and colleagues (see Pomar *et al.*, Chapter 12, this volume). Both approaches rely on phenotyping or monitoring of the animals, and this information has to be transformed into model inputs. We feel strongly that there is a future for phenotyping animals in combination with modelling so that practical management decisions can be applied to the herd or to individual animals. However, (real-time) information on individual animals is scarce and methods to acquire and to use this information as model inputs have to be developed.

References

Bikker, P., Verstegen, M.W.A., Campbell, R.G. and Kemp, B. (1994) Digestible lysine requirement of gilts with high genetic potential for lean gain, in relation to the level of energy intake. *Journal of Animal Science* 72, 1744–1753.

Bikker, P., Verstegen, M.W.A. and Campbell, R.G. (1996) Performance and body composition of finishing gilts (45 to 85 kilograms) as affected by energy intake and nutrition in earlier life: II. Protein and lipid accretion in body components. *Journal of Animal Science* 74, 817–826.

Black, J.L., Campbell, R.G., Williams, I.H., James, K.J. and Davies, G.T. (1986) Simulation of energy and amino acid utilisation in the pig. *Research and Development in Agriculture* 3, 121–145.

Brossard, L., Dourmad, J.Y., Rivest, J. and van Milgen, J. (2009) Modelling the variation in performance of a population of growing pigs as affected by lysine supply and feeding strategy. *Animal* 3, 1114–1123.

Conde-Aguilera, J.A., Barea, R., Le Floc'h, N., Lefaucheur, L. and van Milgen, J. (2010) A sulfur amino acid deficiency affects the amino acid composition of body protein in piglets. *Animal* 4, 1349–1358.

de Lange, C.F.M., van Milgen, J., Noblet, J., Dubois, S. and Birkett, S. (2006) Previous feeding level influences plateau heat production following a 24 h fast in growing pigs. *British Journal of Nutrition* 95, 1082–1087.

Dourmad, J.Y., Étienne, M., Valancogne, A., Dubois, S., van Milgen, J. and Noblet, J. (2008) InraPorc: a model and decision support tool for the nutrition of sows. *Animal Feed Science and Technology* 143, 372–386.

Emmans, G.C. and Kyriazakis, I. (1997) Models of pig growth: problems and proposed solutions. *Livestock Production Science* 51, 119–129.

Ferguson, N.S., Gous, R.M. and Emmans, G.C. (1994) Preferred components for the construction of a new simulation model of growth, feed intake and nutrient requirements of growing pigs. *South African Journal of Animal Science* 24, 10–17.

Gloaguen, M., Le Floc'h, N., Brossard, L., Barea, R., Primot, Y., Corrent, E. and van Milgen, J. (2011) Response of piglets to the valine content in diet in combination with the supply of other branched-chain amino acids. *Animal* 5, 1734–1742.

Gloaguen, M., Le Floc'h, N., Primot, Y., Corrent, E. and van Milgen, J. (2013) Response of piglets to the standardized ileal digestible isoleucine, histidine and leucine supply in cereal–soybean meal-based diets. *Animal* 7, 901–908.

Kloareg, M., Noblet, J. and van Milgen, J. (2006) Estimation of whole body lipid mass in finishing pigs. *Animal Science* 82, 241–251.

Knap, P.W. (1995) Aspects of stochasticity: variation between animals. In: Moughan, P.J., Verstegen, M.W.A. and Visser-Reyneveld, M.I. (eds) *Modelling Growth in the Pig*. Wageningen Pers, Wageningen, the Netherlands, pp. 165–172.

Knap, P.W. (1996) Stochastic simulation of growth in pigs: protein turn-over-dependent relations between body composition and maintenance requirements. *Animal Science* 63, 549–561.

Koong, L.J., Nienaber, J.A., Pekas, J.C. and Yen, J.T. (1982) Effects of plane of nutrition on organ size and fasting heat production in pigs. *Journal of Nutrition* 112, 1638–1642.

Le Bellego, L., van Milgen, J. and Noblet, J. (2002) Effects of high ambient temperature on protein and lipid deposition and energy utilization in growing pigs. *Animal Science* 75, 85–96.

Lister, D. and McCance, R.A. (1967) Severe undernutrition in growing and adult animals. 17. The ultimate results of rehabilitation: pigs. *British Journal of Nutrition* 21, 787–799.

McCance, R.A. and Mount, L.E. (1960) Severe undernutrition in growing and adult animals. *British Journal of Nutrition* 14, 509–518.

Moughan, P.J. (1998) Protein metabolism in the growing pig. In: Kyriazakis, I. (ed.) *A Quantitative Biology of the Pig*. CAB International, Wallingford, UK, pp. 299–331.

Noblet, J., Karege, C., Dubois, S. and van Milgen, J. (1999) Metabolic utilization of energy and maintenance requirements in growing pigs: effects of sex and genotype. *Journal of Animal Science* 77, 1208–1216.

Pomar, C., Kyriazakis, I., Emmans, G.C. and Knap, P.W. (2003) Modeling stochasticity: dealing with populations rather than individual pigs. *Journal of Animal Science* 81 (E. Suppl. 2), E178–E186.

Quiniou, N., Vautier, B., Salaün, Y., van Milgen, J. and Brossard, L. (2013) Modélisation de l'effet de la stratégie alimentaire et du contexte de prix de matières premières sur les performances moyennes, leur variabilité et les rejets azotés à l'échelle d'une population de porcs. *Journées de la Recherche Porcine* 45, 155–160.

Sauvant, D., Perez, J.-M. and Tran, G. (2004) *Tables of Composition and Nutritional Value of Feed Materials. Pigs, Poultry, Cattle, Sheep, Goats, Rabbits, Horses, Fish.* INRA Editions, Paris.

Schulin-Zeuthen, M., Kebreab, E., Dijkstra, J., Lopez, S., Bannink, A., Darmani Kuhi, H., Thornley, J.H.M. and France, J. (2008) A comparison of the Schumacher with other functions for describing growth in pigs. *Animal Feed Science and Technology* 143, 314–327.

van Milgen, J. and Noblet, J. (1999) Energy partitioning in growing pigs: the use of a multivariate model as an alternative for the factorial analysis. *Journal of Animal Science* 77, 2154–2162.

van Milgen, J., Valancogne, A., Dubois, S., Dourmad, J.Y., Sève, B. and Noblet, J. (2008) InraPorc: a model and decision support tool for the nutrition of growing pigs. *Animal Feed Science and Technology* 143, 387–405.

Vautier, B., Quiniou, N., van Milgen, J. and Brossard, L. (2013) Accounting for variability among individual pigs in deterministic growth models. *Animal* 7, 1265–1273.

Vautier, B., Quiniou, N., van Milgen, J. and Brossard, L. (2011a) Modelling the dynamics of feed intake in growing pigs; interest for modelling populations of pigs. *Book of Abstracts of the 62nd Annual*

Meeting of the European Federation of Animal Science. Wageningen Academic Publishers, Wageningen, the Netherlands, p. 105.

Vautier, B., Quiniou, N., van Milgen, J. and Brossard, L. (2011b) Modélisation de la cinétique de consommation en fonction du poids chez le porc en croissance selon le mode d'expression de l'ingéré. *Journées de la Recherche Porcine* 43, 139–140.

Vautier, B., Quiniou, N., van Milgen, J. and Brossard, L. (2013) Accounting for variability among individual pigs in deterministic growth models. *Animal* 7, 1265–1273.

Whittemore, C.T. and Fawcett, R.H. (1974) Model responses of the growing pig to the dietary intake of energy and protein. *Animal Production* 19, 221–231.

Whittemore, C.T. and Fawcett, R.H. (1976) Theoretical aspects of a flexible model to simulate protein and lipid growth in pigs. *Animal Production* 22, 87–96.

3 Modelling Reproduction in Broiler Breeder and Laying Hens

R.M. Gous*
University of KwaZulu-Natal, Pietermaritzburg, South Africa

Abstract
The aim of this chapter is to describe the potential reproductive performance of individuals, such that the potential reproductive performance of a population of hens may be simulated. This requires an understanding of systems such as the attainment of sexual maturity in a flock of pullets and the physiological control of egg production in hens. The potential performance, that is, the number of eggs produced over the production cycle of a single laying hen is dependent on the age at which it becomes sexually mature, on its internal ovulatory cycle length and egg weight, and the rates at which these change over time, all of which are genetically determined and may be satisfactorily modelled. Using stochasticity, the potential laying performance of a flock may then be simulated from individual responses. While laying hens are usually given *ad libitum* access to feed, the daily food intake of broiler breeders is restricted. In both cases it is useful to be able to predict the amount of energy and of each nutrient that is required to meet the maintenance and potential laying performance of each hen so that the voluntary intake of a feed of any given composition can be predicted, and the consequences on performance of food intake being constrained can be determined. It may not be economically justifiable to meet the requirements of the most demanding hens in a population: the economic optimum intake of nutrients would depend on the relative cost of feeding these birds and the revenue derived from the sale of the eggs they produce. The optimum daily nutrient intake must then be converted to a dietary concentration for feed formulation purposes, and to do this successfully voluntary food intake must be accurately predicted. If this can be done, such a model may then be used to optimize the way in which these different strains of laying hen should be fed so as to maximize profit for the enterprise.

Introduction

Emphasis in this chapter is on being able to describe the potential performance of a flock of commercial laying hens, from which it would be possible to calculate the daily nutrient intakes required to meet the potential performance of each individual in terms of numbers of eggs produced over the production cycle. This would improve the possibility of optimizing the composition (and daily allocation, in the case of broiler breeders) of the feed offered to the flock. In order to achieve these goals, a comprehensive understanding is required of the factors influencing the attainment of sexual maturity in these birds, of the ovulatory cycle and how this changes during the laying cycle, of the changes that occur in

---

*E-mail: gous@ukzn.ac.za

© CAB International 2015. *Nutritional Modelling for Pigs and Poultry*
(eds N.K. Sakomura *et al.*)

egg and body component weights over time and, ultimately, of the physiological and environmental factors that may prevent each bird from consuming sufficient of a given feed to meet its potential performance each day. Without a comprehensive simulation model that incorporates all these concepts it is unlikely that the consequences of offering feeds of different quality to flocks of laying hens or broiler breeders kept in different environments on the rate of egg production and the weight and composition of the eggs produced could be accurately predicted. Nor is there a better way of optimizing the feeding of these birds than being able to predict these consequences before the feed is offered to the flock.

Much of the information required to develop such a model has been published and many of the relevant publications will be referred to in this chapter. But there are still some concepts that have not been researched, where further information would be valuable. Thus, by developing a simulation model for predicting responses in laying hens and broiler breeders, the relevant information from the literature has been synthesized into a workable theory for each system, the various systems have been integrated and gaps in our knowledge of these systems have been identified.

Predicting the Age at Sexual Maturity

The age and body weight of a bird on the day it lays its first egg has a very strong influence on future egg weight and the number of eggs laid, which are important considerations for both the layer and broiler breeding industries. These characteristics can be modified by lighting and/or the nutritional control of growth: in full-fed, egg-type hens, a 10-day delay in sexual maturity that has been achieved through a lighting programme results in an increase of 1.3 g in mean egg weight and a reduction of seven eggs over 52 weeks lay, but the total egg output will be similar (Lewis and Morris, 2006). Clearly, to predict the laying performance of a hen, her age at sexual maturity (ASM) must first be defined, and this can be predicted.

Important considerations in predicting sexual maturity in hens are that gonadal development advances whatever lighting programme is used, that lighting modifies the age at sexual maturity, that changing photoperiods have a greater influence than do constant photoperiods (Lewis and Morris, 2006), and that the response of a broiler breeder to light differs from that of a commercial laying hen because broiler breeders, unlike commercial laying hens, exhibit photorefractoriness (Lewis *et al.*, 2003). The attainment of sexual maturity is therefore under both genetic and environmental influences, with broiler breeders still exhibiting photorefractoriness, while this has been eliminated in laying pullets by selection.

Commercial laying pullets

In full-fed commercial pullets, lighting is the most important environmental factor influencing age at first egg (AFE) (Lewis *et al.*, 2002). When pullets are reared under constant daylengths the length of the photoperiod used can influence AFE (Lewis *et al.*, 1998), and when one or two changes are made to the daylength during rearing, the length of each photoperiod also has an influence (Lewis and Perry, 1994; Lewis *et al.*, 1996). While the initial and final photoperiods are the principal components of a lighting programme influencing AFE in full-fed pullets, the effects of a given change in photoperiod are not the same at all ages. Also, the advance in AFE for birds started on 8-h photoperiods and given a single increment in photoperiod at a defined age is proportional to the size of the increment up to about 13 h (Lewis *et al.*, 1998), but not for longer final photoperiods (Lewis *et al.*, 1996).

Lewis *et al.* (2002) proposed a model to predict AFE of full-fed pullets when changes were made to the photoperiod during rearing. The four components of the empirical model, each of which is calculated separately, deal with: (i) the genetic differences in AFE in birds maintained on constant photoperiods from hatching; (ii) the change in AFE as a function of age at transfer to the final photoperiod; (iii) the acquisition of sensitivity to increases in photoperiod in the young pullet; and (iv) the onset of spontaneous rapid gonadal development, that is, the proportion of birds maturing under the influence of the initial photoperiod, without responding to a late change in photoperiod. In this latter case it is assumed that a pullet will lay its first egg at the age expected for a long-day rearing treatment even if the photoperiod is reduced during the final 13 days before that egg is due, this being the length of time taken for final rapid development of the largest ovarian follicle (Etches, 1996). Responses to constant photoperiods must remain an integral part of any model even though a change in photoperiod exerts a greater influence on sexual maturation than either the initial or final photoperiod itself.

Lewis and Morris (2008) modified their original model to accommodate subsequent evidence related to the effect of follicle stimulating hormone (FSH) on the process of sexual maturity. They found that when two opposing changes in photoperiod are given within an interval of <30 days, rate of sexual maturation is determined by the change in circulating FSH concentration achieved during the time of the second photoperiod. If a decrease in photoperiod is given within a week of an increase, a period in which circulating FSH concentration rises very little, AFE will not be significantly different from constant short-day controls.

Broiler breeder pullets

Following a series of trials with broiler breeders, Lewis *et al.* (2007) conducted a meta-analysis of relevant data for broiler breeder pullets, which indicated a linear advance in sexual maturity up to 10 h similar to that described by Lewis and Morris (2004) for early strains of egg-type pullets. However, responses to photoperiods >10 h were very different due to the fact that broiler breeders still exhibit photorefractory tendencies. While egg-type pullets experienced a minimal delay in ASM of about 1 day between 10 and 13 h, broiler breeders maintained on 13 h matured about 25 days later than birds held on 10 h. Exposure to a photoperiod longer than 13 h then resulted in a steady advance in ASM, which is in complete contrast to the continued delay that occurred in egg-laying strains. The relationships in the three phases (≤10 h, 10 < 13 h, and ≥13 h) may be described by the following equations:

$$P \leq 10\,\text{h:} \quad y = (202.5 - 1.15P) - 20(BW - 2.1) \qquad (3.1)$$

$$P = 10 < 13\,\text{h:} \quad y = A10 + p(A13 - A10) - 20(BW - 2.1) \qquad (3.2)$$

$$P \geq 13\,\text{h:} \quad y = (224.7 - 0.76P) - 20(BW - 2.1) \qquad (3.3)$$

Where y = mean age at 50% egg production (days); $A10$ = age at 50% egg production for P = 10 h (days) from Eqn 3.1; and $A13$ = age at 50% egg production for P = 13 h (days) from Eqn 3.3; p = the area under a normal curve (mean 11.5 h, SD = 0.43 h) to the left of a standard normal deviate x; where $x = (P - 11.5)/0.43$, and BW = mean body weight at 20 weeks (kg). The SD of 0.43 was established by choosing the value that resulted in the smallest residual sum of squares when the distribution was fitted to the observed data.

Only one change in photoperiod is accommodated in this model, unlike in the laying hen model. The photosexual response in broiler breeders is strongly influenced by the feed allowance and hence the rate of prepubertal growth. Mean age at 50% lay in birds given either a constant photoperiod or a single increase was advanced by 2 days for every 100-g increase in body weight at 20 weeks (Lewis *et al.*, 2007). Because broiler breeders exhibit juvenile photorefractoriness they require up to 20 weeks to dissipate this, although faster growth allows quicker dissipation. As a consequence, birds grown to a typical weight of 2.1 kg at 20 weeks do not start to be photoresponsive until about 10 weeks and are not uniformly responsive until 19 or 20 weeks. A transfer to a stimulatory photoperiod before a bird has dissipated photorefractoriness causes a delay of about 3 weeks in its sexual development, and this results in a bimodal distribution of ages at maturity when a flock is photostimulated between 10 and 20 weeks. A flock of broiler breeders with typical feed restriction starts to mature spontaneously under the influence of the initial photoperiod from about 25 weeks. The broiler breeder model is fully described in Lewis *et al*. (2007).

These empirical models for commercial laying pullets and for broiler breeders enable the prediction of AFE for individuals making up a laying flock. Using appropriate means and standard errors for each of the parameters in the models it is possible to allocate randomly an AFE to each bird in the simulated flock, which contributes to its potential rate of laying, as will be described in the next section.

Modelling Potential Egg Output

Describing the potential rate of lay of a laying hen is complex because of the number of interacting factors involved, and the fact that the potential varies over time within each individual. The mathematical model of Etches and Schoch (1984), based on the theory of Fraps (1955), demonstrated that two functions, representing two independent but interacting systems of the hen's asynchronous ovulatory cycle, were able to predict realistic ovulation times and intrasequence ovulation intervals. Johnston and Gous (2003) extended this model by defining a set of continuous functions, representing the changes required to the values of the different parameters, such that the prediction of any sequence length is possible.

Mean rate of lay in a flock of hens at a particular age is determined by the individual patterns of sequential laying at that time. Within a population of birds, individuals of the same age show considerable variation about a mean sequence length, which may be due to variation in the length of the open period for luteinizing hormone release, or variation in follicular dynamics. This variation may be accounted for using mean values and standard errors for each of the parameters in the model (Johnston and Gous, 2003). Such a population of birds would generate a range of ovulation times, the distribution of which is unimodal and positively skewed in young hens, becoming bimodal with age. Reproductive senescence in hens manifests as an increase in the intrasequence ovulation and oviposition intervals with time, as well as an increase in the number of pause days.

Different approaches have been used to model the decline in rate of lay over time. Most of these have been empirical in nature (Gavora *et al*., 1971; McNally, 1971; McMillan *et al*., 1986; Foster *et al*., 1987; Yang *et al*., 1989; Koops and Grossman, 1992; Fialho and Ledur, 1997), all of which are severely limiting when making use of a mechanistic approach for describing the decay in the rate of laying of an individual hen over time. Emmans and Fisher (1986) suggested that the hen's internal cycle length increased with time from first egg, resulting in a linear decline in the rates of ovulation and oviposition with age. They suggested that, at the start of the laying period, some hens had the capacity to lay at a rate greater than one egg in 24 h, but that laying performance of these birds was constrained by the external cycle length. Eventually, the internal cycle length would become longer than the external cycle length, when ovulation rate would begin to decline. However, there is evidence to show that sequence length tends to rise initially (Lewis and Perry, 1991; Johnston, 2004), with most hens exhibiting a single characteristically long (prime) sequence about the time of peak egg production, which then declines at different rates between individuals (Robinson *et al*., 1990), so the model of Emmans and Fisher (1986) is unsatisfactory in describing the change in ovulation rate over time.

In order to reproduce these changes in sequence length over time, the internal cycle length initially needs to be long (usually more than 24 h), before decreasing with advancing time from first egg to close to, or below 24 h, and subsequently increasing. Internal cycle lengths longer than the external cycle length will cause the time of lay to be later each day, whereas those shorter than the external cycle length will enable the hen to lay long sequences with oviposition occurring at a similar time each day (Morris, 1978). Internal cycle lengths are under genetic control and can be manipulated (Foster, 1981), thus the constraining effect of the external cycle length on potential rate of lay may be reduced either by reducing the internal cycle length or making use of ahemeral cycles greater in length than 24 h (Morris, 1978). External cycle lengths longer or shorter than 24 h can be accommodated when such an approach is used. When the ovulation curves of individuals in the flock are integrated, the characteristic laying curve is faithfully reproduced. The slope of the initial rise in flock egg production to peak rate of lay is influenced by the distribution of ages at sexual maturity and by the lengths of the individual prime sequences. The incidence of internal laying at onset of maturity plays a role in modifying rate of lay but not ovulation rate. The persistency of lay after peak will be determined by the rate at which sequence lengths of individual hens shorten over time, as well as by the number of pause days. Hence the prediction of sequence length is a logical step in predicting the performance of a flock of laying hens over an entire laying cycle.

The reproductive rates of flocks of commercial laying hens and broiler breeders may be simulated by making use of the Monte Carlo simulation method, which requires the choice of appropriate values for the means and standard errors of the parameters in the various equations used to simulate ovulation rate, the rate of decay in internal cycle length and the incidence of pause days, internal laying and soft shelled eggs (Johnston and Gous, 2006, 2007a,b,c). The potential performance of each hen in the population is simulated in this way, thereby producing information necessary for predicting the nutrients required by each hen on each day of lay. For more precision in determining these nutrient requirements, the weight of the egg and the proportions of yolk and albumen in the egg need to be known, and these can be modelled as described below.

Modelling Egg Weight and Composition

When modelling the nutrient requirements of a hen over a production cycle, based on the daily outputs of each nutrient, egg weight needs to be predicted as the sum of the three components, since each has a unique chemical composition, and these proportional changes will therefore influence the nutrient requirements of the hen. Egg weight increases as hens age, but the eggs contain proportionally more yolk and less albumen and shell. However, at a given age, larger eggs contain proportionally more albumen (Johnston and Gous, 2007b). Yolk weight is dependent mainly on the genotype, but within a strain because it is related to hen age it may be calculated using an appropriate (logistic) function. Allometric functions may then be used to predict albumen weight from yolk weight and shell weight from the weight of the egg contents. The methods described by Johnston and Gous (2007b) for this purpose appear also to work satisfactorily for broiler breeders (Gous and Nonis, 2010) as long as appropriate functions are used to describe the relationships between age and yolk weight, albumen and yolk weight, and shell and egg content weight. These relationships differ not only between laying hens and broiler breeders, but also between strains. Examples of the coefficients that may be used to predict yolk weight from age of hen, albumen weight from yolk weight and shell weight from yolk + shell weight for an egg-laying and two broiler breeder strains are given in Table 3.1. The only difference between the two broiler breeder strains is in their allometric relationship between albumen and yolk weight.

The position of an egg in the sequence also influences the proportions of the weight of the egg and its components. The weight of consecutive eggs within a sequence gradually decreases (Belyavin *et al.*, 1987; Miyoshi *et al.*, 1997) and similar patterns have been observed with yolk weights (Bastian and Zarrow, 1955; Zakaria *et al.*, 1984; Zakaria, 1999) with the heaviest yolks occurring more frequently in the first two places

Table 3.1. Examples of the coefficients that may be used to predict yolk weight from age of hen, albumen weight from yolk weight and shell weight from yolk + shell weight for an egg-laying and two broiler breeder strains. (From Johnston and Gous, 2007b and Nonis and Gous, 2013.)

Coefficient[a]	Laying strain	Cobb broiler breeder	Ross broiler breeder
a	–225	28.1	28.1
b	243	34.2	34.2
c	–0.01268	–0.01836	–0.01836
d	10.99	9.526	14.877
e	0.4491	0.5002	0.3250
f	0.3388	0.1707	0.1707
g	0.6896	0.8686	0.8686

[a] Yolk weight = *a* + *b*/(1 + *c* × hen age, in days); albumen weight = *d* × yolk weight *e*; shell weight = *f* × (yolk + albumen weight) *g*.

of a sequence (Gilbert, 1972). Egg shell weight tends to be heaviest in the terminal egg of the clutch (Miyoshi *et al.*, 1997), presumably because the lag in oviposition time is longest for this last egg, which means a longer period of time is devoted to shell deposition.

When nutrient intake is constrained this will have consequences on both rate of lay and egg weight: Morris and Gous (1988) showed that these are equally reduced when the feed is marginally deficient in an amino acid, but that as the deficiency becomes more severe, rate of lay is reduced to a far greater extent than is egg weight. So there is very little scope for the laying hen nutritionist to manipulate egg size without also affecting rate of lay. The practice of altering the amino acid (usually methionine) content of the feed as a means of altering egg size and not rate of lay, which is commonly applied when economic conditions appear to warrant this (Leeson and Summers, 2005), appears attractive because the coefficient of variation for rate of lay is very high (around 25%), whereas that for egg weight is only between 6% and 8%. So it is far more difficult to show statistically significant differences in rate of lay between treatments than in egg weight, and consequently the wrong message has been broadcast, that rate of lay is not affected by a decrease in amino acid supply, but that egg weight is. It is important to be aware that egg weight cannot be adjusted nutritionally without also adjusting rate of lay.

The revenue derived from the sale of commercial eggs is a function of the size of the egg, given that in most markets eggs are graded according to weight, and that the price for each grade is usually different. The weights of eggs produced on any one day by a flock of hens will be normally distributed around the mean, so the proportion of the total that fall into each grading category can be determined mathematically, and the revenue derived from the sale of a given number of those eggs may be calculated accordingly. As egg output increases, as a result of an increase in the supply of a limiting nutrient, both the number of eggs produced and the mean egg weight will be equally affected if egg output is close to the potential of each hen, and the additional revenue derived as a result of the higher nutrient supply can be calculated. But because the effect of a more severe deficiency influences rate of lay more than egg weight, this relative change in the outputs needs to be accounted for when determining the revenue derived from the sale of eggs.

Predicting Body Weight and Composition of a Hen

A large proportion of the daily intake of energy and amino acids by a laying hen or a broiler breeder hen is used for maintenance, so the prediction of the bird's maintenance requirement, when determining her optimum daily intake of energy and amino acids, is of considerable importance. In most factorial models these maintenance requirements are based on body weight, but because body lipid does not need to be maintained (Emmans and Fisher, 1986), a more accurate basis for calculating these requirements would be the body protein content of the bird. Emmans and Fisher (1986) and Fisher (1998) have raised this issue in the past, and the concept has been successfully incorporated into some broiler (EFG Software, 1995) and pig (Ferguson *et al.*, 1997) growth models. But little useful information is available on the carcass protein content of layers or broiler breeders during lay or the extent to which this varies over time, to enable such calculations to be made of the maintenance requirements of these birds.

Changes in body composition of the broiler breeder hen have been measured during the rearing period (Bennett and Leeson, 1990), at the end of the rearing period (Blair *et al.*, 1976; Pearson and Herron, 1980, 1981, 1982; Spratt and Leeson, 1987; Renema *et al.*, 1999), during the period when the ovary and oviduct are developing (Bowmaker and Gous,1989), and at the end of the laying period (Blair *et al.*, 1976; Pearson and Herron, 1980, 1981, 1982; Spratt and Leeson, 1987; Attia *et al.*, 1995; Wilson *et al.*, 1995). However, the pattern of changes in body composition over time in the mature hen has not been rigorously investigated.

Pearson and Herron (1980) found that feather-free body protein content of a broiler breeder hen continued to increase between 22 and 34 weeks of age. However, a large part of this increase will be in the growth of the ovary and oviduct during the period when the pullet reaches sexual maturity (Bowmaker and Gous, 1989). Differences in age at sexual maturity between birds in the flock will also contribute to the variation in the apparent increase in body weight during this period, with early maturing birds no longer growing, and perhaps even losing weight because of the reproductive demands placed on her, while those not yet sexually mature continue to grow until they have laid their first egg.

In laying hens it is well established that body protein content is maximal at sexual maturity and that little further protein growth occurs during lay (Fisher and Gous, 2008). It could be argued that broiler breeder hens are further from their somatically mature protein weight at sexual maturity than are laying hens, and hence that body protein growth may continue when the opportunity arises. Such might be the case in poor egg producers, where body protein may be deposited if the number of pause days becomes excessive, but there is no evidence to substantiate this. Provision for slow body weight gain in broiler breeder hens is often recommended, assuming a mean gain of about 650 g from 50% egg production to the end of lay. However, it has been demonstrated in mammals that protein growth does not occur when the animal is in a lactating state, equivalent to the egg production state in hens. Sows, for example, show very little protein growth, if any, during gestation (Shields and Mahan, 1983; King, 1987), while they may lose considerable amounts of body protein during lactation (Whittemore and Yang, 1989) unless adequately fed (Coop and Kyriazakis, 1999).

As the weight of body protein remains relatively stable throughout the laying period, and as any growth in body protein may be regarded as taking place among non-laying hens only, it should not be necessary to assume that protein growth is obligatory when determining nutrient requirements of laying hens or broiler breeder hens. Also, because changes in body lipid content are the consequence of the way in which the hen has been fed, it is unnecessary to make provision for any obligatory gain in body protein or lipid during lay. Maintenance requirements may thus be considered to be constant over the laying period for those birds that continue to lay in closed cycles, and these should be based on the body protein content at the age of first egg.

Predicting Food Intake

To be of any real value, models that attempt to optimize the feeding of laying hens and broiler breeders must be capable of predicting voluntary food intake. Where this variable is an input to the model, as is most often the case, it is naive to believe that feeding programmes can be successfully optimized, when the composition of the food offered has such important effects on voluntary food intake. Food intake must therefore be an output from, and not an input to, a model. A reproducing animal needs to be supplied with nutrients in order to meet the requirements for maintenance of the body and for reproduction. The theory of food intake and growth proposed by Emmans (1981, 1989) is based on the premise that birds attempt to grow at their genetic potential, which implies that they attempt to eat as much of a given feed as would be necessary to grow and reproduce at that rate. The same principle can be applied to laying hens (Emmans and Fisher, 1986). To calculate the daily energy and nutrient requirements of a laying hen, her protein weight (for maintenance) and potential protein and lipid output (in eggs) needs to be known. By comparing these requirements with the content of nutrients in the feed, the 'desired' feed intake can be determined: this is the amount of feed that would be needed to meet the requirement for the first limiting nutrient in the feed (Emmans, 1981). The bird may not be capable of consuming this amount of feed, its intake possibly being constrained by either the bulkiness of the feed or the inability to lose sufficient of the heat generated to the environment. In this case feed intake will be less than desired and performance would be compromised.

This theory has been shown to predict food intake and hence growth and carcass composition with considerable accuracy (Ferguson and Gous, 1997, 2002; Ferguson *et al.*, 1997; Wellock *et al.*, 2004). Burnham *et al.* (1992) and Gous *et al.* (1987), among many others, have shown that broilers and laying hens increase food intake as the limiting nutrient in the feed is reduced, attempting thereby to obtain more of the limiting nutrient, until a dietary concentration is reached where performance is so constrained that food intake falls. The common misconception that 'birds eat to satisfy their energy requirements' is clearly naive and of no value in predicting voluntary food intake.

The critical features of a model to predict food intake in hens would be predictions of the body protein weight of the bird and its potential egg output on each day, from which nutrient requirements for maintenance and output may be calculated; a description of the nutrient content of the feed on offer; and a description of the effective temperature of the environment in which the bird is housed. Although the principle of predicting food intake is the same for growing and reproducing birds, the description of potential growth and of egg output differs markedly between the two.

The situation with broiler breeder hens differs from that of full-fed laying hens in that a daily allowance of feed is allocated, this being less than would normally be consumed if the birds were given *ad libitum* access to feed. Yet the principles applied to voluntary intake prediction, described above, remain: the difference is that the desired food intake of the birds may not always be achieved, thus the actual food intake would be that constrained by the farm manager. Consequently, egg output will be a function of the amount of limiting nutrient remaining after the maintenance requirement of the hen has been met. Whether the consequences of underfeeding are more likely to be evident with broiler breeders than with commercial laying hens, given that laying hens are fed *ad libitum*, would depend on the daily amount of food allocated to the breeders in relation to their potential egg output, and on the density of the feed allocated to the laying hens and the environmental temperature to which they are subjected.

Not all hens in a broiler breeder flock will consume exactly the same amount of feed, some birds being more aggressive than others. These differences in intake may be accommodated in a simulation model by allocating an aggressiveness factor to each hen based on a range of deviations from a mean of zero (Wellock *et al.*, 2004). The correlation between aggressiveness and potential egg output is not known, but could be varied in the model to determine the consequence of differences in this relationship.

In determining nutrient requirements, rules must be applied to account, for example, for the size of amino acid pools for potential albumen formation (which must be filled before ovulation can proceed), and for the rates at which lipid can be deposited in, or withdrawn from, body reserves as a means of accounting for differences in energy balance. If it is assumed that birds and animals have an inherent ratio of body lipid to protein, which they attempt to maintain at all times (Emmans, 1981, 1989), where possible, the bird will make use of excess lipid reserves as an energy source. This has an impact on the voluntary food intake of hens, with energy being stored on non-laying days and being utilized on laying days, which would tend to buffer the changes in food intake required on these days. Presumably there is a minimum amount of body lipid that needs to be maintained (Gous *et al.*, 1990) that will be unavailable as an energy source.

Optimization

Until recently, mechanistic models developed for poultry have dealt with the simulation of responses in a single bird. Such responses are usually linear to the point where the genetic potential is reached (Fisher *et al.*, 1973). Poultry nutritionists are interested in responses to nutrients in economically important outputs such as body weight (or protein) gain, breast meat yield, egg output, numbers of chicks produced per hen, etc. Because such responses are usually measured using groups of birds, they are invariably curvilinear, being the result of integrating the responses of individuals making up that population (Fisher *et al.*, 1973). Populations of birds therefore cannot have ‘requirements’ for nutrients: what nutritionists seek are the optimum economic dietary contents of each nutrient, and for this they need to know how populations respond to increasing dietary contents of the essential nutrients. Descriptions of such responses, whilst taking account of marginal costs and revenues, are therefore invaluable in determining how to maximize or minimize the objective function chosen for any given commercial operation. In the models of commercial laying hens and broiler breeders described here, the theory is applied to an individual and then a population is simulated using appropriate means and standard errors for the variables concerned. The responses thus obtained are acceptable representations of reality, and are thus ideal for determining the optimum method of feeding these simulated flocks.

Optimizing the feed and feeding programme for a flock of laying hens can be achieved with three components, namely, a feed formulation program, an egg production model and an optimization routine. The flow of information for such a procedure bears similarities to the continuous quality improvement model of Deming (1986), which consists of four repetitive steps (Plan, Do, Check, Act), this continuous feedback loop being designed to assist managers to identify and then reduce or eliminate sources of variation. In the case of the nutritionist, the optimizer defines nutritional constraints for practical layer or breeder feeds, which are passed to the feed formulation program where the least-cost feed that meets these constraints is determined. The characteristics of this formulated feed are then passed, as input, to the laying hen model. The performance expected from this feed when given to a defined flock of hens in a given environment is predicted by the model, and this predicted performance is then passed to the optimizer to complete the cycle. The next cycle starts with the optimizer modifying the feed specifications, moving, according to some in-built rules, to an optimum point. A single feed could be fed throughout the laying period, or different feeds might be more beneficial as the flock ages. In the case of broiler breeders, both the composition of the food and the amount to be supplied may be altered during the laying period. The objective function to be maximized or minimized can be defined in terms of any output from the simulation model, but realistically would be an economic index of some sort. Examples are maximizing the margin, based on the value of egg output and the cost of feeding; or, in the case of broiler breeders, because of the high value of the hatched chick, maximizing the number of eggs per hen.

Conclusions

The major limitation in determining the optimum economic amino acid and energy supply for a flock of laying hens and broiler breeders has been the inability to predict how much of a given food the flock would consume. Thus, even though it is possible to determine the optimum intakes of these nutrients as their marginal costs and the marginal revenue for eggs change, it is not possible to convert these into concentrations in the feed. The models described here now offer the possibility of being able to describe the potential reproductive performance characteristics of laying and broiler breeder hens, from which it would be possible to predict food intake, and as a result the optimization of feeds for laying hens and broiler breeders is now possible. Predicting food intake is only possible once the potential laying performance of each hen can be predicted, which is in itself dependent on a large number of interacting systems, all of which can now be simulated, although not perfectly.

References

Attia, Y.A., Burke, W.H., Yamani, K.A. and Jensen, L.S. (1995) Energy allotments and reproductive of broiler breeders. 2. Females. *Poultry Science* 74, 261–270.

Bastian, J.W. and Zarrow, M.X. (1955) A new hypothesis for the asynchronous ovulatory cycle of the domestic hen (*Gallus domesticus*). *Poultry Science* 34, 776–788.

Belyavin, C.G., Boorman, K.N. and Volynchook, J. (1987) Egg quality in individual birds. In: Wells, R.G. and Belyavin, C.G. (eds) *Egg Quality – Current Problems and Recent Advances*. Butterworths, London, pp. 105–120.

Bennett, C.D. and Leeson, S. (1990) Body composition of the broiler-breeder pullet. *Poultry Science* 69, 715–720.

Blair, R., McCowan, M.M. and Bolton, W. (1976) Effect of food regulation during the growing and laying stage on the productivity of broiler breeders. *British Poultry Science* 17, 215–223.

Bowmaker, J.A. and Gous, R.M. (1989) A quantification of reproductive changes and nutrient requirements of broiler breeder pullets at sexual maturity. *British Poultry Science* 30, 663–675.

Burnham, D., Emmans, G.C. and Gous, R.M. (1992) Isoleucine responses in broiler chickens. Interactions with leucine and valine. *British Poultry Science* 33, 71–87.

Coop, R.L. and Kyriazakis, I. (1999) Nutrition-parasite interaction. *Veterinary Parasitology* 84, 187–204.

Deming, W.E. (1986) *Out of the Crisis*. MIT Press, Cambridge, Massachusetts, USA.

EFG Software (1995) EFG Software. Available at: www.efgsoftware.net (accessed 1 April 2013).

Emmans, G.C. (1981) A model of the growth and feed intake of ad libitum fed animals, particularly poultry. In: Hillyer, G.M., Whittemore, C.T. and Gunn, R.G. (eds) *Computers in Animal Production.* Occasional Publication No. 5. British Society of Animal Production, Edinburgh, UK, pp. 103–110.

Emmans, G.C. (1989) The growth of turkeys. In: Nixey, C. and Grey, T.C. (eds) *Recent Advances in Turkey Science*. Butterworths, London, pp. 135–166.

Emmans, G.C. and Fisher, C. (1986) Problems in nutritional theory. In: Fisher, C. and Boorman, K.N. (eds) *Nutrient Requirements of Poultry and Nutritional Research*. Butterworths, London, pp. 9–40.

Etches, R.J. (1996) *Reproduction in Poultry*. CAB International, Wallingford, UK.

Etches, R.J. and Schoch, J.P. (1984) A mathematical representation of the ovulatory cycle of the domestic hen. *British Poultry Science* 25, 65–76.

Ferguson, N.S. and Gous, R.M. (1997) The influence of heat production on voluntary food intake in growing pigs given protein-deficient diets. *Animal Science* 64, 365–378.

Ferguson, N.S. and Gous, R.M. (2002) The response of growing pigs to amino acids as influenced by environmental temperature: tryptophan. *Animal Science* 74, 103–110.

Ferguson, N.S., Gous, R.M. and Emmans, G.C. (1997) Predicting the effects of animal variation on growth and food intake in growing pigs using simulation modelling. *Animal Science* 64, 513–522.

Fialho, F.B. and Ledur, M.C. (1997) Segmented polynomial model for estimation of egg production curves in laying hens. *British Poultry Science* 38, 66–73.

Fisher, C. (1998) Amino acid requirements of broiler breeders. *Poultry Science* 77, 124–133.

Fisher, C. and Gous, R.M. (2008) Recent evidence about the protein and amino acid nutrition of broiler breeder hens. *XXIII World's Poultry Congress, July 2008*. WPSA, Brisbane, Australia.

Fisher, C., Morris, T.R. and Jennings, R.J. (1973) A model for the description and prediction of the response of laying hens to amino acids. *British Poultry Science* 14, 469–484.

Foster, W.H. (1981) A selection experiment on a White Leghorn strain under ahemeral light-dark cycles. *British Poultry Science* 22, 35–48.

Foster, W.H., Robertson, D.V. and Belyavin, C.G. (1987) Forecasting egg production in commercial flocks. *British Poultry Science* 28, 623–630.

Fraps, R.M. (1955) Egg production and fertility in poultry. In: Hammond, J. (ed.) *Progress in the Physiology of Farm Animals*. Butterworths, London, pp. 661–740.

Gavora, J.S., Parker, R.J. and McMillan, I. (1971) Mathematical model of egg production. *Poultry Science* 50, 1306–1315.

Gilbert, A.B. (1972) The activity of the ovary in relation to egg production. In: Freeman, B.M. and Lake, P.E. (eds) *Egg Formation and Production*. British Poultry Science Ltd, Edinburgh, UK, pp. 3–17.

Gous, R.M. and Nonis, M.K. (2010) Modelling egg production and nutrient responses in broiler breeder hens. *Journal of Agricultural Science* 148, 287–301.

Gous, R.M., Griessel, M. and Morris, T.R. (1987) Effect of dietary energy concentration on the response of laying hens to amino acids. *British Poultry Science* 28, 427–436.

Gous, R.M., Emmans, G.C., Broadbent, L.A. and Fisher, C. (1990) Nutritional effects on the growth and fatness of broilers. *British Poultry Science* 31, 495–505.

Johnston, S.A. (2004) A stochastic model to predict annual egg production of a flock of laying hens. PhD thesis. The University of KwaZulu-Natal, Pietermaritzburg, South Africa.

Johnston, S.A. and Gous, R.M. (2003) An improved mathematical model of the ovulatory cycle of the laying hen. *British Poultry Science* 44, 752–760.

Johnston, S.A. and Gous, R.M. (2006) Modelling egg production in laying hens. In: Gous, R.M., Morris, T.R. and Fisher, C. (eds) *Mechanistic Modelling in Pig and Poultry Production*. CAB International, Wallingford, UK, pp. 188–208.

Johnston, S.A. and Gous, R.M. (2007a) A mechanistic, stochastic, population model of egg production. *British Poultry Science* 48, 224–232.

Johnston, S.A. and Gous, R.M. (2007b) Modelling the changes in the proportions of the egg components during a laying cycle. *British Poultry Science* 48, 347–353.

Johnston, S.A. and Gous, R.M. (2007c) Extent of variation within a laying flock: attainment of sexual maturity, double-yolked and soft-shelled eggs, sequence lengths and consistency of lay. *British Poultry Science* 48, 609–616.

King, R.H. (1987) Nutritional anoestrus in young sows. *Pig News and Information* 8, 15–22.

Koops, W.J. and Grossman, M. (1992) Characterization of poultry egg production using a multiphasic approach. *Poultry Science* 71, 399–405.

Leeson, S. and Summers, J.D. (2005) *Commercial Poultry Nutrition*. Nottingham University Press, Nottingham, UK.

Lewis, P.D. and Morris, T.R. (2004) Research note: amendments to the model for predicting age at sexual maturity for growing pullets of layer strains following changes in photoperiod. *Journal of Agricultural Science* 142, 613–614.

Lewis, P.D. and Morris, T.R. (2006) *Poultry Lighting: the Theory and Practice*. Northcot, Andover, UK.

Lewis, P.D. and Morris, T.R. (2008) Research note: an amendment to the model for predicting age at sexual maturity for growing pullets of layer strains given two opposing changes in photoperiod. *Journal of Agricultural Science* 146, 591–594.

Lewis, P.D. and Perry, G.C. (1991) Oviposition time: correlations with age, egg weight and shell weight. *British Poultry Science* 32, 1135–1136.

Lewis P.D. and Perry, G.C. (1994) Factors that influence sexual maturation in the laying hen. In: Raw, M.E. and Parkinson, T.J. (eds) *The Veterinary Annual 34*. Blackwell Scientific Publications Ltd, Oxford, pp. 89–96.

Lewis, P.D., Perry, G.C. and Morris, T.R. (1996) Effect of constant of changing photoperiods on age at first egg and related traits in pullets. *British Poultry Science* 37, 885–894.

Lewis, P.D., Perry G.C., Morris, T.R., Douthwaite, J.A. and Bentley, G.E. (1998) Effect of constant and of changing photoperiod upon plasma LH and FSH concentrations and age at first egg in layer strains of domestic pullets. *British Poultry Science* 39, 662–670.

Lewis, P.D., Morris, T.R. and Perry, G.C. (2002) A model for predicting the age at sexual maturity for growing pullets of layer strains given a single change in photoperiod. *Journal of Agricultural Science* 138, 441–458.

Lewis, P.D., Ciacciariello, M. and Gous, R.M. (2003) Photorefractoriness in broiler breeders: sexual maturity and egg production evidence. *British Poultry Science* 44, 634–642.

Lewis, P.D., Gous, R.M. and Morris, T.R. (2007) A model to predict age at sexual maturity in broiler breeders given a single increment in photoperiod. *British Poultry Science* 48, 625–634.

McMillan, I., Gowe, R.S., Gavora, J.S. and Fairfull, R.W. (1986) Prediction of annual production from part record egg production in chickens by three mathematical models. *Poultry Science* 65, 817–822.

McNally, D.H. (1971) Mathematical model for poultry egg production. *Biometrics* 27, 735–738.

Miyoshi, S., Inoue, K., Luc, K.M., Kuchida, K. and Mitsumoto, T. (1997) Intra-clutch changes in egg composition and shell quality in laying hens. *Japanese Poultry Science* 34, 273–281.

Morris, T.R. (1978) The photoperiodic effect of ahemeral light-dark cycles which entrain circadian rhythms. *British Poultry Science* 19, 207–212.

Morris, T.R. and Gous, R.M. (1988) Partitioning of the response to protein between egg number and egg weight. *British Poultry Science* 29, 93–99.

Nonis, M.K. and Gous, R.M. (2013) Modelling changes in the components of eggs from broiler breeders over time. *British Poultry Science* 54, 603–610.

Pearson, R.A. and Herron, K.M. (1980) Feeding standards during lay and reproductive performance of broiler breeders. *British Poultry Science* 21, 171–181.

Pearson, R.A. and Herron, K.M. (1981) Effects of energy and protein allowances during lay on the reproductive performance of broiler breeder hens. *British Poultry Science* 22, 227–239.

Pearson, R.A. and Herron, K.M. (1982) Relationship between energy and protein intakes and laying characteristics in individually-caged broiler breeder hens. *British Poultry Science* 23, 145–159.

Renema, R.A., Robinson, F.E., Newcombe, M. and McKay, R.I. (1999) Effects of body weight and feed allocation during sexual maturation in broiler breeder hens. 1. Growth and carcass characteristics. *Poultry Science* 78, 619–628.

Robinson, F.E., Hardin, R.T. and Robblee, A.R. (1990) Reproductive senescence in domestic fowl: effects on egg production, sequence length and inter-sequence pause length. *British Poultry Science* 31, 871–879.

Shields, R.G. and Mahan, D.C. (1983) Effects of pregnancy and lactation on the body composition of first-litter female swine. *Journal of Animal Science* 57, 594–603.

Spratt, R.S. and Leeson, S. (1987) Broiler breeder performance in response to diet protein and energy. *Poultry Science* 66, 683–693.

Wellock, I.J., Emmans, G.C. and Kyriazakis, I. (2004) Modeling the effects of stressors on the performance of populations of pigs. *Journal of Animal Science* 82, 2442–2450.

Whittemore, C.T. and Yang, H. (1989) Physical and chemical composition of the body of breeding sows with differing body subcutaneous fat depth at parturition, differing nutrition during lactation and differing litter size. *Animal Production* 48, 203–212.

Wilson, J.L., Robinson, F.E., Robinson, N.A. and Hardin, R.T. (1995) Effects of feed allocation on female broiler breeders. *Journal of Applied Poultry Research* 4, 193–202.

Yang, N., Wu, C. and McMillan, I. (1989) New mathematical model of egg production. *Poultry Science* 68, 476–481.

Zakaria, A.H. (1999) Ovarian follicular growth in laying hens in relation to sequence length and egg position in various sequence lengths. *Archiv für Geflügelkunde* 63, 264–269.

Zakaria, A.H., Miyaki, T. and Imai, K. (1984) The relationships of clutch length and egg position on ovarian follicular growth in laying hens. *Poultry Science* 63, 1250–1254.

4 Modelling Nutrient Utilization in Sows: A Way Towards the Optimization of Nutritional Supplies

J.Y. Dourmad,* J. van Milgen, A. Valancogne, S. Dubois, L. Brossard and J. Noblet
INRA, Saint-Gilles, France

Abstract

In recent years, the reproductive performance of sows has been drastically improved. Nowadays, on many farms, with the use of hyperprolific sows, the average litter size exceeds 13 piglets at farrowing and 11.5 at weaning. These changes in performance have had major effects on the nutritional requirements during both pregnancy and lactation. At the same time, from the results obtained over the past 20 years on energy, amino acid and mineral utilization in sows, it has become possible to improve the determination of nutrient requirements (factorial approach) and the prediction of an animal's response to nutrients supplies (modelling). The aim of this chapter is to describe how the current state of knowledge on sow nutrition can be included in an integrated model, as well as in a software tool, designed for end-users, mainly nutritionists in the pig industry and students in animal nutrition. Different examples are given to illustrate how the use of such a model can help in optimizing the productivity of sows, while considering new priorities such as the reduction of the environmental impact of pig production, which can be achieved through a more precise adjustment of nutrient supply to requirement.

Introduction

In mammals, the process of reproduction, from conception to weaning, can be considered as directed to buffer the developing progeny from nutritional distress (Oldham, 1991), involving both homeostatic and homeorhetic controls of nutrient partitioning (Bauman and Currie, 1980). Reproductive problems, which may result in a reduction in sow productivity and early culling, are often related to extreme variations in body reserves (Dourmad *et al.*, 1994). Nevertheless, body reserves should be considered more as an indicator of risk than as the cause of the problem. During gestation, sufficient body reserves must be built to restore adequate body condition and compensate for possible nutritional deficits that may occur in the following lactation. However, these reserves should not be excessive in order to avoid farrowing problems, which are typical for fat sows, or impairing feed intake after farrowing (Dourmad, 1991). During lactation, it is recommended to adapt daily nutritional supplies to requirements to maximize milk production and growth of the piglets, and to minimize the risk of reproductive problems of sows after weaning. Until recently, most attention has been paid

---

*E-mail: jean-yves.dourmad@rennes.inra.fr to the role of body fat reserves. However, recent results in high producing lean animals suggest that body protein mass may also play an important role (Quesnel *et al.*, 2005; Solignac *et al.*, 2010). Consequently, nutritional supplies to sows have to be modulated to maintain body reserves so that the sows will be in optimal condition throughout their productive life, thereby optimizing reproductive performance. On farm, this requires adjusting the feeding level and feed composition according to the performance of individual sows but also to housing conditions, which may affect nutrient utilization and voluntary feed intake.

Over the past 20 years reproductive performance of sows has been drastically improved. Maternal lines, most often Landrace and Large White breeds, have been intensively selected for litter size and, nowadays, hyperprolific sows are available in most countries. In some cases, the use of Chinese breeds has also contributed to that improvement in prolificacy. Selection for improved growth performance and carcass quality has also resulted in decreased sow body fatness and increased mature body weight and size. These changes in sow performance have had major effects on their nutritional requirements. During pregnancy, the increase in prolificacy affects nutrient requirements for litter growth, especially during the last weeks of pregnancy. During lactation, the drastic improvement in milk production and litter growth rate results in a significant increase in nutritional requirements, whereas the sow's spontaneous feed intake remained relatively constant.

At the same time, from the results obtained over the past 20 years on energy, amino acid and mineral utilization in sows, it has become possible to improve the determination of nutrient requirements through the development of models and decision support tools, such as InraPorc (Dourmad *et al.*, 2008), allowing a global approach to better understanding of nutrient use by sows, including the resulting performance.

The purpose of this chapter is to illustrate how the use of such a model can help in optimizing the productivity of sows, while considering new priorities such as reducing the environmental impact of pig production, which can be achieved through a more precise adjustment of nutrient supply to requirement. Because the reliability of the outcome of a simulation depends on the concepts used in the model, it is essential that model users have some knowledge about the model structure and the limitations of its use. For the purpose of this chapter, we will focus only on the feed and sow modules of InraPorc (INRA, 2006). The tool can be downloaded from http://www.rennes.inra.fr/inraporc/.

General Description of the Sow Module of InraPorc

In InraPorc, the sow is represented as the sum of different compartments (i.e. body protein, body lipids, body minerals and uterus), which change during the reproductive cycle (Fig. 4.1). The main nutrient flows are energy, amino acids and minerals. In gestating sows, priority is given to maintenance requirements, requirements for fetuses, and the development of uterus and mammary gland. If the nutrient allowance exceeds these requirements, nutrients in excess contribute to the constitution of the sow body reserves. Conversely, body reserves can be mobilized when the nutrient demand is greater than the nutrient intake, especially in late gestation. In lactating sows, priority is given to maintenance and milk production, and body reserves often contribute to the supply for these priority functions. The approach for representing energy supply in sows differs slightly from that chosen for growing pigs, where energy originating from each different nutrient is considered separately in the model, based on the net energy (NE) concept (van Milgen *et al.*, 2008). In the sow model it was decided to maintain the concept of metabolizable energy (ME), because the available information was based on this concept, and also, the efficiency of energy use varies according to the physiological status of the sow. However, a corrected ME value is calculated to take into account the effects of diet composition on the utilization

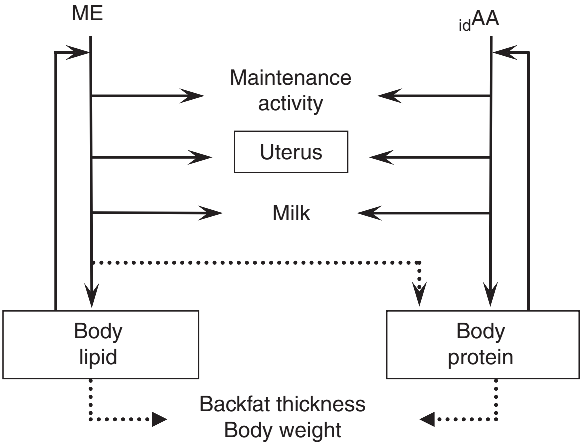


Fig. 4.1. Description of nutrient utilization in the InraPorc sow model. (From Dourmad *et al*., 2008.)

of ME according to the NE system proposed by Noblet *et al*. (1994). The supply of amino acids is considered as standardized ileal digestible (SID) amino acid (INRA-AFZ, 2004), implying that the indigestible fraction and specific endogenous amino acid losses are combined together. The supply of phosphorus is considered as apparent digestible phosphorus (INRA-AFZ, 2004), but the supply of calcium is considered in terms of total calcium.

The different equations describing the utilization of nutrients and energy by gestating and lactating sows were derived from the literature and used to build a computerized simulator (Dourmad *et al*., 2008). This simulator determines on a daily basis the flow of nutrients and energy from the feed to storage in the body, excretion or dissipation.

Other functionalities were added to the simulator so that it can be used as a decision support tool (Fig. 4.2). An animal module (‘sow profile’) is used to describe the animal’s characteristics and adjust some model parameters to account for variation in genotype and performance. Three other modules are used to describe the types of feeds used (‘feed sequence plan’), the quantity of feed consumed (‘feed rationing plan’) and the housing conditions (‘housing plan’). The sow module is connected to the ‘feed’ modules, which can be used to calculate dietary nutrients from feed ingredients using the INRA-AFZ (2004) database. When defining the sow profile, a calibration procedure is used to adjust some model parameters for each specific sow genotype/phenotype in relation to observed traits in a reference situation. This calibration is based on an automated optimization procedure that minimizes the difference between observed and predicted performances.

The model can then be used to determine the nutritional requirements according to a classical factorial approach, or to predict performance and analyse nutrient utilization, including nutrient excretion, through simulations. In the current version of the software, reproductive performance data (i.e. litter size, piglet weight, milk production) are considered as user inputs and are therefore not sensitive to nutrient supply.

Factorial Calculation of Sow Requirements

As an example of the use of InraPorc, the energy, amino acid and phosphorus requirements of sows from a herd weaning 25 piglets per sow per year, with, respectively, 12.5 and 10.8 piglets born alive and weaned per litter have been calculated (Table 4.1). The daily energy requirement during gestation increases from parity 1 to parity 3 and remains constant thereafter. Conversely, the amino acid requirement (lysine), expressed per day or per kilogramme of feed, decreases

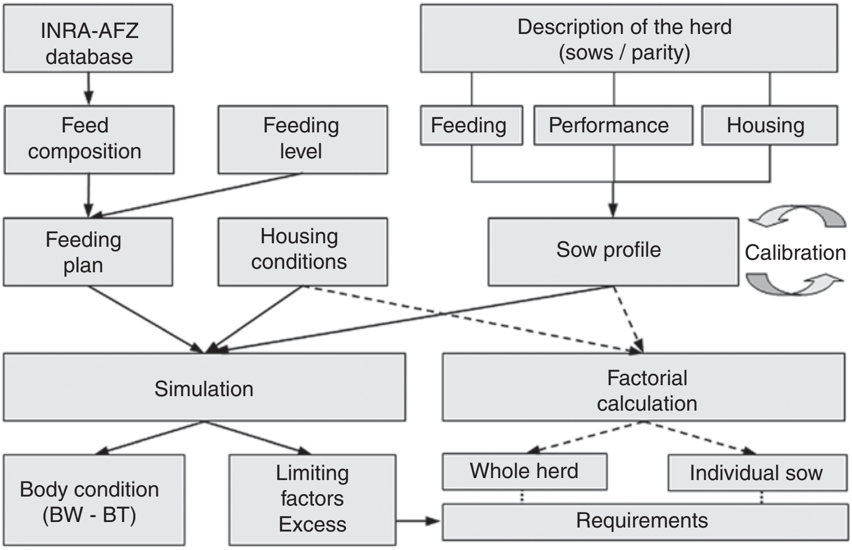


Fig. 4.2. Description of the InraPorc decision support tool for sow nutrition. (From Dourmad *et al.*, 2008.) Sow profile is calibrated from a description of the herd. 'Feeding plan' aggregates feed composition and feeding strategy. 'Housing conditions' aggregates the description of housing and climate, considering also the effect of sow's activity. The tool can be used to simulate the response to a feeding strategy or to predict the requirements according to a factorial approach.

with parity. The energy requirement for lactation also increases up to parity 5.

On average, voluntary energy intake is sufficient to meet 83% of the energy requirement during lactation, with a lower coverage in primiparous sows (75%). During gestation, the amino acid requirement per kilogramme of feed is higher for first and second parity sows, mainly because of a lower feed intake and the further accretion of lean body mass.

The effect of different causes of variation (e.g. housing conditions or level of performance) on requirements can also be evaluated. In the previous example, when gestating sows were housed outdoors at 10°C ambient temperature, their energy requirement would be approximately 25% higher, while the lysine/energy requirement would be 20% lower (Table 4.1). Similarly, if the litter growth rate during lactation is higher (3.0 vs 2.6 kg/day; +15%), energy and amino acid requirements increase by approximately 10%.

Using the factorial calculation of requirements it is also possible to evaluate the effect of stage of pregnancy or prolificacy on SID amino acids or digestible phosphorus requirements (Table 4.2), as well as the effect of litter growth rate and sow appetite on requirements during lactation (Table 4.3).

Short- and Long-term Simulation of Performance

InraPorc can also be used to evaluate the short- and long-term effects of different housing or feeding strategies on nutrient utilization and body condition of sows. The information required for running such a simulation and an example of the predicted responses are given in Table 4.4 for a first parity sow. In practice, these simulations can be useful to predict the risk of an excessive mobilization or reconstitution of body reserves, which might impair long-term reproductive performance. The existence of nutrient deficiencies or excesses can also be identified.

In the second example, the changes in body condition of sows for two phenotypes

Table 4.1. Change in the average requirements for energy, standardized ileal digestible lysine and apparent fecal digestible phosphorus (P) of sows according to parity.[a]

Parity	1	2	3	4	5	6
Gestation (thermoneutrality)						
Energy (ME MJ/day)	33.5	37.2	37.5	36.6	36.3	36.0
Digestible lysine						
g/day	13.5	12.9	12.2	11.8	11.6	11.4
g/kg feed[b]	5.14	4.41	4.16	4.11	4.06	4.03
Digestible P						
g/day	7.1	7.4	7.4	7.1	6.9	6.8
g/kg feed[b]	2.67	2.54	2.52	2.47	2.43	2.40
Lactation (2.7 kg/day litter gain)						
Energy (ME MJ/day)						
Requirement	90.1	94.9	100.0	102.0	101.0	99.3
Intake	68.1	78.8	86.2	86.2	86.2	86.2
Intake, % requirement	75%	83%	86%	85%	85%	87%
Digestible lysine						
g/day	43.3	44.6	46.5	46.5	45.8	44.9
g/kg feed[c]	8.3	7.4	7.0	7.0	6.9	6.8
Digestible P						
g/day	15.7	16.5	17.5	17.6	17.4	17.1
g/kg feed[c]	3.22	2.93	2.84	2.86	2.83	2.77
Change in requirement (%)						
Gestation (10°C)						
ME supply	+24%	+25%	+27%	+29%	+30%	+31%
Lysine content	–19%	–20%	–21%	–22%	–23%	–24%
Lactation (3.0 kg/day litter weight gain)						
ME supply	+11%	+10%	+10%	+10%	+10%	+10%
Lysine content	+10%	+10%	+10%	+10%	+10%	+10%

[a] Calculated for a herd with an average productivity of 25 piglets weaned per sow per year, with sows with a mature body weight of 270 kg and an average herd lactation feed intake of 6.2 kg/day.

[b] For a diet containing 12.7 MJ ME/kg.

[c] For a diet containing 13.0 MJ ME/kg.

Table 4.2. Digestible phosphorus and SID lysine requirements of pregnant sows (parity 2).

Gestation stage		End (80–114 days)		
Litter size	Beginning (0–80 days)	12	14	16
Digestible phosphorus				
g/day	3.8	6.9	7.4	7.9
g/kg diet	1.4	2.5	2.6	2.8
SID lysine				
g/day	8.9	11.9	12.7	13.6
g/kg diet	3.1	4.3	4.5	4.8

differing in average voluntary feed intake during lactation (low (L): 5.0 and high (H): 7.0 kg/day) were simulated over four successive parities. Feed supply during gestation was calculated so that sows attained mature body weight (BW) at parity 4, while maintaining a backfat thickness (BT) of at least 13 mm. The simulated evolution in BW and BT in these two situations is given in Fig. 4.3. The BW loss during lactation was much greater for L

Table 4.3. Digestible phosphorus and SID lysine requirement of lactating sows according to litter growth rate and sow feed intake (parity 2).

Litter growth rate (g/day)	2250	2500	2750	3000	3250
Digestible phosphorus					
g/day	14.7	16.0	17.3	18.5	19.8
g/kg (4 kg FI/day)	3.68	4.00	4.33	4.63	4.96
g/kg (5 kg FI/day)	2.94	3.20	3.46	3.70	3.96
g/kg (6 kg FI/day)	2.45	2.67	2.88	3.09	3.30
Digestible lysine					
g/day	40.3	43.3	46.4	49.4	52.5
g/kg (4 kg FI/day)	10.1	10.8	11.6	12.4	13.1
g/kg (5 kg FI/day)	8.1	8.7	9.3	9.9	10.5
g/kg (6 kg FI/day)	6.7	7.2	7.7	8.2	8.7

FI = feed intake.

Table 4.4. Example of a simulation for a primiparous sow during pregnancy and lactation. (From Dourmad *et al.*, 2008.)

Sow and litter characteristics[b]			
Animal profile:	Large White × Landrace (270 kg body weight at maturity)		
Parity	1		
Housing:	Indoor on slatted floor		
Feeding:	Standard gestation/lactation sequence		
	Born alive	Weaned	Gain/day
No. piglets	12.0	10.3	
Piglets (kg)	1.4	8.0	0.244
Litter (kg)	16.8	82.7	2.520
Simulated sow performance	Gestation	Lactation	Total[a]
Duration (days)	114	27	149
Feed intake			
Total (kg)	308	135	463
Total (kg/day)	2.7	4.98	3.11
Body weight (kg)			
Initial	140.0	198.0	140.0
Final	223.2	174.4	177.8
Total gain	83.2	–23.6	–
Net gain	58.0	–23.6	37.8
Backfat (mm)			
Initial	14.0	19.0	14.0
Final	19.0	13.6	14.3
Gain	5.0	–5.4	0.3
Deposition (g/day)			
Protein	73	–81	44
Lipid	171	–457	59
Milk (kg/day)	–	8.85	–

[a] Including period from weaning to mating.

[b] Sows and litter characteristics are used as inputs as well as feed composition and feeding strategy. The model simulates the changes in body weight, backfat thickness, deposition of protein and lipids, and the dynamics of utilization of each nutrient (results not presented).

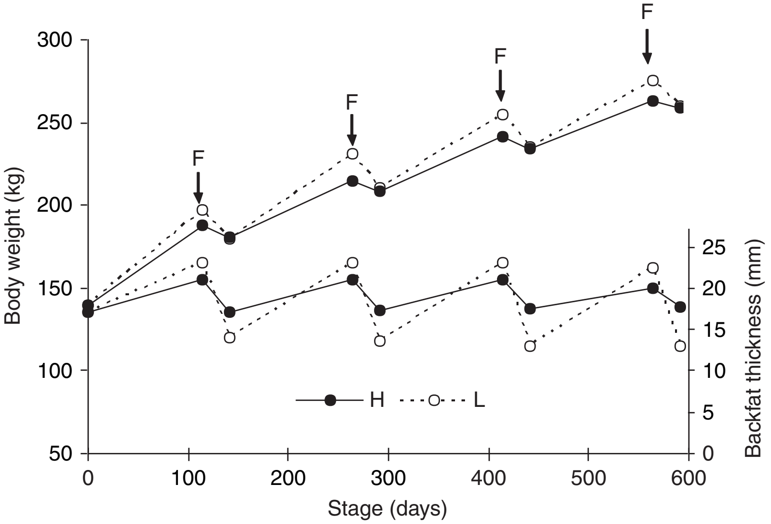


Fig. 4.3. Simulated long-term effect of appetite during lactation (L: 5.0 kg/day, H: 7.0 kg/day) on the change in body weight and backfat thickness over the first four parities (F: farrowing). (From Dourmad *et al.*, 2008.)

than for H sows, and this was compensated for by a higher weight gain during gestation. The same was observed for backfat thickness: L sows were leaner at weaning and fatter at farrowing. This results in an increased risk of reproductive problems in L sows, both at weaning because they are too lean, and at farrowing because they are too fat. Average daily feed intake over the complete reproductive cycle (3.5 kg/day) did not differ between L and H sows. However, SID lysine and digestible phosphorus requirements during lactation were much higher, per kilogramme of feed, in L than in H sows, whereas no noticeable difference was found during gestation.

Dealing with the Variability of Requirements

An important question in the practical nutrition of sows is how to deal with variability in requirements among sows. This variability originates from variability in reproductive performance (e.g. litter size), in productive capacity (e.g. milk production) and appetite (e.g. during lactation). Moreover, the requirements also differ according to parity and physiological stage.

During gestation, the strategy to reach the target of body condition at farrowing is first to adapt the total energy or feed supply according to body condition at mating, parity, expected litter performance and housing conditions. In this context, measuring or estimating sow BW and BT is important to adapt the feeding allowance to the situation of each sow. When the total amount of feed or energy is defined, different strategies can be used to partition this amount over gestation. It is generally recognized that increasing feed allowance in late pregnancy, over the last 3 weeks, may improve piglet vitality and survival at birth, especially in hyperprolific sows. The strategy during the first two-thirds of pregnancy is less clear and may depend on the type of housing and the available equipment for feed distribution. Two strategies are mainly found in practice during that period: either a rather constant level of feeding, or a period of overfeeding of thin sows, over about 4 weeks, followed by a period of restriction. This second strategy, which allows a rapid reconstitution of sow body reserves in early gestation, is becoming more common in the context of European Union legislation on sow welfare, which requires group housing after 4 weeks of pregnancy. Defining a feeding strategy for gestating sows may also require adapting nutrient content (amino acids, minerals, vitamins, etc.) according to gestation stage and/or parity; although in practice the most common strategy is still to use the same diet for all sows. Indeed, amino acid and mineral requirements decrease with parity and also vary according to gestation stage. Feeding the same diet to all pregnant sows results in an oversupply of nutrients in many situations and a risk of undersupply in late gestation, especially for primiparous sows. This could be improved by using two different gestation diets or multiphase feeding. The role of such strategies in the reduction of nitrogen and phosphorus excretion will be described in the next section.

During lactation, nutrient requirements are mainly affected by milk production and appetite of sows. It is clear from the results presented in Table 4.1 that young sows have a lower appetite and should be fed a diet more concentrated in nutrients, especially amino acids and minerals. In practice, the appetite of lactating sows varies widely according to parity, ambient temperature and body condition, etc. Moreover the potential for milk production varies among sows, increasing the variability of the requirement.

Using individual data of litter growth rate (LGR) and feed intake from a farm with average LGR of 2970 g/day and feed intake of 6.5 kg/day, we calculated the digestible lysine requirement according to InraPorc. Average requirements for parities 1 to 4 amounted to 8.20 ± 2.68, 7.81 ± 2.53, 7.60 ± 2.44 and 7.10 ± 2.15 g/kg digestible lysine, respectively. However, because of the variability, higher supplies are required to meet the requirements of all sows as illustrated in Fig. 4.4. For instance, to meet the requirement of 80% of all sows, a diet with 9.3 g/kg digestible lysine should be fed. From these results, the question could be raised of the possibility of feeding a specific lactation diet to first parity sows.

Improving Nutrient Utilization and Reducing Excretion

The first task in improving the efficiency of nutrient utilization and consequently reducing excretion is to ensure an adequate protein and amino acid supply over time according to the production potential and physiological status of the animals (Rigolot *et al*., 2010). In sows, nitrogen and phosphorus excretion can be reduced by 20% to 25% when specific diets are provided

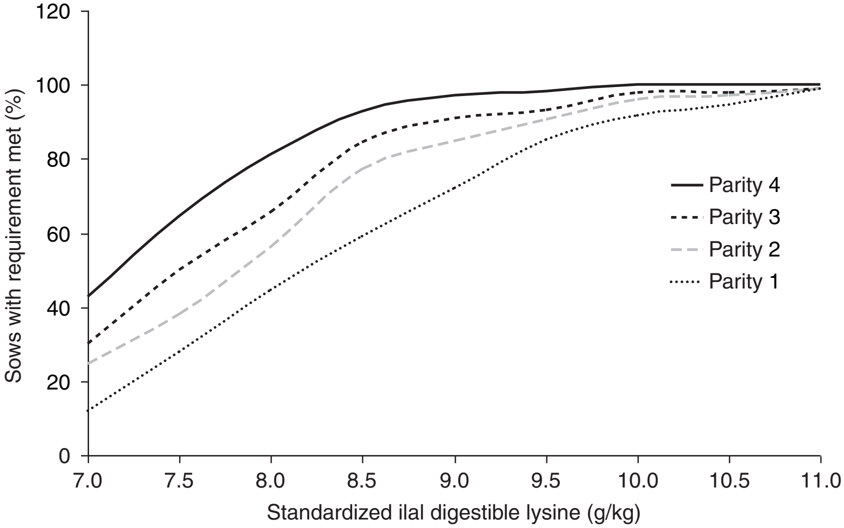


Fig. 4.4. Effect of digestible lysine content on the percentage of lactating sows from different parities with their requirements met. (Dourmad, 2013, unpublished data.)

separately for gestation and lactation instead of providing a single diet for the whole period (Dourmad *et al*., 1999). In practice, this is already achieved in most farms. Nevertheless, excretion could be reduced even further by using two- or multiphase feeding programmes during gestation. However, this requires a precise evaluation of requirements, which can be achieved using modelling approaches.

Using InraPorc, we simulated the utilization of SID lysine by sows over four parities, with three different feeding strategies that differed in nutrient supplies during gestation. In the first feeding strategy the sows received a single gestation diet during the entire gestation period and a lactation diet during lactation. The feeding level during gestation was adjusted according to body condition, and increased by 400 g/day during the last 3 weeks of gestation. During lactation, feed intake was assumed to be close to *ad libitum*. Diets were formulated on a least-cost basis and their composition is given in Table 4.5. From the results presented in Fig. 4.5a, it is clear that the digestible lysine requirement is much higher at the end than at the beginning of gestation. Moreover, the lysine requirement decreases with parity and this decrease is even more marked when the requirement is expressed per kilogramme of feed rather than per day. This means that when the same diet is fed to all gestating sows, the amino acids and protein supplies exceed the requirement, especially during the beginning of gestation and in older sows. This can be improved by feeding two different diets to gestating sows, depending on parity and gestation stage.

This strategy was evaluated (Fig. 4.5b) and two gestation diets were formulated differing in their amino acid and protein contents. The first diet contained 3.8 g of digestible lysine and 102 g of crude protein (CP) per kilogramme of feed. It was used during the first 80 days of gestation, except for first parity sows. The second diet contained 5.5 g of digestible lysine and 145 g of CP per kg of feed and was used in first parity sows throughout gestation, and in other sows from day 80 of gestation. Other amino acids were supplied according to the ideal protein requirement. This two-phase feeding strategy allowed for a much better adjustment of amino acids supplies to sows' requirements. With this strategy total consumption of CP and SID lysine were reduced by 10% and 11%, respectively. This resulted

Table 4.5. Effect of different feeding strategies (one phase, two-phase and multiphase) of sows on nitrogen and phosphorus excretion and the cost of feed ingredients.

	One-phase	Two-phase	Multiphase
Diet composition (g/kg)			
Crude protein			
Gestation 1	–	102.1	99.7
Gestation 2	145.0	145.0	145.0
Lactation	160.0	160.0	160.0
Digestible lysine			
Gestation 1	–	3.80	3.00
Gestation 2	5.50	5.50	5.50
Lactation	8.75	8.75	8.75
Cost of feed (€/sow)[a]			
Per cycle	80.7	76.0	74.4
Per day	0.550	0.518	0.507
% of strategy 1	100%	94%	92%
Nitrogen excretion (g/sow)			
Per cycle	8309	7071.5	6718
Per day	56.6	48.2	45.8
% of strategy 1	100%	85%	81%

[a] 2009 prices for feed ingredients in Western France.

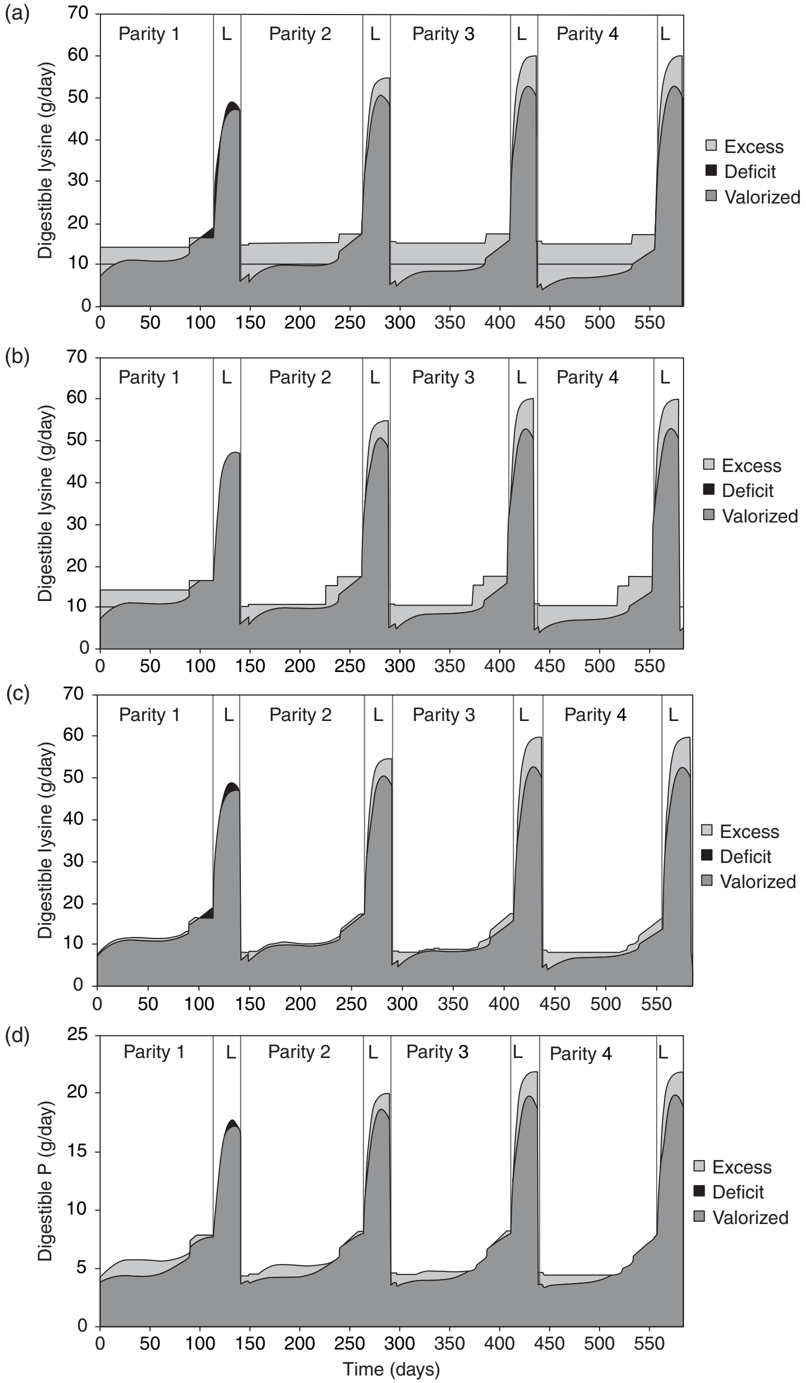


Fig. 4.5. Simulated effect of different gestation feeding strategies on the utilization of ileal digestible lysine. (a) One diet, (b) two diets in multiparous sows with a change at 80 days of gestation, (c) two diets mixed in adequate proportions to meet lysine and apparent digestible phosphorus requirements, and on the utilization of digestible phosphorus (d) with the same feeding strategy as (c).

in an average reduction in nitrogen excretion of 15% over the four parities (Table 4.5).

Further improvements can be achieved by the use of multiphase feeding during gestation. This can be realized in practice by using computerized automated feeding systems. Two gestation diets were formulated differing in amino acids and CP contents. The diets contained 3.0 g digestible lysine and 99.7 g CP, and 5.5 g digestible lysine and 145 g CP per kilogramme of feed, respectively. The two diets were mixed in adequate proportions to meet, on a daily basis, the amino acid (and digestible phosphorus) requirement (Fig. 4.5c). Compared to the single diet feeding strategy, the multiphase strategy reduced intake of CP and SID lysine by 14% and 17%, respectively, and nitrogen excretion by 20% (Table 4.5). With this strategy, over the four parities, gestation diets 1 and 2 contributed to 35% and 65% of total gestation feed intake, respectively.

Compared to the one-phase feeding strategy, the two-phase and the multiphase feeding strategies (Fig. 4.5d) reduced consumption and excretion of phosphorus by 5% and 9%, and by 7% and 12%, respectively (Table 4.5). When the change in feeding strategy was combined with phytase supplementation, phosphorus excretion was reduced by 20% between the extreme strategies.

The effect of the feeding strategy on feed cost is not easy to assess because of its high sensitivity to the relative price of the different feed ingredients. Moreover changing the feeding strategy may result in extra costs for storage or distribution of feed when the number of feeds used on the same farm increases. The cost of feed is about 6% lower with the two-phase strategy compared with the one-phase feeding strategy (Table 4.5), and 8% lower with multiphase feeding. This indicates that improving the feeding strategy of sows during gestation appears a promising approach to reducing nitrogen and phosphorus excretion while simultaneously reducing feeding cost.

Conclusion

Simulation models and decision support tools, such as InraPorc, can be used to evaluate different feeding strategies for sows, from both a nutritional and environmental perspective. These tools address nutrient utilization in a dynamic way and allow identification of the limiting factors in the diets and/or excessive supplies. Knowledge of how nitrogen and phosphorus deposition evolve over time in relation to feed intake is essential if nitrogen and phosphorus excretion are to be reduced.

Adapting the feeding strategy during gestation to better account for the evolution of nutrient requirement appears a promising approach to reducing nitrogen and phosphorus excretion without increasing feed cost. However, from a practical point of view, this may be difficult to achieve, especially in smaller herds. The two-phase feeding strategy during gestation requires differentiating the type of diets according to parity and stage of gestation. The multiphase feeding strategy could be easier to adopt by using automated sow feeding stations. Moreover, this strategy allows one to better account for the variability in nutrient requirements between sows, by considering individual body condition at mating.

In the future, different objectives could be identified for the evolution of such models. The first objective would be to combine a sow nutrition model, such as InraPorc, and a sow farm model, such as the stochastic dynamic model developed by Martel *et al.* (2008). This would allow consideration of the effect of nutrition in the farm model, for example, on sows delay of return into oestrus after weaning, as well as to predict the variability in nutritional requirements resulting from variability of performance between sows, or according to time. The second objective would be use the set of equations from the InraPorc model in order to develop algorithms for real-time calculation of nutrient requirements according to housing conditions based on actual (and previous) performance of each individual sow, and implement these algorithms in automated sow feeding stations, as proposed by Pomar *et al.* (2010) for growing pigs.

References

Bauman, D.E. and Currie, W.B. (1980) Partitioning the nutrients during pregnancy and lactation: a review of mechanisms involving homeostasis and homeorhesis. *Journal of Dairy Science* 63, 1514–1529.

Dourmad, J.Y. (1991) Effect of feeding level in the gilt during pregnancy on voluntary feed intake during lactation and changes in body composition during gestation and lactation. *Livestock Production Science* 27, 309–319.

Dourmad, J.Y., Etienne, M., Prunier, A. and Noblet, J. (1994) The effect of energy and protein intake of sows on their longevity: A review. *Livestock Production Science* 40, 87–97.

Dourmad, J.Y., Sève, B., Latimier, P., Boisen, S., Fernandez, J., Van de Peet-Schwering, C. and Jongbloed, A.W. (1999) Nitrogen consumption, utilisation and losses in pig production in France, The Netherlands and Denmark. *Livestock Production Science* 58, 199–211.

Dourmad J.Y., Etienne, M., Valancogne, A., Dubois, S., Van Milgen, J. and Noblet, J. (2008) InraPorc: a model and decision support tool for the nutrition of sows. *Animal Feed Science Technology* 143, 372–386.

INRA (2006) InraPorc®, a decision support tool for pig nutrition. Available at: http://w3.rennes.inra.fr/inraporc/ (accessed 29 May 2014).

INRA-AFZ (2004) Tables of composition and nutritional value of feed materials. In: Sauvant, D., Pérez, J.M. and Tran, G. (eds) *Tables of Composition and Nutritive Value of Feed Materials Pigs, Poultry, Cattle, Sheep, Goats, Rabbits, Horses, Fish.* Institut National de la Recherche Agronomique, Association Française de Zootechnie, Paris, pp. 1–304.

Martel, G., Dedieu, B. and Dourmad, J.Y. (2008) Simulation of sow herd dynamics with emphasis on performance and distribution of periodic task events. *Journal of Agricultural Science Cambridge* 146, 365–380.

Noblet, J., Fortune, H., Shi, X.S. and Dubois, S. (1994) Prediction of net energy value of feeds for growing pigs. *Journal of Animal Science* 72, 344–354.

Oldham, J.D. (1991) AFRC technical committee on responses to nutrients. Theory of response to nutrients by farm animals. Pregnancy and lactation. *Nutrition Abstract and Review* 61, 683–722.

Pomar, C., Hauschild, L., Zhang, G.H., Pomar, J. and Lovatto, P.A. (2010) Precision feeding can significantly reduce feeding cost and nutrient excretion in growing animals. In: Sauvant, D., van Milgen, J., Faverdin, P. and Friggens, N. (eds) *Modelling Nutrition Digestion and Utilization in Farm Animals*. Wageningen Academic Publishers, Wageningen, The Netherlands, pp. 327–334.

Quesnel, H., Mejia-Guadarrama, C.A., Pasquier, A., Dourmad, J.Y. and Prunier, A. (2005) Dietary protein restriction during lactation in primiparous sows with different live weights at farrowing: II. Consequences on reproductive performance and interactions with metabolic status. *Reproduction Nutrition Development* 45, 57–68.

Rigolot, C., Espagnol, S., Pomar, C. and Dourmad, J.Y. (2010) Modelling of manure production by pigs and NH_3, N_2O and CH_4 emissions. Part I: animal excretion and enteric CH_4, effect of feeding and performance. *Animal* 4, 1401–1412.

Solignac, T., Keita, A., Pagot, E. and Martineau, G.P. (2010) The over-muscle sow syndrome: a new emerging syndrome in hyperprolific sow herds. Preliminary observations on farrowing duration. *21st International Pig Veterinary Congress, Vancouver*, 18–21 July 2010, Oral Proceedings – 124.

van Milgen, J., Valancogne, A., Dubois, S., Dourmad, J.Y., Sève, B. and Noblet, J. (2008) InraPorc: a model and decision support tool for the nutrition of growing pigs. *Animal Feed Science and Technology* 143, 387–405.

5 Statistical Issues in Nutritional Modelling

N. St-Pierre*
The Ohio State University, Columbus, Ohio, USA

Abstract

Most models in biology have a deterministic structure: they make definite predictions for quantities without any associated probability distribution. A stochastic model, on the other hand, contains random elements and probability distributions within the model itself. Historically, the predominant perspective was that the stochasticity of a model represented the unknown part of a system, with the implication that stochasticity should be absent in a model of sufficient complexity. This characterization of stochasticity is at best naive, and at worst plain wrong. In general, a univariate model can be represented as: $\boldsymbol{Y} = f(\boldsymbol{X}, \boldsymbol{\beta}) + \boldsymbol{\varepsilon}$, where $\boldsymbol{Y}$ is a vector of observations, f is some unknown function or set of functions, $\boldsymbol{X}$ is a matrix of input variables (observed), $\boldsymbol{\beta}$ is a vector of parameters to the function f and $\boldsymbol{\varepsilon}$ is a vector of errors. Stochasticity enters the model at four locations. First, $\boldsymbol{\varepsilon}$ represents the outcome from many sources of error. Measurement errors on the $\boldsymbol{Y}$ appear in $\boldsymbol{\varepsilon}$; this component is generally referred to as pure error. But $\boldsymbol{\varepsilon}$ also contains some of the errors associated with having an incorrect model, what has been called the lack-of-fit component. A proper experimental design allows separate estimates of these two components. The second source of stochasticity is related to $\boldsymbol{\beta}$. In a frequentist framework, $\boldsymbol{\beta}$ are fixed, errorless parameters. Their estimates $\boldsymbol{B}$, however, are stochastic variables with a multivariate distribution (often considered multivariate normal in application). Thus, the prediction error of any model includes components related to $\boldsymbol{\varepsilon}$, but also the variances and covariances associated with the estimated $\boldsymbol{\beta}$. A simulation of the model errors, even in a frequentist paradigm, must include the variance in the $\boldsymbol{B}$ as well as in the $\boldsymbol{\varepsilon}$. In a Bayesian framework, the $\boldsymbol{\beta}$ are themselves random parameters. Thus their stochastic property is evident and explicitly considered during estimation and must therefore be retained during model evaluation and simulation. A third source of stochasticity relates to the $\boldsymbol{X}$ elements. Inputs to models are never known with certainty. The error in the measurements of the variables must be accounted for during parameterization. This is a very complicated problem for dynamic models expressed in the form of differential equations. Last, the function f is itself an approximation to the true but unknown function. Thus, the uncertainty surrounding f adds uncertainty to model predictions. This stochasticity can be included in the analysis in instances when there is more than one competing model (functions). Additionally, global as opposed to local sensitivity analysis techniques must be used. The probability distributions of the model outcomes can be compared to the probability distributions of the experimental outcomes, thus answering the question of whether the two are from the same process. Viewed this way, stochasticity is an inherent characteristic of biological models the same way that errors and probability distributions are inherent characteristics of experiments.

---

*E-mail: st-pierre.8@osu.edu

Nutritional Modelling for Pigs and Poultry (eds N.K. Sakomura *et al.*)

Introduction

Mathematical models are increasingly used in biology (Yeargers *et al.*, 1996) and agriculture (France and Thornley, 1984) to make quantitative inferences and predictions about complex systems under various discrete or continuous inputs. Most biological models have a deterministic structure. That is, they make definite predictions for quantities without any associated probability distribution. Successive runs of the model yield identical outcomes if initial states, parameter values and inputs are the same. Although such models are useful for understanding the complex interactions that occur in biology, they lack a fundamental characteristic of biological systems: variation. Regardless of the precision of measurements, replications of an experiment even when done on the same subjects do not yield the same identical outcomes. In contrast stochastic models contain random elements and probability distributions within the models themselves. Thus, stochastic models help us understand not only the mean outcome of a system, but also the reasons as to why such outcomes vary under apparently identical situations. In this chapter, we first present a very simple biological process and model it using both a deterministic and a stochastic approach. This serves to illustrate the enhanced value of stochastic models. This is followed by a section identifying the sources of stochasticity in models. Methods used to identify important elements are then presented followed by methods of validation of stochastic models.

Linear Birth–Death Process

Suppose that we are interested in modelling the number of bacteria in a bacterial colony (Wilkinson, 2006). We define the birth rate, λ, as the average number of offspring produced by each bacterium in a unit of time. Likewise, the death rate, μ, is defined as the average proportion of bacteria that die in a unit time. The number of bacteria at time t is $X(t)$, and the initial number ($t = 0$) is x_0. In a deterministic view:

$$\frac{dX(t)}{dt} = (\lambda - \mu)X(t) \tag{5.1}$$

Integrating Eqn 5.1, we get:

$$X(t) = x_0 e^{(\lambda - \mu)t} \tag{5.2}$$

In Eqn 5.2, the slope of the process through time is entirely determined by $\lambda - \mu$. If $\lambda - \mu > 0$ (i.e. $\lambda > \mu$), this indicates exponential growth. If $\lambda - \mu < 0$ (i.e. $\lambda < \mu$), this indicates exponential decay. In fact, the solution to Eqn 5.2 depends exclusively on ($\lambda - \mu$). For example, the solution if $\lambda = 20$ and $\mu = 19$ is identical to the solution if $\lambda = 2$ and $\mu = 1$. Thus Eqn 5.2 is fundamentally overparameterized: experimental data can only provide information about ($\lambda - \mu$), and Eqn 5.2 must be restated as:

$$X(t) = x_0 e^{\rho t} \tag{5.3}$$

Where $\rho = (\lambda - \mu)$. Experimental data can only provide information on the difference between birth and death rates.

A stochastic view of the linear birth–death process takes a very different approach. First, the number of bacteria varies discretely. That is, the number of bacteria can only take integer values at all times. Second, stochasticity is introduced to the system because each bacterium has its own probability of giving birth and of dying over each unit of time. Simulated results for a decaying process where $x_0 = 50$, $\lambda = 3$ and $\mu = 4$ are presented in Fig. 5.1. At $t = 2$, the deterministic model yields $X = 6.77$, whereas the stochastic model yields predictions ranging from 3 to 20. In an actual experiment, a bacterial count of 6.77 could never be observed; bacterial counts can only take an integer value. The prediction of 6.77 represents the mean, that is, the expected value over a very large number of replicates. The stochastic approach actually models the expected variation among replicates, something that is completely absent in the deterministic model.

The time to extinction is infinity (∞) for the deterministic model, but takes values ranging from 2.2 to undetermined (i.e. not extinct by $t = 5$) for the stochastic model. If the experiment were actually performed,

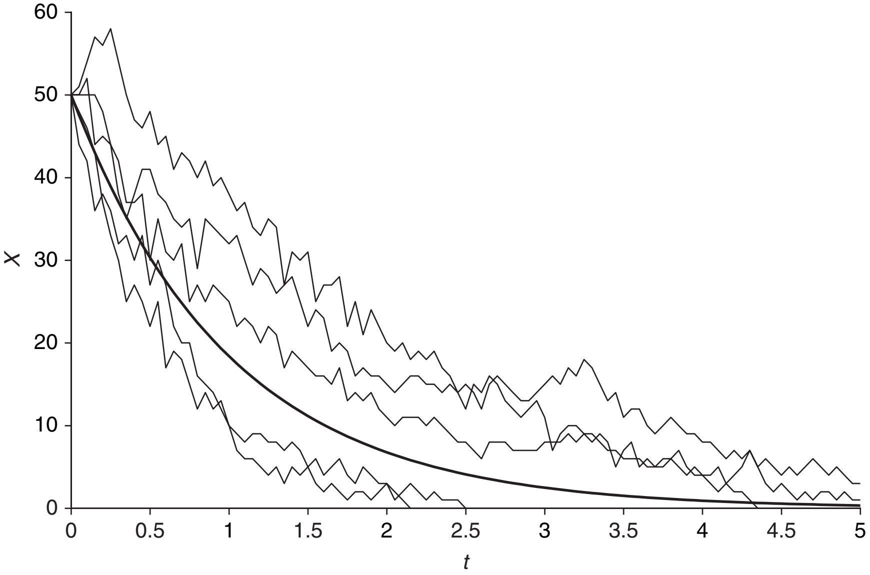


Fig. 5.1. Five realizations of a stochastic linear birth–death process together with the continuous deterministic solution (x_0 = 50, λ = 3, μ = 4; see text for model description).

there would be replicates where the bacterial colony becomes extinct before $t = 5$, and there would be replicates where there are still a few individuals left at $t = 5$. No experiment could actually wait until $t = \infty$ to actually verify that all colonies over an infinite number of replicates become extinct. In essence, the average colony under the deterministic view never becomes extinct.

The deterministic solution depends only on $(\lambda - \mu)$. The same deterministic curve as seen in Fig. 5.1 would be obtained if $\lambda = 30$ and $\mu = 31$. This is not the case for the stochastic model, whose solution depends explicitly on both λ and μ: $(\lambda - \mu)$ controls the essential shape, whereas $(\lambda + \mu)$ controls the volatility. If five replicates of the experiment were actually performed, the spread of the various outcomes at a given time would allow the estimation of $\lambda + \mu$, whereas the overall trajectory would allow for the estimation of $\lambda - \mu$. Estimation techniques require high-quality, calibrated, high-resolution time-course measurements of levels of a reasonably large subset of model variables. This is difficult to obtain. Methods for such estimation are complex and currently based on Bayesian inference coupled with Markov chain Monte Carlo methods (Gibson and Renshaw, 1998). Research in this area is very active and substantial progress should be made in the near future. The point, however, is that when using the same experimental data a deterministic model can only estimate the difference between the birth and death rates, whereas the stochastic model yields separate estimates of both λ and μ. This illustrates the additional knowledge gained from using a stochastic view of the system. It also demonstrates that one cannot fit a deterministic model to available experimental data and then use the inferred rate constant in a stochastic simulation. As we shall see, there is more to stochastic modelling than just appending a random error to a deterministic model.

Sources of Stochasticity in Models

A univariate model (one that has only one dependent variable) has the following general structure:

$$\boldsymbol{Y} = f(\boldsymbol{X}, \boldsymbol{\beta}) + \boldsymbol{\varepsilon} \tag{5.4}$$

Where ***Y*** is a vector of observation; *f* is some unknown function or set of functions; ***X*** is a matrix of input variables (observed); **β** is a vector of parameters to the function *f*; and **ε** is a vector of errors.

Stochasticity can enter Eqn 5.4 at four different locations: *f*, ***X***, **β** and **ε**.

The vector of errors, **ε**, is a random variable that aggregates many sources of errors. Measurement errors on the ***Y*** appear in **ε**. This component has traditionally been labelled as pure error (Draper and Smith, 1998). But **ε** also contains some of the errors associated with having an incorrect model, the lack-of-fit component (Draper and Smith, 1998). Often, experimental data do not allow the partitioning of **ε** into pure error and lack-of-fit. This partitioning requires replicated observation at identical levels of all ***X*** values. This can easily be done when an experiment is designed for the specific purpose of model parameterization. In many instances, however, models are parameterized using literature data. In such instances, the partitioning of **ε** into its two basic components is at best difficult and often impossible. This is unfortunate because the true error represents the variance from measurement errors in the ***Y***. This true error represents a limit of accuracy of any potential model. The lack-of-fit component, however, represents the uncertainty regarding *f*. It is in essence a measure of functional adequacy. Figure 5.2 shows a residual plot of non-ammonia-non-microbial nitrogen flow through the duodenum (NANMN) for the NRC (2001) dairy cattle model. Over the whole range of predictions, the average residual error (observed minus predicted values) is very close to zero, but the spread of the errors is quite large. In fact, the standard error (i.e. the standard deviation of the residual error) amounts to approximately 40% of the average NANMN prediction (St-Pierre, 2001). This can result from large errors in the measurements themselves (pure error) or from an inadequate model that doesn't account for a sufficient number of variables that affect NANMN (lack-of-fit). If pure error is the predominant factor explaining the large standard error, then little gain can be made in model accuracy until the precision of the measurements is improved. If, however, lack-of-fit dominates the error, then the model is grossly inadequate.

The uncertainty of the parameters **β** is the second source of stochasticity in Eqn 5.4. This uncertainty can be expressed statistically using either a frequentist or a Bayesian framework. For a frequentist, the **β** are fixed parameters and thus, without errors. The **β**, however, are unknown. Their estimates, conventionally known as ***B***, are random variables.

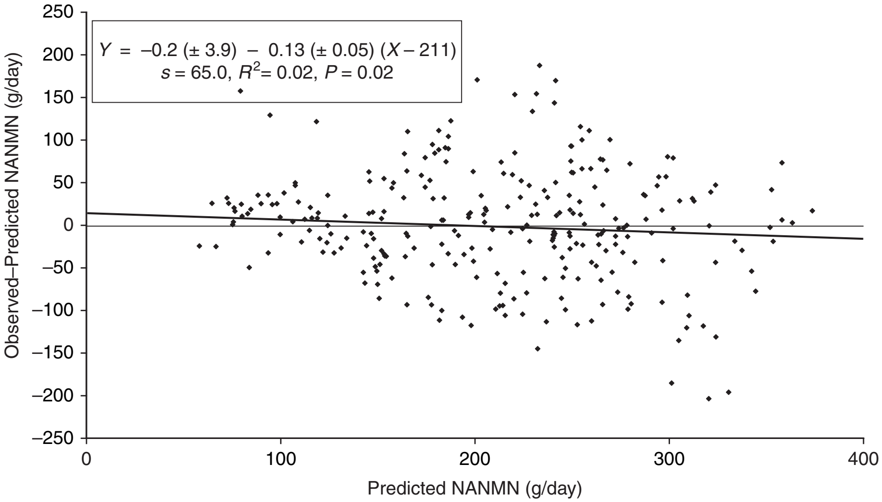


Fig. 5.2. Plot of observed minus predicted non-ammonia–non-microbial nitrogen flow to the duodenum (NANMN) vs predicted NANMN. (Data are from NRC, 2001, figure 5–7.)

They are generally assumed to have a multivariate normal distribution, although other multivariate distributions could be handled, at least theoretically. The multivariate normal assumption implies that the conditional distributions are normal and that the elements of $\boldsymbol{B}$ are possibly correlated. Thus, the prediction error of any model includes a component associated with $\boldsymbol{\beta}$, but also the variances and covariances associated with the estimated $\boldsymbol{B}$. The analytical derivation or the simulation of the model errors, even in a frequentist paradigm, must include the variance and covariance in the $\boldsymbol{B}$ as well as the variance in the $\boldsymbol{\varepsilon}$. This is easily illustrated using a simple example.

Suppose we want to predict the value of a variable $\boldsymbol{Y}$ using measurements on another variable $\boldsymbol{X}$. Suppose also that a simple linear model is adequate in this case. The model for the whole population is:

$$\boldsymbol{Y} = \boldsymbol{\beta_0} + \boldsymbol{\beta_1}\boldsymbol{X} + \boldsymbol{\varepsilon} \tag{5.5}$$

A set of n observations of $\boldsymbol{Y}$ and $\boldsymbol{X}$ are made. From this set, estimates of $\boldsymbol{\beta_0}$ and $\boldsymbol{\beta_1}$ are made, labelled $\boldsymbol{B_0}$ and $\boldsymbol{B_1}$, respectively. The model for the sample data is:

$$\boldsymbol{Y} = \boldsymbol{B_0} + \boldsymbol{B_1}\boldsymbol{X} + \boldsymbol{e} \tag{5.6}$$

The estimates $\mathbf{B_0}$ and $\mathbf{B_1}$ are calculated from the data. The variance of a prediction (mean value) is then given by the following equation (Draper and Smith, 1998):

$$VAR\left(\bar{Y}_0\right) = S^2\left\{\frac{1}{n} + \frac{\left(X_0 - \bar{X}\right)^2}{\Sigma\left(X_i - \bar{X}\right)^2}\right\} \tag{5.7}$$

At the mean value of X (i.e.$\bar{X}$), the variance of prediction is minimized at a value of S^2/n. The last term in Eqn 5.7 gets larger the further away the prediction is from the mean of the predictor variable. This explains the double funnel shape for the prediction error of any linear models (Draper and Smith, 1998). Equation 5.7 applies only to simple (single predictor) linear regression models. A general equation is available for the prediction (mean values) of any linear model:

$$VAR\ (\bar{Y}_0) = \mathbf{X_0^T}\ (\mathbf{X^TX})^{-1}\mathbf{X_0}\sigma^2 \tag{5.8}$$

Where $\mathbf{X_0}$ is a $p \times 1$ vector with the values of the regressor variables; $\mathbf{X}$ is an $n \times p$ matrix with the values of the p regressor variables for all n observations; and σ^2 is the residual variance.

In Eqn 5.8, $(\mathbf{X^TX})^{-1}$is a $p \times p$ matrix containing the variance of $\mathbf{B}$ on the diagonal, and their covariances on the off-diagonals. Unless the design matrix $\mathbf{X}$ has a unique structure (orthogonal), the elements of $\mathbf{B}$ are correlated.

The variance of an individual observation in a linear model is calculated as:

$$VAR\ (Y_0) = \mathbf{X_0^T}\ (\mathbf{X^TX})^{-1}\mathbf{X_0}\sigma^2 + \sigma^2 \tag{5.9}$$

In Eqn 5.9, the first term on the left-hand side represents the variance due to the $\boldsymbol{B}$, whereas the second term represents the variance due to the residual error. The covariances in the first term can be made equal to zero by the selection of an orthogonal design (Mead and Pike, 1975). This is useful when an experiment is specifically designed for model parameterization.

The Bayesian view is different from the frequentist view, in that the $\boldsymbol{\beta}$ are explicitly considered random parameters. Bayesian statistics allow the calculation of the posterior distribution of the $\boldsymbol{\beta}$ from a prior distribution coupled with a set of observations. In the Bayesian framework, the stochasticity of the parameters is implicit. The frequentist approach that we just described is in fact equivalent to a Bayesian approach with a non-informative prior distribution (i.e. all values of the parameters are equally likely). In this instance, the posterior distribution is entirely determined by the observations (data). In Bayesian statistics, the posterior is nothing more than a conditional distribution for the parameters given the data. In a frequentist framework, it is because the parameters have to be estimated from data that we must account for the uncertainty and the distribution of these parameter estimates when simulating data. In a Bayesian framework, parameters themselves have a distribution. Consequently, any simulation of the model must therefore include their distributional properties.

The third source of stochasticity in Eqn 5.4 comes from the errors in the predictors (or input variables) $\boldsymbol{X}$. This source of errors can usually be modelled using the Monte Carlo technique (Fishman, 1978). As an example, the NRC (2001) model of dairy cattle calculates the net energy for lactation (NE_L) of feedstuffs based on their chemical composition in dry matter, crude protein, neutral detergent fibre, lignin, ether extracts, ash, neutral detergent insoluble protein and acid detergent insoluble protein. The chemical composition of a given feedstuff does vary. Knowing the variances and covariances among the chemical elements of a given feedstuff allows the estimation of the distribution of NE_L in that feed. Figure 5.3 shows the frequency distribution of NE_L concentration for two feeds commonly used in dairy cattle feeding: soybean meal and distiller's dried grains with solubles (DDGS). It is obvious that the biggest difference between the energy concentration of soybean meal and DDGS is not in their mean energy contents, which are nearly identical, but in the variability of their actual energy content. Based on energy, a deterministic approach would conclude that animal performance should be equal regardless of which one of the two sources is used. From a stochastic viewpoint, one would expect animal performance to be much more variable with DDGS than with soybean meal-based diets.

The last source of error entering Eqn 5.4 is the error in the functional form. Regardless of whether the model is a simple linear regression or a complex set of differential equations, models are always simplifications of the true but very complex world that is being investigated. For any given phenomena or system being modelled, there exists a nearly infinite set of possible functional forms

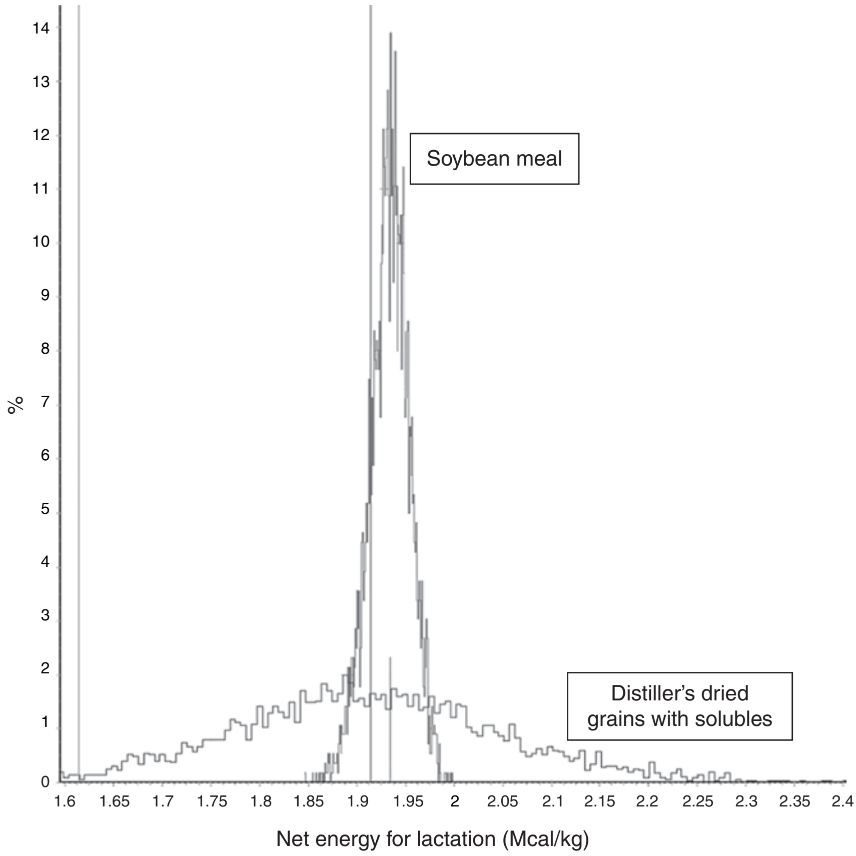


Fig. 5.3. Frequency distribution of net energy for lactation (NE_L) concentration of soybean meal and distiller's dried grains with solubles based on a Monte Carlo simulation. (From Table 15–1 of NRC, 2001.)

to choose from. For example, there are many functional forms that can be used to model the S-shaped curve generally associated with the growth of animals. The logistic, Gompertz, Richards and Normal cumulative distribution functions have all been used to model animal growth, and in many instances equally well. These functions, however, have very different properties (first derivative, point of inflection, etc.). Thus, the choice of a particular function, which frequently is arbitrary, results in vastly different inferred properties and implications even in instances where alternate models fit data equally well (St-Pierre *et al.*, 1987).

Sensitivity Analysis of Stochastic Models

Sensitivity analysis is used for the identification of important model elements. Historically, univariate sensitivity (UnS) analysis has been the dominant method used. In a UnS approach, all variables are set at a given (control) value except one that is iteratively varied from its minimum to its maximum. Sensitivity is generally expressed as dY/dX_i, although it is truly an approximation to a partial derivative (i.e. $\delta Y/\delta X_i$). This procedure was used by St-Pierre and Cobanov (2007) for the analysis of a complex stochastic model of quality costs in forage storage and feeding to dairy cattle. The model consists of 13 input variables and 3 design variables that characterize the optimum sampling design for forage in dairy production. The sampling design identifies the optimal sampling interval (*h*), number of samples to be taken (*n*) and level of change in nutrient analysis (expressed in standard deviations) before the process is considered out of control (*L*). Figure 5.4 shows the outcome of a UnS analysis for herd size, expressed as number of cows (N_c). Of the three design variables, only h appears to be sensitive to N_c. However, one must be very careful in the interpretation of these results because all variables are maintained constant, while N_c is varied. In the real system, it is very likely that input variables are correlated. In addition, parameter estimates to the model are generally highly correlated. The conventional UnS analysis ignores this important aspect of stochastic models and can lead to erroneous conclusions.

Global linear sensitivity analysis (Saltelli *et al.*, 2004) and non-linear sensitivity

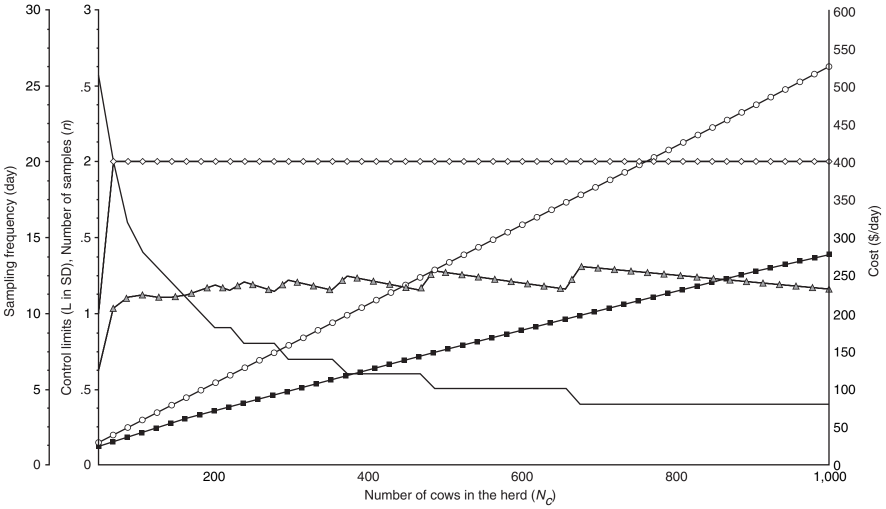


Fig. 5.4. Effect of number of cows in the herd (N_c) on optimal sampling design and total quality cost per day. – = the sampling frequency (*h*) in days; ▲ = number of standard deviations used as control limits of the *X*-bar chart (*L*); ◊ = number of samples taken (*n*); ■ = the total daily quality cost (*C*); and o = the total daily quality cost from current sampling design in the dairy industry (*h* = 30 days, *n* = 1, *L* = 2 SD).

analysis (Saltelli *et al.*, 2000, 2004) provide a much more accurate assessment of sensitivity to model inputs or parameter estimates. While UnS analysis assesses sensitivity in only one dimension, global sensitivity (GS) analysis offers a measure of sensitivity that is multi-dimensionally averaged, meaning that GS coefficients provide a measure of variance contribution for an input variable X_i that is averaged over all possible values of the remaining variables $X_{j\neq i}$. One such GS method that has gained wide acceptance is the Fourrier amplitude sensitivity test (FAST). Software to implement FAST is now available and relatively easy to implement (Saltelli *et al.*, 2004; Giglioli and Saltelli, 2013). For the total quality cost model of forage, the FAST analysis showed that 55.9% of total cost sensitivity is attributable to N_c, whereas 19.1% of sampling interval sensitivity is linked to N_c. This is because 85.0% of the cost sensitivity to N_c is linear compared to only 20.2% for sampling interval.

Model Validation

Model validation is as much an issue with stochastic models as with deterministic ones. However, the conceptual framework is vastly different. In the deterministic realm, model outcomes are fixed and errorless. Differences between observed and predicted values are entirely due to errors in the observations. In the stochastic realm, both observations and model predictions contain errors. The validation of such models is really an attempt at answering the question: are model outcomes from a system similar to those from physical observations. This is a concept similar to that of inter-observer agreement. Observations and predictions play a symmetrical role because they are both transformations of other (hidden) variables. That is:

$$\boldsymbol{O} = f_1(X_1, X_2, \ldots, X_i; \phi_1, \phi_2, \ldots, \phi_k)$$
$$\boldsymbol{P} = f_2(Z_1, Z_2, \ldots, Z_j; \gamma_1, \gamma_2, \ldots, \gamma_m) \quad (5.10)$$

Where $\boldsymbol{O}$ is a vector of observed values; $\boldsymbol{P}$ is a vector of predicted values; f_1 and f_2 are some unknown functions; X_i are variables affecting observations; ϕ_k are unknown parameters to function f_1; Z_j are variables affecting model predictions; and γ_m are unknown parameters to function f_2.

Ultimately, deciding which method (i.e. observations vs model) to call $\boldsymbol{O}$ and $\boldsymbol{P}$ should be totally incidental. The conclusion being reached regarding the two systems should be totally invariant to what system constitutes the observations and which system is deemed the predictor. That is, we should reach the same conclusion regardless of whether we ask 'Are the predictions close to the observations?' or 'Are the observations close to the predictions?'

Validation methods for stochastic models can be classified into three groups: deviance analysis, concordance analysis, and linear functional relationship.

Deviance Analysis

The expectation of the square of the difference between two random variables Y_1 and Y_2 is (van Belle, 2002):

$$E\,(Y_1 - Y_2)^2 = (\mu_1 - \mu_2)^2 + (\sigma_1 - \sigma_2)^2 + 2\,(1 - \rho)\sigma_1\sigma_2 \quad (5.11)$$

Where E stands for the mathematical expectation; μ_1 is the mean of the i^{th} variable; σ_2 is the standard deviation of the i^{th} variable; and ρ is the correlation between the two variables.

If the two variables agreed perfectly, then they would fall perfectly on a 45° line through the origin. The average of the square of the distances of each pair from the 45° line is equal to $2E\,(Y_1 - Y_2)^2$. Thus Eqn 5.11 offers potential to assess the agreement between two random variables such as observed values and output from a stochastic model. Equation 5.11 can be rewritten as:

$$\frac{E(Y_1 - Y_2)^2}{2\sigma_1\sigma_2} = \frac{(\mu_1 - \mu_2)^2}{2\sigma_1\sigma_2} + \frac{(\sigma_1 - \sigma_2)^2}{2\sigma_1\sigma_2} + (1 - \rho) \quad (5.12)$$

In Eqn 5.12, the left-hand side is known as the deviance, and the three terms on the right-hand side are known as bias, scale difference and imprecision, respectively. We can easily deduce that for the deviance to be equal to zero all three terms on the right-hand side must be equal to zero. This occurs when there is no bias (i.e. the two means μ_1 and μ_2 are equal), no scale difference (i.e. the standard deviations σ_1 and σ_2 are equal) and no imprecision (i.e. the correlation ρ is equal to 1). The deviance is an omnibus statistic. The contributions to the sample deviance can be tested formally in analysis of variance fashion with partitioning of the sum of squares at the total level (van Belle, 2002).

Concordance analysis

We first define a location shift *u* as follows:

$$u = \frac{(\mu_1 - \mu_2)}{2\sigma_1\sigma_2} \tag{5.13}$$

Likewise, a scale shift *v* is defined as:

$$v = \frac{(\sigma_1 - \sigma_2)}{2\sigma_1\sigma_2} \tag{5.14}$$

Lin (1989) used these quantities to identify a measure of accuracy as:

$$\text{Accuracy} = \frac{1}{1 + \frac{(\mu_1 - \mu_2)^2}{2\sigma_1\sigma_2} + \frac{(\sigma_1 - \sigma_2)^2}{2\sigma_1\sigma_2}} \tag{5.15}$$

Accuracy thus defined is a quantity that varies between 0 and 1, with a value of 1 when the location shift and scale shift are 0. The precision is simply stated as the correlation coefficient, ρ. Lin (1989) defined the concordance coefficient ρ^c as:

$$\rho^c = \text{accuracy} \times \text{precision} \tag{5.16}$$

The concordance coefficient is equal to 1 when there is no location differential, no scale differential and perfect correlation between two variables. The concordance coefficient ρ^c is a unit-free, omnibus statistic. Its unit-free property is both an asset and a liability. The scale used to express Y_1 and Y_2 (e.g. grammes vs kilogrammes) has no effect on the statistic – this is good. But as with the correlation coefficient, there is no direct relationship between the value of ρ^c and the size of the average error between Y_1 and Y_2. Thus, we can conclude that two variables are concordant, but we can't express the error of using Y_2 in place of Y_1 in an absolute or even relative scale.

Linear functional relationship

First, we must change our notation so as to simplify our notation later on. Instead of using Y_1 and Y_2 to represent the two random variables, we now annotate them as *X* and *Y*, understanding that we are not making any reference to a dependent and an independent variable. The linear relationship between the two random variables can be modelled as follows (Casella and Berger, 1990):

$$\begin{aligned} X_i &= \xi_i + \delta_i \\ Y_i &= \eta_i + \varepsilon_i \quad i = 1, \ldots, n \\ \eta_i &= \phi + \beta\xi_i \end{aligned} \tag{5.17}$$

Where X_i and Y_i are measurements by the two methods; ξ_i and η_i are the unobserved true values of X_i and Y_i; and δ_i and ε_i are measurement errors.

The measurement errors are generally considered bivariate Gaussian, uncorrelated, with variance σ_δ^2 and σ_ε^2, respectively. Thus, the precision ratio $\lambda = \sigma_\delta^2 / \sigma_\varepsilon^2$ compares the relative efficiency in terms of precision. If the stochastic model has the same precision as the measurements (i.e. $\lambda = 1$), then the maximum likelihood estimate (MLE) of β in Eqn 5.17 is:

$$\hat{\beta} = \frac{S_{yy} - S_{xx} + \sqrt{\left(S_{yy} - S_{xx}\right)^2 + 4S_{xx}^2}}{2S_{xy}} \tag{5.18}$$

Where $S_{xx} = \Sigma\,(X_i - \mathrm{X})^2$; $S_{yy} = \Sigma\,(Y_i - \mathrm{Y})^2$; $S_{xy} = \Sigma\,(X_i - \mathrm{X})\,(\mathrm{Y}_i - \mathrm{Y})$.

This is also known as orthogonal least-squares (Tan and Iglewicz, 1999). If the precision of the two methods is not the same (i.e. $\lambda \neq 1$), then the MLE becomes:

$$\hat{\beta} = \frac{S_{yy} - \lambda S_{xx} + \sqrt{\left(S_{yy} - \lambda S_{xx}\right)^2 + 4\lambda S_{xx}^2}}{2S_{xy}} \tag{5.19}$$

Tan and Iglewicz (1999) showed that confidence intervals on β can be constructed by transforming parameters to polar coordinates:

$$\beta = \tan\theta, \text{ and } \theta = \arctan\beta$$

$$\phi = \tau/\cos\theta, \text{ and } \tau = \operatorname{sgn}(\beta)\,\alpha/(1+\beta^2)^{1/2} \quad (5.20)$$

Using Eqn 5.20, practical equivalence can be tested as:

$$H_o: \theta \le \theta_o - \psi_1 \text{ or } \theta \ge \theta_0 + \psi_2 \text{ vs}$$

$$H_A: \theta_o - \psi_1 \le \theta \le \theta_o + \psi_2 \quad (5.21)$$

This is in contrast to a test of equivalence, which would translate to the following hypotheses:

$$H_o: \theta = \theta_o \text{ vs}$$

$$H_A: \theta \ne \theta_o. \quad (5.22)$$

Tan and Iglewicz (1999) showed that Eqn 5.21 is the right set of hypotheses and not Eqn 5.22. In this structure, practical equivalency forms the alternate hypothesis, whereas non-equivalency forms the null hypothesis. Thus we will conclude that the outcomes of the stochastic model are not equivalent to the outcomes of the real system (the measurements) unless we can show that the two are within ψ_1 and ψ_2 in the polar system. Because tan(45°) = 1 and arctan(1) = 45°, and that the 45° slope would indicate perfect correspondence between the two methods Eqn 5.21 has an inherent intuitive interpretation.

The linear functional relationship approach is appealing because the hypothesis being tested is not one of equivalence but one of practical equivalence. For example, practical equivalence could be stated for slope as $\pi/4 - \psi < \theta < \pi/4 + \psi$, with ψ determined before the validation based on the intended usage of the model. For example, one could use $\psi = \pi/30$, which roughly corresponds to $0.8 < \beta < 1.25$.

Much work is needed in the area of stochastic model validation to compare the methods outlined previously.

Conclusions

Stochasticity is an inherent characteristic of biological models in the same way that errors and probability distributions are inherent characteristics of experiments. Although more complex in their formulation and calibration than deterministic models, stochastic models capture the inherent uncertainty characteristics of biological systems. If stochastic effects are present in the system being studied, one cannot understand the true system dynamics using a deterministic framework. One cannot simply fit a deterministic model to available experimental data and then use the inferred rate constants in a stochastic simulation.

References

Casella, G. and Berger, R.L. (1990) *Statistical Inference*. Wadsworth, Pacific Grove, California, USA.

Draper, N.R. and Smith, H. (1998) *Applied Regression Analysis*. Wiley, New York.

Fishman, G.S. (1978) *Principles of Discrete Event Simulation*. Wiley, New York.

France, J. and Thornley, J.H.M. (1984) *Mathematical Models in Agriculture*. Butterworth, London.

Gibson, G.J. and Renshaw, E. (1998) Estimating parameters in stochastic compartmental models using Markov chain methods. *IMA Journal of Mathematical and Applied Medical Biology* 15, 19–40.

Giglioli, N. and Saltelli, A. (2013) *Simlab 1.1. Software for Sensitivity and Uncertainty Analysis*. Joint Research Center, European Commission, Institute for Systems Informatics and Safety. Available at: http://simlab.jrc.ec.europa.eu (accessed 30 April 2013).

Lin, L. (1989) A concordance correlation coefficient to evaluate reproducibility. *Biometrics* 45, 255–268.

Mead, R. and Pike, D.J. (1975) A review of response surface methodology from a biometric viewpoint. *Biometrics* 31, 803–851.

National Research Council (NRC) (2001) *Nutrient Requirements of Dairy Cattle*. National Academy Press, Washington, DC.

Saltelli, A., Chan, K. and Scott, M. (2000) *Sensitivity Analysis*. Wiley, New York.

Saltelli, A., Tarantola, S., Campolongo, F. and Ratto, M. (2004) *Sensitivity Analysis in Practice: a Guide to Assessing Scientific Models*. Wiley, New York.

St-Pierre, N.R. (2001) Reassessment of biases in predicting nitrogen flows to the duodenum by NRC 2001. *Journal of Dairy Science* 86, 344–350.

St-Pierre, N.R. and Cobanov, B. (2007) Optimal sampling schedule of diet components: model derivation and sensitivity analysis. *Journal of Dairy Science* 90, 5383–5394.

St-Pierre, N.R., Thraen, C.S. and Harvey, W.R. (1987) Minimum cost nutrient requirements from a growth response function. *Journal of Animal Science* 64, 312–327.

Tan, C.Y. and Iglewicz, B. (1999) Measurement-methods comparisons and linear statistical relationship. *Technometrics* 41, 192–201.

van Belle, G. (2002*) Statistical Rules of Thumb*. Wiley, New York.

Wilkinson, D.J.W. (2006) *Stochastic Modelling for Systems Biology*. CRC Press, Boca Raton, Florida, USA.

Yeargers, K.E., Shonkwiller, R.W. and Herod, J.V. (1996) *An Introduction to the Mathematics of Biology*. Birkhauser, Boston, Massachusetts, USA.

6 Basics and Applications of an Exponential Nitrogen Utilization Model (‘Goettingen Approach’) for Assessing Amino Acid Requirements in Growing Pigs and Meat Type Chickens Based on Dietary Amino Acid Efficiency

F. Liebert*
Georg-August-University Goettingen, Goettingen, Germany

Abstract
Validated protein evaluation systems are required for improved efficiency of protein conversion processes in food producing animals. Up to now, different procedures have been developed to connect feed protein evaluation based on the value of individual amino acids and estimates of the individual amino acid requirement. An exponential function for the relationship between intake of the limiting amino acid in the diet and observed response on nitrogen deposition in the body is utilized within the ‘Goettingen approach’. This approach has the potential to model the process of converting feed into food protein by taking into account an efficiency-based optimized dietary amino acid supply at a desired level of performance within the estimated threshold value of genetic potential for growth. This chapter provides an overview of the basics and current applications of the procedure. Finally, the results are applied to give conclusions about the ideal dietary amino acid ratio for growing pigs and growing chickens. An important factor that may impact both on the derived requirements and the resultant ideal dietary ratios is the variation of amino acid efficiency in feed. This factor has not been systematically investigated.

Introduction

Evaluation of feed protein quality is, today, a ‘must have’ for modern farming systems and a precondition to fulfill actual needs both for resource management and sustainability of processes to convert feed to food protein for human nutrition. Several generations of nutrition scientists created concepts to improve the basic knowledge about utilization processes in the ‘black box’ of food producing animals and in human beings. As a consequence, based on nitrogen (N) balance studies, fundamental concepts were developed to provide comparable information about the protein value of individual feedstuffs or diets. Parameters like net protein utilization (NPU) according to Block and Mitchell (1946) or biological value (BV) as applied by Mitchell (1924) yielded first

---

*E-mail: flieber@gwdg.de

© CAB International 2015. *Nutritional Modelling for Pigs and Poultry*
(eds N.K. Sakomura *et al.*)

indications about the efficacy of protein utilization processes as a whole (NPU) or limited to post-absorptive utilization (BV). The latter was achieved by relating N retention data to the uptake of truly digested feed protein. In addition, measurement of the balance of the gastrointestinal tract (GIT) as a parameter of nutrient digestibility provided additional information about nutrient efficiency at the absorption level.

In principle, this was the situation when the basic concept for the 'Goettingen approach' was developed by Gebhardt (1966) in the last century, based on N balance experiments with the laboratory rat. A significant background for this research was the observed limitation for applying traditional procedures to describe the complex protein value of individual feedstuffs or protein mixtures independent of the actual level of dietary protein supply. Similar problems with protein evaluation systems for human nutrition were an additional driving force at this time. Consequently, first developments of the basic approach of Gebhardt (1966) were focused on standardization of individual protein values to improve comparability of feed protein sources. This application is still in use but is currently more interesting for evaluation of the complex protein value of mixed feeds. However, the field of applications for the approach was, in the meantime, significantly extended and also adapted to the current expectations of research in protein nutrition of food-producing animals. Details of these developments and applications are described subsequently. However, it will not be possible to outline in detail how the different issues of the current procedure differ from other approaches that are in use. Consequently, further descriptions will be focused on important steps of development and applications of the exponential N utilization model as basically proposed by Gebhardt (1966), but will not include a discussion as related to other procedures. Actually, studies have been initiated to provide amino acid requirement data by simultaneous applications of both supplementation technique and the Goettingen approach. However, the results are still under investigation and will be discussed below.

Exponential N Utilization Model ('Goettingen Approach')

Background for developments

The basic scenario is illustrated in Fig. 6.1, showing that the traditional procedures may evaluate a low quality feed protein at a low level of uptake as equal to a high quality

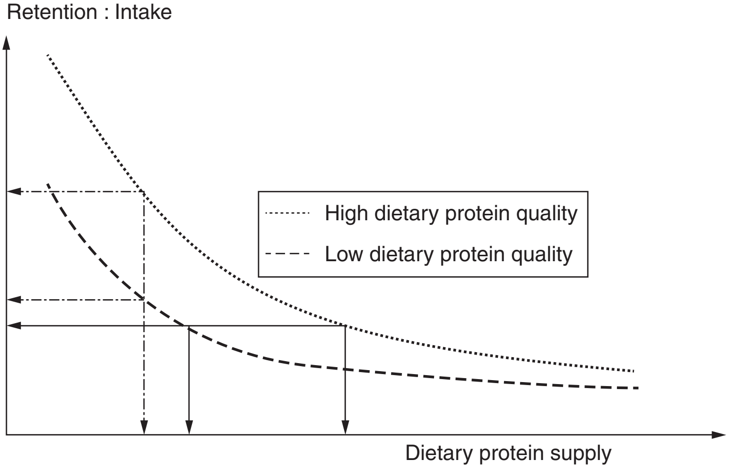


Fig. 6.1. Effect dietary protein supply on observed net protein utilization (NPU) and consequences for derived dietary protein quality depending on protein supply.

protein when given in an elevated quantity. However, this is a misleading conclusion and not in accordance with reality.

Consequently, a validated comparison of both single feed protein sources and mixed diets required a standardization of the intake level. Under such circumstances (Fig. 6.1) a clear difference between the examined protein sources was obviously achieved. In this way the application of NPU data standardized for daily N intake could improve this critical situation in developing protein evaluation parameters. However, no validated or scientifically based tools were available for such a standardized approach. Gebhardt (1966) proposed a physiologically based description of the course of body N retention, dependent on both the quantity and quality of N intake and using an exponential function conforming to biological laws of growth, as described by von Bertalanffy (1951).

Basics of the model development

In fact, the designation 'Goettingen approach' is partly misleading because the procedure had already been developed to a significant extent in the years between 1970 and 1990 at Leipzig University under the scientific leadership of Günter Gebhardt who held the post of chair of animal nutrition for 25 years.

However, during the past 15 years the Division Animal Nutrition Physiology at Goettingen University has focused on filling in gaps in the procedure for current applications in animal nutrition. Because of the great potential for applying modelling procedures in modern feed to food conversion systems with farm animals, both the evaluation of the efficacy of dietary amino acids and modelling of amino acid (AA) requirements by accounting for dietary AA efficiency were of special interest during this working period.

Model parameters used in current applications of the non-linear model are based on recent publications (Liebert *et al.*, 2000; Thong and Liebert, 2004a,b,c; Samadi and Liebert, 2006a,b, 2007a,b, 2008; Liebert and Benkendorff, 2007; Liebert, 2008, 2009; Liebert and Wecke, 2008; Wecke and Liebert, 2009, 2010, 2013) and are defined as follows:

$$NR = NR_{max}T\,(1 - e^{-NI \cdot b}) \qquad (6.1)$$

$$ND = NR_{max}T\,(1 - e^{-NI \cdot b}) - NMR \qquad (6.2)$$

Where NR = daily N retention ($ND + NMR$) in mg/$BW_{kg}^{0.67}$; ND = daily N deposition or N balance = $NI - NEX$ in mg/$BW_{kg}^{0.67}$; NI = daily N intake in mg/$BW_{kg}^{0.67}$; NEX = daily N excretion in mg/$BW_{kg}^{0.67}$; and NMR = daily N maintenance requirement in mg/$BW_{kg}^{0.67}$; $NR_{max}T$ = theoretical maximum for daily N retention in mg/$BW_{kg}^{0.67}$; $ND_{max}T = NR_{max}T - NMR$ = theoretical maximum for daily N deposition in mg/$BW_{kg}^{0.67}$; b = slope of the N retention curve (indicator of dietary protein quality; the slope of the curve for a given protein quality is independent on NI); e = basic number of natural logarithm (ln); and BW = body weight.

The attribute 'theoretical' suggests that the threshold values ($ND_{max}T$ or $NR_{max}T$) are generally not in the scope of practical performance data but estimate the genetic potential (Samadi and Liebert, 2006a). In so doing, the genetic potential is defined as an unreachable 'theoretical' threshold value. The growth potential defined in this way cannot be realized even with an optimized feeding strategy or in ideal environmental conditions. If the ranking of such a threshold value is clear, no problem exists for further model applications. Accordingly, individual AA requirement data are derived using daily protein deposition data in line with practical growth data. As a consequence, the threshold value ($ND_{max}T$ resp. $NR_{max}T$) is used only as a parameter to relate the real rate of deposition to the assumed genetic potential. An example of $ND_{max}T$ prediction in a meat type chicken is given in Fig. 6.2.

The experimental data for such a prediction result from N response experiments in which a graded protein supply is used. Generally the aim is to achieve a very high variation in the average individual daily NI by varying the dietary protein content. Physiological mechanisms set a limit for the upper range of the achievable daily NI. Force-feeding could partly extend the upper NI level, but this practice is prohibited by

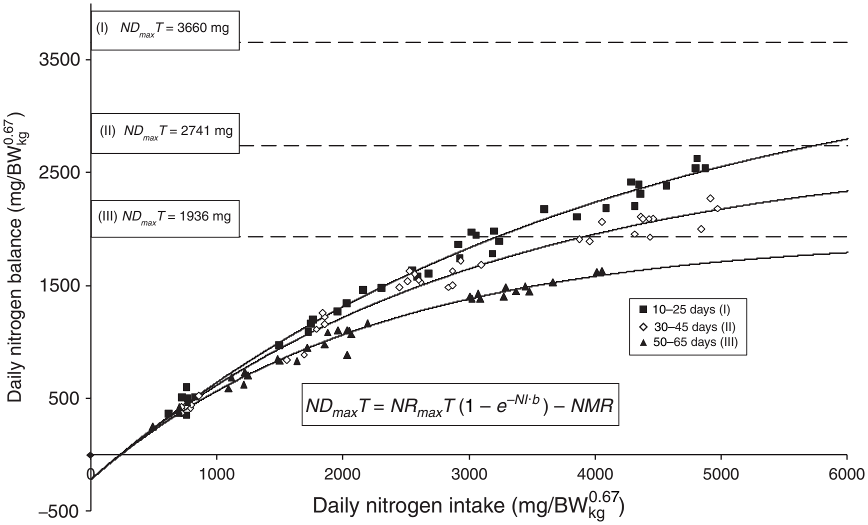


Fig. 6.2. Prediction of the $ND_{max}T$ of male meat type chickens (Ross 308) depending on age and making use of diets with graded protein supply. (From Samadi and Liebert, 2008.)

animal protection regulations. As a consequence the aim is not only to maximize dietary protein content, but in addition to achieve a high voluntary food intake. Incidentally, the diet construction for this type of N response experiment needs to fulfil a further compromise: to ensure that the response to protein utilization is not limited by other dietary factors, the energy to protein ratio should be held constant, but this is difficult to achieve. An example of diet construction is given in Tables 6.1 and 6.2 in which the difficulties in preventing a decline in the energy to protein ratio with high dietary protein contents are demonstrated. Both of the tables demonstrate that graded protein supply results in several changes in dietary nutrient composition; starch supply declines dramatically as the protein content increases and has to be compensated for by increasing fat supplementation to prevent a significant loss of energy supply in the diets.

As demonstrated in Table 6.3, this principle has also been applied in current studies with male modern genotype meat type chickens by Pastor *et al.* (2013). Diet formulation for such experiments remains a compromise between meeting the need for energy and ensuring the efficient utilization of the graded dietary protein supply. However, its success depends on both the food intake pattern and the concentration of energy in the diet.

Finally, these examples demonstrate how it could be possible to achieve a response curve to graded dietary protein supply that is not under the influence of limiting factors such as energy supply. A physiologically based control is provided in an experiment when the observed model parameter reflecting dietary protein quality independent of protein intake (b) remains unchanged. If this precondition is fulfilled, the individual N balance data can be utilized to estimate the threshold value of $NR_{max}T$ and hence $ND_{max}T$. For this estimation several iteration steps of the Levenberg-Marquardt algorithm (Moré, 1977) within the program package SPSS (19.0.0 windows) are required.

The N balance experiments of Pastor *et al.* (2013) could demonstrate no significant effect on parameter b (Table 6.4), indicating that dietary protein quality in this study was not limited by any factor other than lysine supply. Under that precondition the further application of the estimated threshold value $ND_{max}T$ is justified, and validated estimates of the theoretical potential from current investigations can be expected, as demonstrated in Fig. 6.3 (Pastor *et al.*, 2013).

Table 6.1. Analysed nutrient content of lysine limiting soybean meal–wheat gluten diets (g/kg dry matter based). (From Samadi and Liebert, 2008.)

	N1	N2	N3	N4	N5	N6
Crude protein	63.0	122	177	246	307	347
Ether extract	25.1	45.0	59.1	51.4	81.0	81.2
Crude fibre	16.0	15.4	17.3	14.4	19.2	21.0
Crude ash	55.4	60.3	63.1	66.0	71.4	73.9
N-free extract	841	757	683	622	521	477
Starch	784	698	615	542	436	348
Sugar	34.9	31.4	91.2	97.3	116	109
ME (MJ/kg)[a]	13.6	13.6	13.7	13.2	13.5	13.3

[a] Calculated, based on WPSA (1984).

Table 6.2. Analysed nutrient content of threonine limiting soybean meal diets (g/kg dry matter based). (From Samadi and Liebert, 2008.)

	N7	N8	N9	N10	N11	N12
Crude protein	59.1	128	192	252	314	362
Ether extract	22.2	45.1	67.0	88.3	116	139
Crude fibre	18.0	16.2	15.4	19.0	30.1	27.4
Crude ash	52.1	63.0	69.4	81.4	83.9	90.8
N-free extract	849	748	656	559	456	381
Starch	785	668	556	428	283	144
Sugar	15.2	15.4	24.0	41.3	61.0	57.1
ME (MJ/kg)[a]	13.3	13.2	13.1	13.1	13.0	13.0

[a] Calculated, based on WPSA (1984).

The model parameter for the theoretical genetic potential can be seen to be under the influence of the genetic progress in poultry breeding, as indicated by an elevated potential for $ND_{max}T$ when the current genotype (Fig. 6.3) is compared to an older one (Fig. 6.2).

However, prior to estimation of the threshold value $ND_{max}T$ it is recommended that the daily N maintenance requirement (*NMR*) is estimated, making use of the relationship between N intake (*NI*) and total N excretion (*NEX*). Within our model applications the resultant *NMR* is not utilized as a real maintenance requirement but is understood to be a part of the total N retention ($NR = ND + NMR$) indicating that $ND > 0$ requires the replacement of endogenous losses via faeces and urine, respectively. Accordingly, the influence of dietary factors on estimated *NMR* cannot be excluded completely. Both the N digestibility of the basal diet and the protein quality resulting from the dietary AA balance may influence the estimate of *NEX* as derived by breakpoint analysis with the *y*-axis (Fig. 6.4). Within our modelling procedure, *NMR* data are not utilized to derive maintenance requirements, but by providing a fixed point on the *NR*-curve (breakpoint with *y*-axis, *NMR*) the iterative process when using the Levenberg-Marquardt algorithm is facilitated.

Similar applications to yield model parameters for further requirement studies have been conducted in growing pigs as a function of age. An example of these experiments is summarized in Table 6.5.

Current Applications

Amino acid requirements based on dietary amino acid efficiency

As indicated from selected experiments (Tables 6.1–6.4), in addition to both the

Table 6.3. Diet composition and analysed nutrients of the experimental diets (g/kg as fed basis) with lysine in limiting position. (From Experiment 1, starter period, Pastor *et al.*, 2013.)

Ingredient	N1	N2	N3	N4	N5	N6	N7	N8
Wheat starch	794	691	587	484	308	205	103	0.00
Wheat	72.4	121	169	217	265	314	362	410
SPC	61.8	103	144	185	226	268	309	350
Wheat gluten	10.5	17.4	24.4	31.4	38.4	45.3	52.3	59.3
Fish meal	6.43	10.7	15.0	19.3	23.6	27.9	32.2	36.4
DCP	28.5	26.0	23.5	21.0	18.5	16.0	13.5	11.0
Soybean oil	10.0	13.5	17.0	20.3	97.0	99.5	103	105
Premix	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
NaCl	2.50	2.50	2.50	2.40	2.30	2.20	2.10	2.06
$CaCO_3$	2.30	3.20	4.00	4.70	5.70	6.50	7.20	8.00
DL-Met	0.90	1.51	2.11	2.71	3.32	3.92	4.52	5.12
L-Val	0.30	0.50	0.70	0.89	1.09	1.29	1.49	1.69
L-Thr	0.18	0.29	0.41	0.53	0.65	0.76	0.88	1.00
L-Trp	0.01	0.02	0.02	0.03	0.04	0.05	0.05	0.06
Analysed (g/kg DM)								
Crude ash	5.03	5.30	5.55	5.78	6.01	6.26	6.51	6.77
Crude protein	6.46	10.8	15.2	19.7	24.1	28.6	33.2	37.8
Crude fat	1.43	1.99	2.56	3.11	11.6	12.1	12.7	13.3
Crude fibre	0.79	1.04	1.29	1.55	1.76	2.03	2.28	2.55
Starch	74.5	69.2	64.0	58.7	46.5	41.2	35.7	30.2
ME (MJ/kg DM)1	14.18	14.18	14.18	14.18	15.74	15.74	15.74	15.74

[a] Calculated, based on WPSA (1984).

Table 6.4. Summarized results of protein quality assessment of lysine limiting chicken diets with graded dietary protein supply. (From Experiment 1, starter and grower period, Pastor *et al.*, 2013.)

Diet	N1	N2	N3	N4	N5	N6	N7	N8
Starter period								
b-value ($b \cdot 10^{-6}$)	196	–[a]	219	213	200	192	203	204
Grower period								
b-value ($b \cdot 10^{-6}$)	197	197	196	198	195	202	206	187

[a] Not detectable, outliers due to feed refusal.

estimation of model parameters ($ND_{max}T$, NMR) and the evaluation of dietary protein quality (parameter *b*), results of these N response experiments are also useful in extending the database of AA requirement studies. For these applications, a valid definition of the limiting AA in the diet under study is a prerequisite.

In this case, the shape of the *NR*-curve is not only a function of *NI*, but also of the daily intake of the limiting AA (*LAAI*) as a part of the feed protein fraction. For that important application, Eqn 6.1 is logarithmically transformed (natural logarithm, ln), providing Eqns 6.3 and 6.4, respectively:

$$NI = [\ln NR_{max}T - \ln(NR_{max}T - NR)]:b \tag{6.3}$$

$$b = [\ln NR_{max}T - \ln(NR_{max}T - NR)]:NI \tag{6.4}$$

The model parameters $NR_{max}T$ and *NMR* for the genotype and the observed data for *NR* are used to calculate *NI* and *b*, respectively. The derived *NI* (Eqn 6.3) gives the daily quantity of dietary protein (in terms of *NI* as defined above) needed to yield the intended level of growth performance (in terms of *NR*, as defined above) at a given or observed dietary protein quality (in terms of

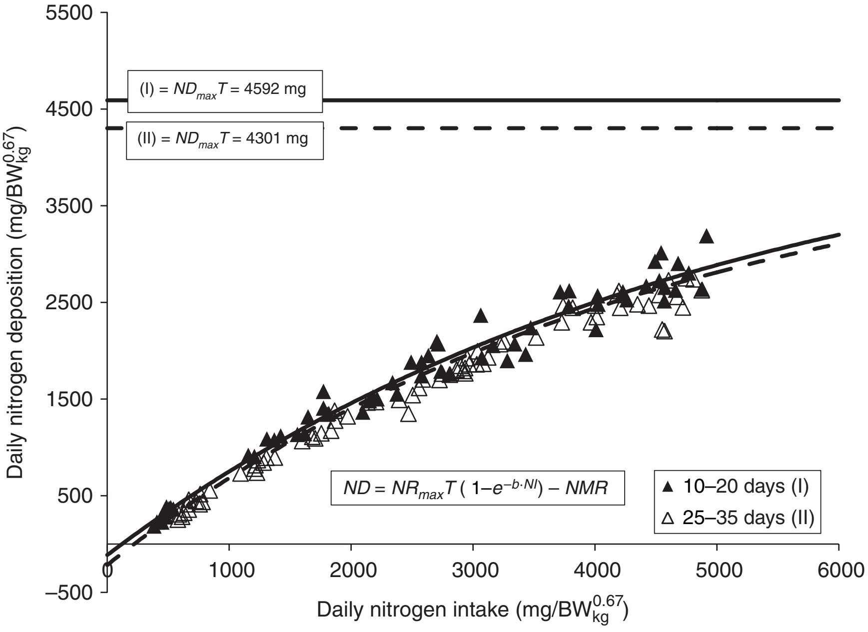


Fig. 6.3. Prediction of the $ND_{max}T$ of male meat type chickens (Ross 308) depending on age and making use of diets with graded protein supply. (From Pastor *et al.*, 2013.)

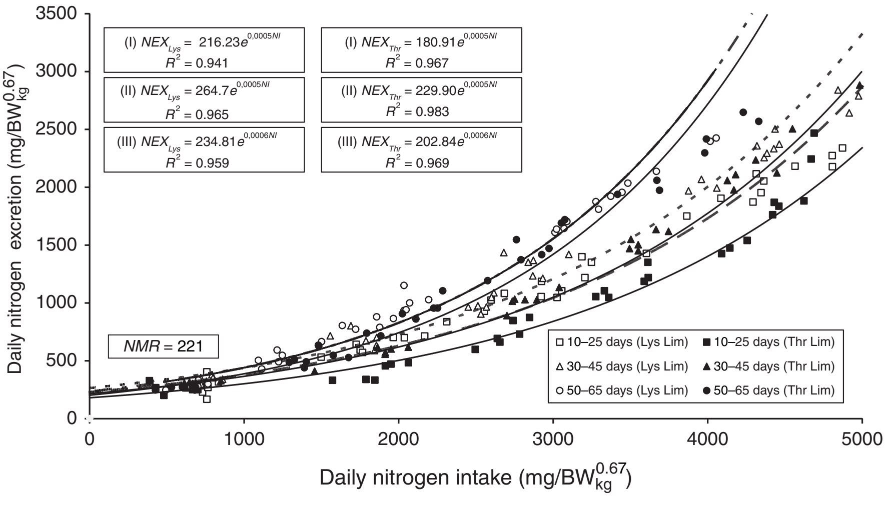


Fig. 6.4. Prediction of the *NMR* of male meat type chicken (Ross 308) depending on age period making use of diets with graded protein supply and observed N excretion. (From Samadi and Liebert, 2008.)

model parameter *b*, as defined above). The *NI* required for any given *NR* can thus be calculated and thus table values of requirement data may be constructed and justified due to the independence of protein quality (*b*) from the observed *NI*. However, this application is much more important for AA requirement tables, as will be discussed below. The model parameter *b* (protein quality) can be calculated using Eqn 6.4 taking into account observed *NI* and corresponding *NR* data, respectively. For quantification of

Table 6.5. Observed model parameters (NMR, $NR_{max}T$) for modern genotype growing barrows depending on BW. (From Wecke and Liebert, 2009.)

Body weight (kg)[a]	NMR[b] (mg/$BW_{kg}^{0.67}$)	$NR_{max}T$[b,c] (mg/$BW_{kg}^{0.67}$)
31.9	424	4124
51.6	399	3365
75.5	368	2732
95.4	342	2352
113.8	318	2067

[a] Mean BW of the pigs during experimental periods.
[b] NMR (mg/$BW_{kg}^{0.67}$) = –1.2863 × BW (kg) + 464.78.
[c] $NR_{max}T$ (mg/$BW_{kg}^{0.67}$) = –1619.3 × ln BW (kg) + 9733.6.

the animal's response (ND, NR) generally N balance or N deposition data from body analyses are useful. However, factors influencing each of the above procedures may yield differing results for N balance and N deposition, respectively. This fact is well known among scientists working in this field, but a solution to the problem has not as yet been found. This problem is not specifically related to the 'Goettingen approach' and consequently it will not be discussed further. To eliminate possible effects of such discrepancies between procedures when quantifying ND, only applications in growing chickens and fattening pigs utilizing N balance studies will be presented below.

Equations 6.1–6.4 have demonstrated earlier model applications where the main focus was on questions of complex protein evaluation and where the AA composition of the feed protein was not of top priority. When the emphasis of the model changes to AA-based applications a further important transformation is required: the function needs to be adapted because the independent variable determining the resultant dietary protein quality (b) is the concentration of the limiting AA in the dietary protein (c). This fundamental connection, already discussed above, needs to be 'translated' into the traditional model applications.

The 'key-translator' to provide this precondition is Eqn 6.5, in which the daily intake of the LAA from NI and dietary concentration of the LAA in the feed protein is calculated:

$$LAAI = (NI \cdot 16):c \qquad (6.5)$$

Where $LAAI$ = daily intake of the LAA in mg/$BW_{kg}^{0.67}$; c = concentration of the LAA in the feed protein in g/16g N; and NI = according to Eqn 6.2.

$$NR = NR_{max}T\,(1 - e^{-LAAI \cdot 16 \cdot b:c}) \qquad (6.6)$$

Where b:c (= bc^{-1}) = observed dietary efficiency of the LAA; $LAAI$ = according to Eqn 6.5; NR = according to Eqn 6.2.

Logarithmic transformation of Eqn 6.6, according to the mathematical treatment of Eqn 6.1 as earlier described, yields the basic Eqn 6.7, which is generally applied for assessing quantitative AA requirements. An important precondition is that experimental data are available that describe the NR response to a defined intake of limiting AA ($LAAI$) at a defined dietary efficiency of the LAA (bc^{-1}):

$$LAAI = [\ln NR_{max}T - \ln(NR_{max}T - NR)]: 16bc^{-1} \qquad (6.7)$$

As pointed out with Eqn 6.3 this application, which makes use of increasing performance over a desired range of NR, is of great interest for tabulating individual AA requirements. Consequently, it is crucial to plot the desired range as a percentage of $NR_{max}T$ (or $ND_{max}T$) and to utilize the absolute daily deposition data for further model calculation of AA requirements taking into account the dietary AA efficiency. An extended example of this application for growing fattening pigs is summarized in Table 6.6, which also shows that the dietary efficiency of the AA under study can be modulated. Therefore, an observed value for the dietary AA efficiency could be increased or lowered but also gradually changed (Table 6.6) to express the implications on derived AA requirements.

Equation 6.7 makes it possible to derive requirement data for individual AAs under the precondition that their efficiency (bc^{-1}) was measured and validated in a limiting position of the protein under study. The question arises as to how this validation could be achieved. In the case of lysine-, methionine- or threonine-limiting diets, based on knowledge of their quantitative and

Table 6.6. Derived lysine requirement data for modern genotype growing barrows depending on BW, aimed percentage of $ND_{max}T$ and graded dietary lysine efficiency. (From Wecke and Liebert, 2009.)

Percentage of $ND_{max}T$[b]		55			65			75		
					Dietary Lys efficiency (EL)[a]					
BW (kg)		EL1	EL2	EL3	EL1	EL2	EL3	EL1	EL2	EL3
30	PD, g/day	128	128	128	151	151	151	174	174	174
	$bc^{-1} \cdot 10^6$	48.6	43.8	38.9	48.6	43.8	38.9	48.6	43.8	38.9
	Lys, g/day	11.4	12.7	14.3	14.6	16.2	18.2	18.8	20.8	23.4
50	PD, g/day	142	142	142	168	168	168	194	194	194
	$bc^{-1} \cdot 10^6$	60.5	54.4	48.4	60.5	54.4	48.4	60.5	54.4	48.4
	Lys, g/day	13.2	14.6	16.5	16.8	18.6	21.0	21.6	24.1	27.1
70	PD, g/day	147	147	147	174	174	174	200	200	200
	$bc^{-1} \cdot 10^6$	72.0	64.8	57.6	72.0	64.8	57.6	72.0	64.8	57.6
	Lys, g/day	14.1	15.6	17.6	17.9	19.9	22.4	22.8	25.3	28.5
90	PD, g/day	147	147	147	174	174	174	200	200	200
	$bc^{-1} \cdot 10^6$	84.0	75.6	67.2	84.0	75.6	67.2	23.3	35.8	29.1
	Lys, g/day	14.4	16.0	18.1	18.3	20.3	22.9	23.3	25.8	29.1
110	PD, g/day	144	144	144	170	170	170	196	196	196
	$bc^{-1} \cdot 10^6$	96.8	87.2	77.5	96.8	87.2	77.5	96.8	87.2	77.5
	Lys, g/day	14.5	16.1	18.1	18.2	20.2	22.8	23.2	25.8	29.0

[a] EL1, dietary Lys efficiency as observed; EL2, dietary Lys efficiency 10% below EL1; EL3, dietary Lys efficiency 20% below EL1.
[b] Theoretical maximum for daily ND.

relative needs, it is not difficult to ensure the individual limiting position in an experimental diet. If the limiting position is not completely certain, a single supplementation step of the AA under study can confirm that the AA is limiting. In the case of AAs where the requirements are still not well defined, this method of validating the limiting position is generally recommended.

Based on this exponential model only one increment of *LAA* in the diet is sufficient to derive AA requirements by modelling, taking into account varying levels of animal performance (*ND* resp. *NR*) by modifying the term ($NR_{max}T - NR$) in Eqn 6.7. Obviously this procedure works quite differently from dose–response studies that make use of the supplementation technique. To create a dose–response curve that can be statistically analysed to derive requirements, several graded increments within the limiting area of the AA under study are needed. In this way disadvantages may arise (Yen *et al.*, 2004) such as the gradual modification of the dietary AA balance and the mixing of both protein-bound and supplemented AA in varying ratios. Both factors may be of importance for ensuring the reliability of derived AA requirements. Nonlinear models are also applied for evaluating such supplementation studies (Gahl *et al.*, 1991, 1995) but nevertheless the noted disadvantages remain.

From model applications in fish nutrition it has been demonstrated (Fig. 6.5) that requirement curves can be calculated for individual AAs. As mentioned above, making use of the observed AA efficiency or graded levels of this parameter may yield such requirement curves, which provide at least the physiological background for deriving individual AA requirements depending both on the intended performance and the assumed or observed AA efficiency in the diet. It has to be pointed out that the efficiency of protein bound AAs is the focus of our procedure. However, diverse applications including the evaluation of supplemental AAs are possible but are more interesting when the efficiency of utilization of supplemented AAs is under scientific discussion, as is the case with aqua feeds.

Finally, a very important area of model application is the evaluation of individual AA efficiency from the viewpoint of feed science.

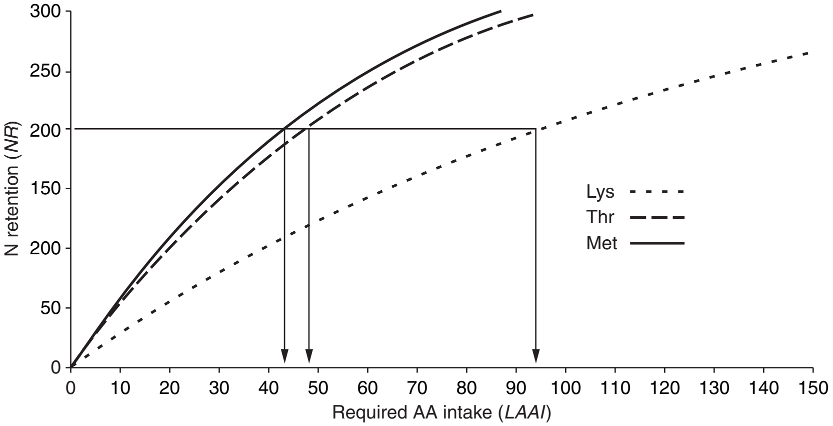


Fig. 6.5. Amino acid requirement curves for juvenile male Nile Tilapia (*Oreochromis niloticus*), *NR* and *LAAI* in terms of mg/BW$^{0.67}_{kg}$/day. (From Liebert, 2009.)

A disadvantage of our approach is that an assessment of dietary AA efficiency is only justified for the AA in the limiting position. Compared to the simultaneous measurement of ileal digestibility for several individual AAs, this restriction acts really as a disadvantage of the procedure. However, it is a physiological fact of the fundamental ‘law of the minimum’ that only the utilizable part of *LAAI* is able to respond in *ND* in the animal. Otherwise, the physiological meaning of ileal disappearance rate of individual AAs for feed evaluation is questionable. In addition, the N losses from digestive processes of food producing animals are much lower as compared to the metabolic N losses from deficiencies of post-absorptive utilization processes. When accounting for these facts the disadvantage is more apparent. In addition, evaluation of feed treatment effects on individual AA efficiency, which may include much more than effects on digestibility only (e.g. heat damaged lysine), needs special methods to reveal more complex impacts. This is an important additional field of application for AA efficiency-based investigations.

Ideal amino acid ratios (IAARs) based on dietary amino acid efficiency

In the most recent application of the ‘Goettingen approach’ we started to improve currently available procedures to derive optimal or ideal dietary AA ratios (*IAARs*). Today, most of the published *IAAR* recommendations are derived from results of quantitative AA requirement studies (supplementation technique) or from supplementation studies in which the optimal ratio of lysine to an individual AA under study is measured by adding graded levels of the test AA (Emmert and Baker, 1997). Maximal response based on varying criteria is used to indicate the *IAAR* to lysine as a reference. Such procedures are widely distributed for evaluation of ideal/optimal dietary AA ratios, but possess similar disadvantages to the supplementation technique in general. Consequently, the varying ratio between native and supplemented AA is a factor of influence that cannot be easily eliminated. Taking into account any assumed difference in ileal digestibility is not a sufficient tool.

Generally, according to our procedure, results from modelling AA requirements can also be utilized to improve the database about the *IAARs* depending on species, age, genotype, sex and other factors. Observed requirements can be related to lysine needs within species, genotype, sex and age at equal levels of desired performance.

In addition, it is also possible to obtain this information about *IAARs* directly from measured bc^{-1} data. What is the physiological meaning of the model parameter ‘AA efficiency’? In fact, it is a reflection of the quantity of AA needed to yield one unit of *ND* in the animal. This quantity depends on the content of the test AA in the body protein being synthesized. Moreover, it also indicates indirectly how the individual AA is involved in metabolic processes other than protein synthesis for protein deposition. Consequently, processes of body protein turnover are reflected by the level of bc^{-1}, but only as an undefined part of the 'black box' protein utilization. Finally, those physiological processes within the black box animal are part of the recommended requirement, but are not known in quantitative detail.

As a consequence, the slope relating dietary concentration of the *LAA* and the achieved *ND* (as described by model parameter *b*, independent of *NI*) is AA-specific too, according to individual AA functions and varying needs for synthesis of body protein. Additionally, this slope is also influenced by varying AA bioavailability in the ingredients used in the test diet. The latter factor is mostly in focus when the dietary efficiency of an AA is evaluated both for feed quality studies and for modelling AA requirements with graded dietary AA efficiency (see Table 6.6).

The question arises as to whether AA efficiency data are directly useful for deriving *IAAR*s from observed individual AA efficiency data. According to the first of our reports dealing with this application (Liebert, 2008; Samadi and Liebert, 2008) Eqn 6.8 defines the *IAAR* as derived from observed AA efficiency data making use of lysine as the reference AA:

$$IAAR = bc_{Lys}^{-1}:bc_{LAA}^{-1} \tag{6.8}$$

However, this application needs individual AA efficiency data to be provided by diet dilution. The first step is to develop an AA-balanced control diet that may be used for further individual AA dilution. Table 6.7 summarizes the results of a meta-analysis about *IAAR*s for growing chickens, which was basically utilized to create such an AA-balanced control diet (Wecke and Liebert, 2013) using crystalline AA supplementation.

In addition, before an individual AA deletion and measurement of AA efficiency is possible, the whole AA-balanced complete diet needs to be diluted with starch, and then refilled with crystalline AAs up to the former level of the balanced AA supply, except for the AA under study, which has to remain in the limiting position. In principle, the procedure has been described previously (Fisher and Morris, 1970; Gous and Morris, 1985; Wang and Fuller, 1989; Baker, 2003). A brief summary of current data from these experiments is shown in Table 6.8. Details of the diet construction and AA composition are given in the full papers (Pastor *et al.*, 2013; Wecke and Liebert, 2013).

It has to be noted that the derived *IAAR*s according to Eqn 6.8 are also a reflection of the measured AA efficiencies typical of the composition of the basal diet used to create the AA-balanced control diet as the starting point for further individual AA deletions. Consequently, it cannot be expected that the observed *IAAR*s will be constant, due to the dependency of AA efficiency on both AA absorption and post-absorptive utilization.

However, if the assumptions about the reference *IAAR*s from meta-analysis are valid, the deletion of added single crystalline AA from the refilled balanced control diet should yield a significant decline in dietary protein quality (*b*). Consequently,

Table 6.7. Summarized optimal dietary AA ratios for growing chickens as derived from meta-analysis. (From Wecke and Liebert, 2013.)

	Optimal dietary ratios for individual AA as related to Lys		
	n	Average	Standard deviation
Lysine	26	100	0
Methionine	22	40	4
Methionine + cysteine	24	74	2
Threonine	24	66	3
Tryptophan	22	16	1
Arginine	25	105	4
Histidine	12	34	4
Isoleucine	24	69	4
Valine	21	80	4
Leucine	12	110	6
Phenylalanine	8	66	3
Phenylalanine + tyrosine	9	120	7

due to this deletion the observed AA efficiency (bc^{-1}) is elevated indicating the change from an adequate or excess AA supply to a limiting supply of the individually deleted AA in the dietary protein. The value of bc^{-1} is generally not valid for further applications within the model if the individual AA efficiency is not measured under guaranteed limiting position. Otherwise the observed increase in bc^{-1} in the deleted diet alone is not sufficient for a validated limiting position. A significant decline in protein quality (model parameter *b*) needs to be observed to ensure this important limiting position of the AA under study. Misleading conclusions about *IAAR*s can be expected if this precondition for valid model application is not fulfilled.

A summary of our current results based on several N balance studies in meat type chickens, in which the ingredients used did not differ much from feeding practice, is given in Table 6.9.

As demonstrated, the observed *IAAR*s in growing chickens are not yet consistent and some earlier conclusions about *IAAR*s are not supported. This is especially the case for the branched chain AAs (BCAA), where available requirement recommendations are not sufficiently well founded. However, if the current conclusions about *IAAR*s are more valid than earlier assumptions, it should be possible to prove the response in protein utilization in the animal. Some initial studies in growing chickens have been conducted that deal with this important question. In spite of the fact that data evaluation from these experiments is still not finished, initial results indicate that the reevaluated *IAAR*s (Table 6.9) yielded elevated dietary protein quality data as compared to the average

Table 6.8. Summarized ideal dietary AA ratios (*IAAR*s) for growing chickens as derived from current studies with meat type chickens in two age periods. (From Wecke and Liebert, 2013.)

	Lysine	Threonine	Tryptophan	Arginine	Isoleucine	Valine
Starter period						
Mean[a]	100	60	19	105	55	63
Grower period						
Mean[a]	100	62	17	105	65	79

[a] Summary of three experiments.

Table 6.9. Comparison of observed *IAAR*s from N balance studies in growing meat type chicken depending on age.

		Pastor *et al*., 2013			Wecke and Liebert, 2013	
AA	Average[a]	AA-balanced diet	Starter	Grower	Starter	Grower
Lysine	100	100	100	100	100	100
Methionine	40	38				
Met+Cys	74	74				
Threonine	66	65			60	62
Tryptophan	16	17			19	17
Arginine	105	106			105	105
Histidine	34	34				
Isoleucine	69	68	55	56	55	65
Valine	80	79	65	72	63	79
Leucine	110	110	94	106		
Phenylalanine	66	66				
Phe+Tyr	120	118				

[a] According to Table 6.7.

*IAAR*s from summarized literature data. In general, more studies are required to evaluate and to validate different assumptions about *IAAR*s in chicken and pig diets.

Applications in evaluation of sustainability of feed to food protein

From the viewpoint of the currently increasing interest in evaluating the sustainability of food-producing systems with agricultural animals, minimized N pollution per unit N deposition is of substantial interest as a means of improving sustainability of nutrient conversion processes with food producing animals.

In this context it would be useful to know what proportion of the genetic potential ($ND_{max}T$) of growing animals would be optimal for maximizing metabolic efficiency. According to the shape of the exponential function (Fig. 6.2) it cannot be expected that a very high percentage of the threshold value could be achieved with high metabolic efficiency. Our model applications dealing with this important question indicated initially that an average level of performance could be more advantageous for minimizing *NEX* per unit *ND* (Liebert and Wecke, 2010). However, decisions in this field are more complex because both the level of daily protein supply and the yielded dietary AA balance (*IAAR*) in terms of AA efficiency have to be taken into account. Variation in dietary AA efficiency of feed ingredients is an important factor of influence. By improving the agreement between the *IAAR*s needed and the AA balance in the diet, the acceptable level of growth performance will be elevated if in the future any reference value or upper limit for the ratio *NEX*:*ND* is fixed for individual food-producing species.

These applications within the non-linear modelling procedure are currently at the starting point and need to be further developed and validated in future investigations. Through this research it will be possible to link evaluations of sustainability in food producing animals more successfully with the physiological processes of nutrient conversion in these animals.

In this chapter the basics and current developments of an exponential modelling procedure were described, and experimental results in growing animals were presented in an effort to contribute to an improved understanding of the 'Goettingen approach'. The objective was not to provide a general overview of the model applications in this field that are based on different hypotheses. Consequently, only a very limited number of references were cited.

In summary, the 'Goettingen approach' has the potential to model the process of converting feed into food protein by taking into account optimized dietary AA supply at a desired level of performance within the estimated threshold value of genetic potential for growth, and the AA efficiency in the feed. However, an important factor that may impact both the derived AA requirements and the resultant *IAAR*s is the extent to which AA efficiency varies in feed, as this has not been systematically investigated. This unknown variation may also have an impact on the derived recommendations for improving sustainability parameters of the conversion process with growing animals. These main factors of influence need more attention in future investigations and will extend the field for validated applications of the 'Goettingen approach' for modelling of nutrient conversion processes in food producing animals.

References

Baker, D.H. (2003) Ideal amino acid patterns for broiler chicks. In: D'Mello, J.P.F. (ed.) *Amino Acids in Animal Nutrition*. CAB international, Wallingford, UK, pp. 223–235.

Block, R.J. and Mitchell, H.H. (1946) The correlation of amino acid composition of proteins with their nutritive value. *Nutrition Abstracts and Reviews*. 16, 249–278.

Emmert, J.L. and Baker, D.H. (1997) Use of the ideal protein concept for precision formulation of amino acid levels in broiler diets. *Journal of Applied Poultry Research* 6, 462–470.

Fisher, C. and Morris, T.R. (1970) The determination of the methionine requirement of laying pullets by a diet dilution technique. *British Poultry Science* 11, 67–82.

Gahl, M.J., Finke, M.D., Benevenga, N.J. and Crenshaw, T.D. (1991) Use of a four-parameter logistic equation to evaluate the response of growing rats to ten levels of each indispensable amino acid. *Journal of Nutrition* 121, 1721–1729.

Gahl, M.J., Cranshaw, T.D. and Benevenga, N.J. (1995) Diminishing returns in weight, nitrogen, and lysine gain of pigs fed six levels of lysine from three supplemental sources. *Journal of Animal Science* 73, 3177–3187.

Gebhardt, G. (1966) Die Bewertung der Eiweißqualität von Nahrungs- und Futtermitteln mit Hilfe des N-Bilanzversuches. In: Hock, A. (ed.) *Vergleichende Ernährungslehre des Menschen und seiner Haustiere.* Gustav Fischer Verlag, Jena, Germany, pp. 323–348.

Gous, R.M. and Morris, T.R. (1985) Evaluation of a diet dilution technique for measuring the response of broiler chickens to increasing concentrations of lysine. *British Poultry Science* 26, 147–161.

Liebert, F. (2008) Modelling of protein metabolism yields amino acid requirements dependent on dietary amino acid efficiency, growth response, genotype and age of growing chicken. *Avian Biology Research* 1, 101–110.

Liebert, F. (2009) Amino acid requirement studies in *Oreochromis niloticus* by application of principles of the diet dilution technique. *Journal of Animal Physiology and Animal Nutrition* 93, 787–793.

Liebert, F. and Benkendorff, K. (2007) Modelling of threonine and methionine requirements of *Oreochromis niloticus* due to principles of the diet dilution technique. *Aquaculture Nutrition* 13, 397–406.

Liebert, F. and Wecke, C. (2008) Models for further developing the evaluation of protein and amino acids as well as for predicting performance from energy and amino acids intake. In: Staudacher, W. (ed.) *Recommendations for the Supply of Energy and Nutrients to Pigs.* DLG-Verlag-GmbH*,* Frankfurt, Germany, pp. 219–230.

Liebert, F. and Wecke, C. (2010) Nitrogen losses per unit of nitrogen deposition as derived from modelling of protein utilization depending on dietary protein quality parameters and age of growing barrows. In: Matteo Crovetto, G. (ed.) *Proceedings of 3rd EAAP International Symposium on Energy and Protein Metabolism and Nutrition.* Wageningen Academic, Wageningen, the Netherlands, pp. 443–444.

Liebert, F., Rimbach, M. and Peisker, M. (2000) Model for estimation of amino acid utilization and its requirement in growing animals. *Proceedings of Australian Poultry Science Symposium* 12, 88–92.

Mitchell, H.H. (1924) The biological value of proteins at different levels of intake. *Journal of Biological Chemistry* 58, 905–922.

Moré, J.J. (1977) The Levenberg-Marquardt algorithm: implementation and theory in numerical analysis. In: Watson, G.A. (ed.) *Lecture Notes in Mathematics.* Springer, Berlin, pp. 105–116.

Pastor, A., Wecke, C. and Liebert, F. (2013) Assessing the age dependent optimal dietary branched-chain amino acid ratio in growing chicken by application of a non-linear modelling procedure. *Poultry Science* 92, 3184–3196.

Samadi and Liebert, F. (2006a) Estimation of nitrogen maintenance requirements and potential for nitrogen deposition in fast-growing chickens depending on age and sex. *Poultry Science* 85, 1421–1429.

Samadi and Liebert, F. (2006b) Modeling threonine requirement depending on age, protein deposition, dietary threonine efficiency and sex of fast growing chickens. *Poultry Science* 85, 1961–1968.

Samadi and Liebert, F. (2007a) Lysine requirement of fast growing chickens – effects of age, sex, level of protein deposition and dietary lysine efficiency. *Journal of Poultry Science* 44, 63–72.

Samadi and Liebert, F. (2007b) Threonine requirement of slow growing male chickens depends on age and dietary efficiency of threonine utilization. *Poultry Science* 86, 1140–1148.

Samadi and Liebert, F. (2008) Modelling the optimal lysine to threonine ratio in growing chickens depending on age and efficiency of dietary amino acid utilisation. *British Poultry Science* 49, 45–54.

Thong, H.T. and Liebert, F. (2004a) Potential for protein deposition and threonine requirement of modern genotype barrows fed graded levels of protein with threonine as the limiting amino acid. *Journal of Animal Physiology and Animal Nutrition* 88, 196–203.

Thong, H.T. and Liebert, F. (2004b) Amino acid requirement of growing pigs depending on efficiency of amino acid utilisation and level of protein deposition. 1. Lysine. *Archives of Animal Nutrition* 58, 69–88.

Thong, H.T. and Liebert, F. (2004c) Amino acid requirement of growing pigs depending on efficiency of amino acid utilisation and level of protein deposition. 2. Threonine. *Archives of Animal Nutrition* 58, 157–168.

von Bertalanffy, L. (1951) *Theoretische Biologie, Zweiter Band: Stoffwechsel, Wachstum.* 2nd edn. A Francke AG, Bern, Switzerland.

Wang, T.C. and Fuller, M.F. (1989) The optimum dietary amino acid pattern for growing pigs. 1. Experiments by amino acid deletion. *British Journal of Nutrition* 62, 77–89.

Wecke, C. and Liebert, F. (2009) Lysine requirement studies in modern genotype barrows dependent on age, protein deposition and dietary lysine efficiency. *Journal of Animal Physiology and Animal Nutrition* 93, 295–304.

Wecke, C. and Liebert, F. (2010) Optimal dietary lysine to threonine ratio in pigs (30–110 kg BW) derived from observed dietary amino acid efficiency. *Journal of Animal Physiology and Animal Nutrition* 94, E277–E285.

Wecke, C. and Liebert, F. (2013) Improving the reliability of optimal in-feed amino acid ratios based on individual amino acid efficiency data from N balance studies in growing chicken. *Animals* 3, 558–573

WPSA (1984) The prediction of apparent metabolizable energy values for poultry in compound feeds. *World's Poultry Science Journal* 40, 181–182.

Yen, J.T., Kerr, B.J., Easter, R.A. and Parkhurst, A.M. (2004) Difference in rates of net portal absorption between crystalline and protein-bound lysine and threonine in growing pigs fed once daily. *Journal of Animal Science* 82, 1079–1090.

7 Artificial Neural Networks

A.S. Ferraudo*
Universidade Estadual Paulista, Jaboticabal, São Paulo, Brazil

Abstract

Artificial neural networks are approaches that try to mimic the complex parallel and non-linear processing of the brain. Their application has become possible due to the development of software and hardware technologies during the past few decades. Artificial neural networks are based on neuroscience, mathematics, statistics and computer engineering. Their architecture consists of layers containing neurons that allow inputs and outputs to be mapped according to learning algorithms. Several neural network models have been developed and one of the most frequently applied, possibly because it has the capacity to generalize acquired knowledge, is the multi-layer perceptron. It is applied in animal science in regression and classification methods, time-series forecasts and curve fitting among others. Although it mimics brain functioning in a very elementary manner, the results obtained with existing neural networks have shown this technique to be a powerful tool for data analysis.

Introduction

An artificial neural network (ANN) is an information processing system that is based on a mathematical model inspired by the complex non-linear and parallel neural structures of information in the brain of intelligent beings that acquire knowledge through experience.

A large ANN may contain hundreds and even thousands of processing units, while the mammalian brain contains several billions of neurons. In the human brain neural networks are able to organize their neurons and find solutions for very complex problems, such as recognizing standards. With only a few stimuli the human brain processes neural structures responsible for very fast and high quality responses, which it may never be possible to replicate artificially. However, the progress achieved in studies involving ANNs in a very short time and in several fields is amazing. Using neurobiological analogy as inspiration and the wealth of accumulated theoretical and technological tools, it is likely that our understanding of ANNs will soon be much more sophisticated than today (Haykin, 2001). ANNs are similar to the brain in at least two respects: knowledge is acquired by the network from its environment through a learning process; and the connection strength among neurons, known as synaptic weights, is used to store acquired knowledge. Neurocomputers, connectionist

---

*E-mail: fsajago@gmail.com

Nutritional Modelling for Pigs and Poultry (eds N.K. Sakomura *et al.*)

networks and parallel distributed processing are also called ANNs.

ANNs, as defined by Schalkoff (1997), are networks comprising a number of interconnected units, each unit having input or output characteristics that implement a local computation or function. Also, they are a functional abstraction of the biological neural structures of the central nervous system (Anderson, 1983; Akkurt *et al*., 2003) and they can exhibit a surprising number of the characteristics of the human brain, for example, learning from experience and generalizing from previous examples to solve new problems (Oztas *et al*., 2006).

An overview of ANN models has been provided over the last years by various authors (Rumelhart *et al*., 1986a,b; Lippmann, 1987; Fausett, 1994; Taylor, 1999) who have conducted research involving the mathematical description of ANN models and algorithm training, such as supervised/unsupervised learning. Literature on ANN models also shows that the development and application of ANNs is not limited to a specific area.

Among artificial neural structures, the multilayer perceptron neural network is highlighted. The increasing number of research applications of ANNs during the last few years has motivated us to describe this model with the aim of promoting its application in animal science. Curve fitting, such as in the regression and classification methods, was used for prediction in time series.

The First Neuron – Perceptron

The first structure built in an attempt to mimic the brain was described by McCulloch and Pitts (1943) as a very simple artificial neuron called perceptron (Fig. 7.1). This consisted of multiple inputs (dendrites) and a single output (axon). Although the first results seemed promising, perceptrons had many limitations. Minsky and Papert (1969) showed that a perceptron is able to learn to differentiate only two linearly separable classes. This simple but important structure marked the birth of neural networks and artificial intelligence.

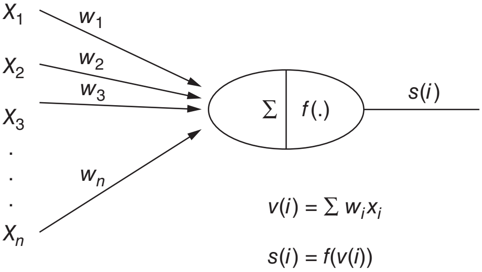


Fig. 7.1. The first neuron – perceptron.

After several discouraging years ANNs remerged in the 1980s with the progress of computer technology. Also, new critical procedures were discovered allowing the advancement of ANNs. These are now acknowledged as a modern approach that can be applied in all fields of knowledge and are consequently the subject of intensive theoretical and applied development.

Multilayer Perceptron Neural Networks

The topology of a neural multilayer perceptron network consists of an input layer, hidden layers and an output layer. When the error between the estimated and the actual values does not satisfy a minimum acceptable criterion, it is back-propagated and distributed to the estimated values of the parameters as many times as necessary until the error is acceptable. An example of a multilayer perceptron network topology is shown in Fig. 7.2; this consists of an initial layer with four input variables, two hidden layers with three neurons each and an output layer.

As a network training method, the backpropagation algorithm (Rumelhart *et al*., 1986a) can effectively train the network for non-linear problems and this has stimulated a torrent of research on and applications for neural networks.

Much progress has been achieved in improving the performance and understanding of neural networks (Hopfield, 1982; Hinton and Sejnowski, 1986; Lippmann, 1987; Peterson and Anderson, 1987; Chen, 1991; Galan-Marin and Perez, 2001; Manry *et al*., 2001; Oh and Pedrycz, 2002; Panchapakesan *et al*., 2002).

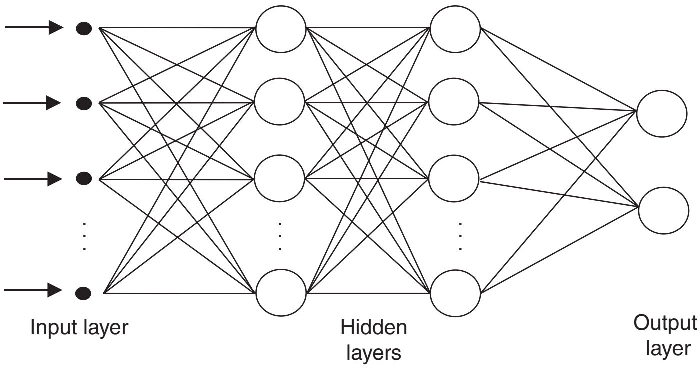


Fig. 7.2. Topology of a multilayer perceptron neural network containing two hidden layers.

However, additional improvements in training these networks are required, because the training process is complex and empirical in nature.

The function of the hidden layers and their neurons in the network topology (architecture) is to increase the capacity of the network to extract statistical information from the inputs. Each layer constitutes an input for the following layer. The input layer provides information to the first hidden layer and its output signals will become inputs for the second layer and so on. The sum of the products of weights multiplied by the inputs that reach a neuron is equalized by a smooth non-linear activation function, allowing the network to learn the non-linear patterns contained in the data (Haykin, 2001).

Learning should be stressed in the study of ANNs, because the synaptic weights are adjusted only during the training stage. Therefore, the training algorithms deserve special attention. The objective is to adjust network weights in order to minimize the difference between the output value and the desired value. The sum-squared error is a method commonly used for this purpose.

The method of back-propagation of errors (Rumelhart *et al.*, 1986a) promoted significant improvement in the performance of ANNs. During the propagation step, synaptic weights are fixed. An error that does not fit a criterion (supervision) is backward propagated from the output and the synaptic weights and bias are adjusted in each processing unit until the error is accepted, generating an output. The bias allows the output of a neuron to be null even when all inputs are null.

The error in an output neuron j in the iteration n is defined as:

$$e_j(n) = d_j(n) - y_j(n) \tag{7.1}$$

Where $d_j(n)$ is the desired value and $y_j(n)$ the calculated value in neuron j. The squared error (SE) in a neuron j is defined as:

$$\mathrm{SE}_j = \frac{1}{2} e_j^2(n) \tag{7.2}$$

Therefore, for a set S, containing all neurons of the output layer:

$$\mathrm{SE}(n) = \sum_{j \in s} \frac{1}{2} e_j^2(n) \tag{7.3}$$

Mean squared error (MSE) during training is calculated as:

$$\mathrm{MSE} = \frac{1}{N} \sum_1^N SE(n) \tag{7.4}$$

This is the measure of the ANN learning performance. Learning means finding the synaptic weights that reduce mean squared error to a minimum. If m represents the total number of inputs applied in neuron j, excluding the bias, then the local induced field produced in the input in the activation function associated to neuron j is:

$$v_j(n) = \sum_{i=0}^{m} w_{ji}(n)\, y_i(n) \tag{7.5}$$

Functional signal $y_j(n)$ at the output of neuron j in iteration n is:

$$y_j(n) = \varphi_j\left(v_j(n)\right) \tag{7.6}$$

The gradient $\frac{\partial(SE(m))}{\partial w_{ji}(m)}$ represents a sensitivity factor, determining the direction of search in weight space for synaptic weight $w_{ji}(m)$.

Using the chain rule, the gradient can be described as:

$$\frac{\partial\left(EQ(n)\right)}{\partial w_{ji}(n)} = \frac{\partial\left(EQ(n)\right)}{\partial e_j(n)} \frac{\partial e_j(n)}{\partial y_j(n)} \frac{\partial y_j(n)}{\partial v_j(n)} \frac{\partial v_j(n)}{\partial w_{ji}(n)} \tag{7.7}$$

But:

$$\frac{\partial\left(EQ(n)\right)}{\partial e_j(n)} = e_j(n), \quad \frac{\partial e_j(n)}{\partial y_j(n)} = -1, \quad \frac{\partial y_j(n)}{\partial v_j(n)} = \varphi_j'\left(v_j(n)\right) \tag{7.8}$$

And:

$$\frac{\partial v_j(n)}{\partial w_{ji}(n)} = y_i(n) \tag{7.9}$$

Then:

$$\frac{\partial\left(EQ(n)\right)}{\partial w_{ji}(n)} = -e_j(n)\varphi_j'\left(v_j(n)\right)y_i(n) \tag{7.10}$$

According to the delta rule:

$$\Delta w_{ji}(n) = -\eta \frac{\partial\left(EQ(n)\right)}{\partial w_{ji}(n)} \tag{7.11}$$

Where η is learning rate and the negative signal determines a direction to change the weight that will reduce SE value. Therefore:

$$\Delta w_{ji}(n) = -\ \eta\left(-e_j(n)\varphi_j'\left(v_j(n)\right)\ y_i(n)\right) = \eta\delta_j(n)y_i(n) \tag{7.12}$$

Where $\delta_j(n) = e_j(n)\varphi_j'(v_j(n))$ is the local gradient.

The local gradient is calculated differently for hidden and output neurons. Neuron *j* of the output layer:

$$\delta_j(n) = e_j(n)\varphi_j'\left(v_j(n)\right) \tag{7.13}$$

Neuron *j* of the hidden layer:

$$\delta_j(n) = \varphi_j'\left(v_j^k(n)\right)'\sum\nolimits_m \delta_m^{k+1}(n)w_{mj}^{k+1}(n) \tag{7.14}$$

Synaptic weights in layer *k* are fitted according to the general delta rule:

$$w_{ji}^k(n+1) = w_{ji}^k(n) + \alpha(w_{ji}^k(n-1)) + \eta\delta_j^k(n)y_i^{k-1}(n) \tag{7.15}$$

Where η is the learning curve and α is momentum (Haykin, 2001).

The lower the η value, the smoother the trajectory in the weight space. This is a disadvantage because learning becomes slow. On the other hand, high η values indicate fast learning but may destabilize the network.

Learning rate is a proportional constant between zero and one. Very low rates, close to zero, make learning very slow, whereas very high rates, close to one, may cause the network to oscillate without learning. Therefore, learning rate must be adaptive and controlled by the network.

Momentum rate is a parameter that also ranges between zero and one and provides sufficient speed to avoid the local minima that may be found which would otherwise prevent the system from reaching the global optimum.

When is the process interrupted? Basheer and Hajmeer (2000) identified some criteria to stop the process, such as minimum error, number of cycles and cross-validation. When the minimized error is lower than an adopted criterion the process stops. The number of cycles defines the number of times a dataset is submitted to training. Excessive training may cause the network to lose its generalization power (overfitting), and too little training results in poor performance (underfitting). It is difficult, therefore, to determine when training should stop.

One way is to determine the beginning of excessive training by cross-validation, which divides the training set into two subsets: one for training and one for validation. Using a training set, training is performed for several periods (cycles) and then the selected models are tested in the validation set for each training cycle. This procedure is called the *early stopping training method*. Training and validation learning curves present different behaviour. During training, the curve monotonously decreases as the number of cycles increase, whereas during validation the curve decreases to a minimum and then starts to increase. Therefore, the minimal point in the validation learning curve may be used as a sensible criterion to stop training (Haykin, 2001).

The error $e_j(n)$ is minimized by a method, and the general delta rule is applied when differential and non-descendent activation functions are applied such as the logistic sigmoidal function and hyperbolic tangent function. The logistic sigmoidal function and hyperbolic tangent function are defined, respectively, as:

$$y = \frac{1}{1+ e^{-x}},\ 0 < y < 1 \tag{7.16}$$

$$y = \frac{1- e^{-x}}{1+ e^{-x}},\ -1 < y < 1 \tag{7.17}$$

Data need to be normalized because the values presented to the neural network are under the domain of the restricted image set activation functions. Data can be normalized by different functions, but the most commonly used is:

$$z_i = \frac{x_i - x_m}{x_M - x_m} \tag{7.18}$$

Where z_i is the normalized value of x_i, and x_m and x_M are the minimum and the maximum values of dataset X.

Training Multilayer Artificial Neural (MLP) networks with back-propagation may demand several steps in the training set and consequently training time is long. When a local minimum is found, the error of the training set stops decreasing and is stuck at a higher than acceptable value. The learning rate can be increased without oscillation by changing the general delta rule including the momentum, a constant that determines the effect of previous weight changes on the current direction of the movement in weight spaces. Momentum is useful in error spaces with long gorges, sharp curves or valleys with smooth declines.

Multilayer Artificial Neural Networks in Animal Science (MLP)

In animal science research, several applications using connectionist methods have been reported for the identification of standards and for solutions to non-linearity problems. Because of the easy access to software programs and hardware, as well as the capacity of neural networks to develop models combined with other techniques, connectionist models are powerful and modern tools that attempt to understand and seek solutions for specific problems in all fields of knowledge. Although the number of artificial intelligence applications in animal science has increased in the last few years, this number is still low. It may be explained by the absence, until recently, of disciplines that include connectionist models in undergraduate and graduate courses. Today, some new curricula have included this subject and this will surely motivate animal scientists to apply connectionist models.

Biological systems are surprisingly flexible in processing information from the real world. Some biological organisms have a central processing unit called a brain. The human brain contains 10^{11} neurons and is capable of intelligent processing in a precise and subjective manner. Artificial intelligence (AI) tries to bring to the digital processing world the heuristics of biological systems in a variety of manners, but still a lot needs to be done. ANNs and fuzzy logic have been shown to be effective in solving complex problems using the heuristics of biological systems. The number of AI applications in animal production systems has increased significantly in the last few years.

Huang (2009) mentions that ANNs have been extensively studied and applied in several fields during the past three decades. Research on back-propagation training algorithms for multilayer perceptron networks has stimulated the development of training algorithms for other neural networks including the radial basis function, recurrent network and Kohonen's self-organized competitive and non-supervised networks. These networks, particularly the multilayer perceptron network with back-propagation training algorithm, have been used in research and applied in several scientific fields, and in engineering. These networks were integrated with other advanced methods, such as fuzzy logic and wavelet, to increase data interpretation and modelling capacity in order to prevent processing subjectivity during the training algorithm.

Very little research on modelling animal growth using ANNs has been carried out. ANNs offer an alternative to regression analysis for biological growth modelling. Roush *et al.* (2006) compared broiler growth modelling using a Gompertz non-linear regression equation with neural networks. Model accuracy was determined by mean squared error (MSE), mean absolute deviation (MAD), mean absolute percentage error (MAPE) and bias. Relative to training data, the neural-developed neural network model presented lower MSE, MAD, MAPE and bias. Also for the validation data, the lowest MSE and MAD were observed with the genetic algorithm-developed neural network. The lowest bias was obtained with the neural-developed network. As measured by bias, the Gompertz equation underestimated the values, whereas the neural- and genetic-developed neural networks produced little or no overestimation of the observed body weight responses.

Wang *et al.* (2012) compared the relationship between egg production and the number of pullets, culled birds and moulted birds in Taiwan using traditional regression methods or neural network models. The results showed that the neural network model is more accurate than the traditional regression model for predicting egg production.

Pandorfi *et al.* (2011) evaluated the precision of multilayer ANNs with error back-propagation for the prediction of performance parameters of pregnant sows based on environmental and physiological variables. The authors used a single hidden layer with sigmoidal tangent activation function. Air temperature and respiratory frequency were considered as input variables and weight of piglet at birth and the number of mummified piglets as output variables. The trained network presented excellent generalization power, allowing the prediction of the response parameters. The gestation and farrowing environment characterization was adequate compared with actual data, presenting few cases of over- or underestimating values. The use of this expert system to predict animal performance is feasible because it showed good results in this application.

A neural network trained to predict the presence or absence of ascites in broilers showed excellent performance (Roush *et al.*, 1996). The network topology consisted of 15 physiological variables as inputs, one hidden layer with 16 neurons and an output layer with two neurons (presence or absence of ascites). Laboratory results were compared with neural network responses, and the network was shown to be efficient in detecting the presence or absence of ascites in broilers before the occurrence of fluid accumulation.

Neural networks with error back-propagation were used to predict the performance of developing replacement pullets belonging to a company in southern Brazil (Salle *et al.*, 2001). The authors concluded that ANNs are able to explain the performance parameters of developing layer pullets. The method aids decision making based on scientifically determined objective criteria. In addition, it allows the consequences of the possible decisions to be simulated, and shows the proportional contribution of each variable to the phenomenon evaluated.

Savegnago *et al.* (2011) studied the capacity of neural networks to adapt to datasets in poultry and animal production areas. Neural networks were applied to an egg production dataset and models were fitted to the egg production curve using two approaches, one being a linear logistic model, and the other using two ANN models (multilayer perceptron (MLP) and radial basis function). The MLP neural network had the best fit in the test and validation phases. The advantage of using neural networks is that they can be fitted to any kind of dataset and do not require model assumptions such as those required in the non-linear methodology. The results confirm that MLP neural networks may be used as an alternative tool for describing egg production. The benefits of the MLP are the great flexibility and their lack of *a priori* assumptions when estimating a noisy non-linear model.

Ghazanfari *et al.* (2011) mentioned that ANNs have been shown to be a powerful tool for system modelling in a wide range of applications. They applied a back-propagation neural network with two hidden layers to predict hen and pullet egg production. The model successfully learned the relationship between input (hen age) and output (egg production). The results suggested that the ANN model could provide an effective means of recognizing data patterns and accurately predicting the egg production of laying hens based on their age.

The group method of data handling (GMDH) algorithm considers the responses to polynomial regressions of all pairs obtained from original data as inputs to multilayer neural networks (Ivakhnenko, 1971). This approach has been successfully applied in several fields, but it is rarely used in poultry science. The results of Ahmadi *et al.* (2007) indicated that a GMDH neural network is an efficient means of recognizing patterns in datasets and in accurately predicting performance based on input investigation. It may also be used to optimize broiler performance as a function of nutritional factors.

Chicken mechanically separated meat (MSM) is a raw material from chicken meat processing derived from low-commercial value chicken parts including back and neck and it is produced using specific equipment, such as deboning machines. Back-propagation ANNs with five input layers (Ca, Fe, P, Mg, Zn), a five-neuron hidden layer and one output layer were trained to determine MSM content in meat products. However, the application of the networks to commercial samples (validation) was inadequate because of the difference between the ingredient composition of the sausages used during training and the commercial samples. The neural network built to determine MSM content was efficient during training and network testing (Sousa *et al.*, 2003).

Conclusions

The objective of this chapter was to introduce the subject of neural networks, particularly multi-layer ANNs. All fields of knowledge now apply ANNs as powerful analysis tools, and there are already many applications in animal science, as shown in this chapter. However, this number is still small. As an emerging field in data analysis, the study of ANNs has experienced exponential growth in the past few decades. In the near future, the human brain will be better understood and new computer technologies will emerge, allowing for the development of more sophisticated hybrid models of ANNs.

References

Ahmadi, H., Mottaghitalab, M. and Nariman-Zadeh, N. (2007) Group method of data handling-type neural network prediction of broiler performance based on dietary metabolizable energy, methionine, and lysine. *Journal of Applied Poultry Research* 16, 494–501.

Akkurt, S, Ozdemir, S., Tayfur, G. and Akyol, B. (2003) The use of GA-ANNs in the modelling of compressive strength of cement mortar. *Cement and Concrete Research* 33, 973–979.

Anderson, J.A. (1983) Cognitive and psychological computation with neural models. *IEEE Transactions on Systems Management and Cybernetics* 13, 799–814.

Basheer, I.A. and Hajmeer, M. (2000) Artificial neural networks: fundamentals, computing, design, and application. *Journal of Microbiological Methods* 43, 3–31.

Chen, M.S. (1991) Analysis and design of the multilayer perceptron using polynomial basis functions. PhD Dissertation, The University of Texas at Arlington, Texas, USA.

Fausett, L. (1994) *Fundamentals of Neural Networks: Architecture, Algorithms and Applications.* Prentice-Hall, Englewood Cliffs, New Jersey, USA.

Galan-Marin, G. and Perez, J. (2001) Design and analysis of maximum Hopfield networks. *IEEE Transactions on Neural Networks* 12, 329–339.

Ghazanfari, S., Nobari, K. and Tahmoorespur, M. (2011) Prediction of egg production using artificial neural network. *Iranian Journal of Applied Animal Science* 1, 10–16.

Haykin, S. (2001) *Redes Neurais, Princípios e Prática, Second Edition.* Bookman, Porto Alegre, Rio Grande do Sul, Brazil.

Hinton, G.E. and Sejnowski, T.J. (1986) *Learning and Relearning in Boltzmann Machines, Parallel Distributed Processing: Explorations in Microstructure of Cognition.* MIT Press, Cambridge, Massachusetts, USA.

Hopfield, J.J. (1982) Neural networks and physical systems with emergent collective computational abilities. *Proceedings of the National Academy of Sciences of the USA* 79, 2554–2558.

Huang, Y. (2009) Advances in artificial neural networks – methodological development and application. *Algorithms* 2, 973–1007.

Ivakhnenko, A.G. (1971) Polynomial theory of complex systems. *IEEE Transactions on Systems Management and Cybernetics* SMC–1(4), 364–378.

Lippmann, R.P. (1987) An introduction to computing with neural nets. *IEEE ASSP Magazine* 4(2), 4–22.

Manry, M.T., Chandraekaran, H. and Hsieh, C. (2001) *Signal Processing using the Multilayer Perceptron*. CRC Press, Boca Raton, Florida, USA.

McCulloch, W.S. and Pitts, W. (1943) A logical calculus of the ideas immanent in nervous activity. *Bulletin of Mathematical Biophysics* 5, 115–133.

Minsky, M.L. and Papert, S.A. (1969) *Perceptrons.* MIT Press, Cambridge, Massachusetts, USA.

Oh, S.K. and Pedrycz, W. (2002) The design of self-organizing polynomial neural networks. *Information Sciences* 141, 237–358.

Oztas, A., Pala, M., Ozbay, E., Kanca, E., Caglar, N. and Bhatti, M.A. (2006) Predicting the compressive strength and slump of high strength concrete using neural network. *Construction and Building Materials* 20(9), 769–775.

Panchapakesan, C., Palaniswami, M., Ralph, D. and Manzie, C. (2002) Effects of moving the centers in an RBF network. *IEEE Transactions on Neural Networks* 13(6), 1299–1307.

Pandorfi, P., Silva, I.J.O., Sarnighausen, V.C.R., Vieira, F.M.C., Nascimento, S.T. and Guiselini, C. (2011) Use of artificial neural networks on the prediction of zootechnical indexes on gestation and farrowing stages of swine. *Revista Brasileira de Zootecnia* 40(3), 676–681.

Peterson, C. and Anderson, J.R. (1987) A mean field theory learning algorithm for neural networks. *Complex Systems* 1, 995–1019.

Roush, W.B., Kirby, Y.K., Cravener, T.L. and Wideman, R.F. Jr (1996) Artificial neural network prediction of ascites in broilers. *Poultry Science* 75(12), 479–487.

Roush, W.B., Dozier III, W.A. and Branton, S.L. (2006) Comparison of Gompertz and neural networks models of broiler growth. *Poultry Science* 85,794–797.

Rumelhart, D.E., Hinton, G.E. and Williams, R.J. (1986a) Learning representations by back-propagating errors. *Nature* 323, 533–536.

Rumelhart, D.E., Hinton, G.E. and Williams, R.J. (1986b) Learning internal representations by error propagation. In: Rumelhart, D.E. and McCleland, J.L. (eds) *Parallel Distributed Processing*, Vol 1. MIT Press, Cambridge, Massachusetts, USA.

Salle, C.T.P., Guahyba, A.S., Wald, V.B., Silva, A.B., Salle, F.O. and Fallavena, L.C.B. (2001) Uso de Redes Neurais Artificiais para Estimar Parâmetros de Produção de Galinhas Reprodutoras Pesadas em Recria. *Revista Brasileira de Ciência Avícola* 3(3), 257–264.

Savegnago, R.P., Nunes, B.N., Caetano, S.L., Ferraudo, A.S., Schmidt, G.S., Ledur, M.C. and Munari, D.P. (2011) Comparison of logistic and neural network models to fit to the egg production curve of White Leghorn hens. *Poultry Science* 90 (3), 705–711.

Schalkoff, R. (1997) *Artificial Neural Networks*. McGraw Hill, Clemson, South Carolina, USA.

Sousa, E.A., Teixeira, L.C.V., Mello, M.R.P.A., Torres, E.A.F.S. and Moita Neto, J.M. (2003) Aplicação de redes neurais para avaliação do teor de carne mecanicamente separada em salsicha de frango. *Ciência e Tecnologia dos Alimentos* 23(3), 307–311.

Taylor, J.G. (1999) *Neural Networks and their Applications*. Wiley, New York.

Wang, B.Y., Chen, S.A. and Roan, S.W. (2012) Comparison of regression and artificial neural network models of egg production. *Journal of Animal and Veterinary Advances* 11, 2503–2508.

8 Challenges Associated with the Application of Poultry Models: The Case of Turkeys

V. Rivera-Torres*
Nutreco Canada, Saint-Hyacinthe, Quebec, Canada.

Abstract
Although several animal models have been developed so far, there are very few that are in use for either research or commercial applications. In poultry, the challenge of model application may be greater than for other species because decision making must be quick and low-risk given the short production cycle of the birds. However, poultry growth models are an important opportunity for both research and commercial applications as they represent a chance to better understand the growth response of birds and to better determine their requirements depending on the growing conditions. Given the limited volume of turkey meat production relative to broiler production, there is a great opportunity to apply turkey models in the industry and in research. This chapter explains the challenges that may be faced when developing and applying models, and proposes a methodology to ensure the successful application of these models using the turkey as an example.

Introduction

Growth models are strategic tools used in both research and industry to adapt nutrient recommendations to turkey performance objectives and decide feeding strategies depending on feed production costs. Mechanistic models are particularly adapted to allow understanding of the interactions and underlying processes of growth (e.g. weight gain composition, efficiency of energy and nutrient utilization). Mechanistic models consist of mathematical equations defined by inputs (e.g. dietary energy level, genetic potential) and variables (e.g. energy requirements, body composition) that interact to generate outputs (e.g. weight gain, feed intake). These models may be a partial substitute for live animal research trials and therefore help to reduce the timeline between investigation and solution application.

In spite of the high added value of applying turkey growth models in research or in industry, scientists and users still face several challenges that limit model development and application. Along with the small tonnage relative to the broiler industry, the longer time to market and high cost of turkey research studies result in a paucity of turkey data and therefore in a lack of knowledge of the growth dynamics and definition of nutrient requirements that are critical inputs to growth models. Also, sexual and

---

*E-mail: virginie.rivera@gmail.com

© CAB International 2015. *Nutritional Modelling for Pigs and Poultry* (eds N.K. Sakomura *et al.*)

breed dimorphism result in large differences in energy and nutrient requirements, and the large range of market weights ranging from 6 kg to 20 kg create challenges in accurate prediction/simulation. Models must be sufficiently flexible to respond to these different types of production.

The present chapter addresses the main questions that need to be answered during the different phases of model development and application in order to maximize the success of research or commercial applications of turkey models. The following steps for developing and applying models are described: (i) framework description; (ii) model development; (iii) evaluation; and (iv) application. Although the turkey is taken as an example, the methodology can be applied to other species.

Framework Description

Defining needs and expectations

Understanding the needs and expectations of the stakeholders of the model is crucial to ensure successful model application. The term ‘stakeholders’ refers to the decision makers (i.e. researchers or business representatives), the users and the scientists who develop the model. Each of these stakeholders may have different needs and expectations, and therefore face different challenges (Table 8.1).

The decision makers are the individuals who make the final judgement on which decision is to be made depending on the model simulation results performed by the user. To optimize their production and minimize the risk in decision making, they expect the model to be precise and accurate. Their challenge lies in understanding the strengths and limitations of the model to help make the appropriate decisions.

As a response to the decision makers’ needs and objectives, the role of the users consists of exploring and comparing alternative strategies (i.e. ‘what-if’ simulations). To facilitate model application, the users expect the model to be friendly and easy to apply. Their challenge lies in accessing data that will facilitate the adjustment of the model to different situations/production conditions. User training and application are key factors in successful application by the user, and will ensure that the simulated outputs are well understood and interpreted by the user.

Table 8.1. Roles, needs, expectations, key success factors and challenges for decision makers, users and scientists of turkey models.

	Decision makers	Users	Scientists
Role	Decide on recommended changes from users to attain technical or economic performance objectives	Make recommendations to the decision makers	Understand user and decision maker needs and develop the model accordingly
Needs	Optimize growth and feeding programme for maximum profitability (business needs) Understand bird’s response and adapt recommendations	Adapt the model to the different situations encountered in the field Explore alternatives for attaining economic or technical objectives	Understand model application
Expectations	Precision and accuracy	Friendly interface Model easy to apply	Data availability
Challenge	Understand the strengths and limitations of the model	Data collection	Model calibration
Key success factors	Awareness	User training and frequent application	Driving force and input definition

As model developers, scientists play a key role in creating the link between science, decision makers and users. While the decision makers will easily formulate their needs on a long-term basis, the scientists need to understand how this will be reflected in terms of model equations and, later, in terms of model application. It is the role of scientists to understand the users' needs and expectations on a short-, medium- and long-term basis, and to develop an adaptive model that can be continuously improved.

Gathering the stakeholders together before starting the model framework description may represent the first important step of model development projects to ensure all needs and expectations are known and understood.

Framework

The model framework defines the inputs, outputs and flows and compartments of the model. It also defines how genetic potential and nutrient requirements are simulated. Independently of the approach used to simulate genetic potential, most of the current poultry models are based on the assumption that genetic potential enables the determination of feed intake as a result of dietary nutrient and environmental constraints (Emmans and Fisher, 1986). To evaluate genetic potential accurately there is a need to evaluate the nutrient partitioning of the animal regularly through body composition analyses (Rivera-Torres *et al.*, 2011b; Rivera-Torres and Ferket, 2012; Murawska, 2013) or calorimetry measurement (Rivera-Torres *et al.*, 2010, 2011a).

Recent body composition analyses of turkeys has facilitated the estimation of the parameters of the Gompertz equations and of allometric relations (Rivera-Torres *et al.*, 2011b; Rivera-Torres and Ferket, 2012) for further use in turkey models. The main advantage of these methods is that the parameters of the allometric and Gompertz equations can be estimated by regression analysis. Also, the simulation of protein and lipid turnover rates (Danfaer, 1991) is an interesting method to simulate turkey growth potential at a metabolic level (Rivera-Torres *et al.*, 2011c). However, protein and lipid turnover rates are difficult and expensive to determine, and the data are scarce and relatively old when considering the rapid advances in genetic selection (Kang *et al.*, 1985). Alternatively, Rivera-Torres *et al.* (2011c) proposed indirect estimates of the protein and lipid turnover parameters by manual calibration using protein and lipid retention rates of turkeys with different breeds and genders.

The challenge to scientists is to determine the most appropriate method for model simulation and application. While the model of Rivera-Torres *et al.* (2011c) used protein and lipid turnover rates to gain flexibility in the description of growth rate, it also allowed the simulation of macronutrient composition effects on energy and nutrient utilization (i.e. amino acids, glucose, fatty acids, acetyl coenzyme-A) for protein and lipid gain. This model is particularly interesting for research application, while more complicated for commercial application. Indeed, increasing the level of complexity of models is usually related to an increasing number of input data required to calibrate the model and ensure an appropriate level of precision of the outputs (Fig. 8.1). As an example, because the model of Rivera-Torres *et al.* (2011c) simulated macronutrient utilization and ATP production, data on energy utilization were generated to calibrate the model in terms of nutrient oxidation rates (i.e. fatty acids, amino acids, glucose, acetyl coenzyme-A) to ensure an adequate level of precision of the outputs (e.g. protein and lipid retention, maintenance heat production, carbon dioxide production).

Model Development

Development strategy

While stakeholders may expect models to deliver a high level of accuracy, they may also expect the model to consider a large number of inputs in order to account for a large spectrum of effects (e.g. individual amino acid level, ambient temperature, stocking

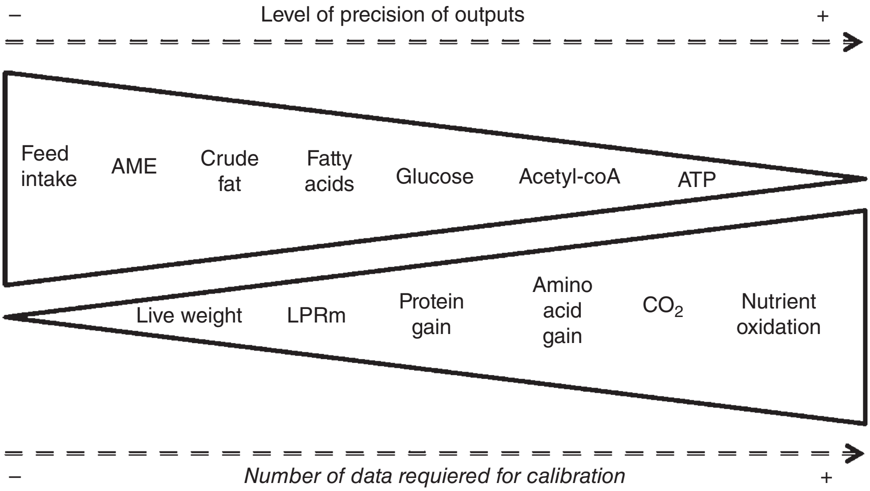


Fig. 8.1. Schematic representation of the relation between the level of precision of model outputs and the number of data required for model calibration.

density), which may result in increased model complexity (i.e. number of parameters and variables). However, by increasing the level of model complexity there is a risk of defining a number of parameters that do not improve model precision. To limit this risk, any parameter or variable added to the model should be justified in the sense that it should demonstrate the gain in the expected level of precision or accuracy. Thus, model development strategy should start from a simple model, going towards a step-by-step increasing level of complexity. A continuous improvement cycle could therefore be considered in model development strategy by: (i) developing a first simple version of the model; (ii) validating this version; (iii) improving the model accuracy by adding other parameters; and (iv) re-evaluating model predictions. Also, this strategy helps minimize the risk of failure while ensuring that users understand the basics of the model before progressing to more complicated simulations.

As an alternative to defining genetic potential and environmental conditions as proposed in other models (EFG Software, 1995; Ferguson, 2006), Rivera-Torres *et al.* (2011c) confounded the effect of environment with genetic potential to facilitate model application on commercial farms. Rather than defining the growth potential of every genotype and environment these authors proposed to characterize growth profiles on the basis of field observations. Growth profiles may therefore be defined for groups of birds of the same genotype and gender and grown under similar environmental conditions. The adjustment of the inputs according to the observed performance therefore enables the user to describe different growth profiles with no need to define the environmental conditions. This approach assists in overcoming the limitations of field data availability to develop a portfolio of growth profiles that can be applied in the turkey industry.

Model interface

Defining the user interface is an important process that needs to be carried out together with users and decision makers. Models may either be developed directly using modelling software that illustrate the flows and the compartments (e.g. Rivera-Torres *et al.*, 2011c) or programmed as independent software with a customized interface (e.g. EFG Software, 1995). Modelling software may be preferred for research purposes, while an independent software tool is the ideal solution for commercial application. To date, no turkey model seems to use independent commercial software.

Specialized modelling software has the advantage of making model development fast while allowing both users and scientists to generate the graphs and tables they need to make informed choices. These tools are also very flexible for the end user who can add new outputs or variables to the model and run sensitivity analyses to compare different scenarios. However, the major limitation to using such tools is that users must be familiar with modelling and must be trained in modelling principles and software utilization (e.g. sensitivity analyses, optimization) to make sure that the user masters the model and understands its limitations.

Depending on the user's needs and skills, developing a friendly interface may be more appropriate especially in today's world where time is a limited resource. However, these software applications do not allow users to add new outputs to the model. Most of the time, an IT team is needed to develop the interface. Such an interface should be preferred when users are non-modellers and do not necessarily need to understand the science of the model. However, it is still recommended that the model is first developed and tested on modelling software to validate its application before allocating time and human resources to program the model as an independent piece of software.

Evaluation

Model evaluation aims at determining model precision, accuracy, robustness and flexibility by comparing simulated outputs with observed values over a wide range of production scenarios. An evaluation of the simulations should first be performed with the data used during model calibration to validate the consistency of model outputs. Once the internal validation is completed, the use of external data (i.e. data that were not used during model development) permits the assessment of model accuracy, limitations and, therefore, its applicability.

Precision and accuracy

Precision 'measures how closely individual model-predicted values are within each other', while accuracy 'measures how closely model-predicted values are to the true values' (Tedeschi, 2006). The linear regression analysis of observed values (i.e. *Y*) with simulated values (i.e. *X*) is a means of evaluating both model precision and accuracy. Intercept and slope estimates that do not significantly differ from zero and unity, respectively, indicate an accurate response or that the predicted values closely fit the actual responses. Log-transformations of the observed and simulated values may be appropriate to avoid the effect of the linear increase in performance (e.g. feed intake, live weight) when estimating linear regression parameters (Fig. 8.2).

Accuracy can be determined as the absolute or relative difference between simulated and observed values, where the relative difference corresponds to the ratio of the absolute difference to the observed value. Both absolute and relative differences should be calculated for the different stages of growth to shed light on which periods are less accurate than others. A challenge with turkey growth models is the maximization of model accuracy early in the growing period to limit increasing cumulative inaccuracy at later ages. Indeed, a 2% accuracy at early ages (i.e. 10 g precision at 500 g live weight) may be fairly satisfying but unacceptable in the finisher phase (i.e. 400 g precision at 20 kg live weight). Finally, the evaluation of model accuracy at different stages of growth can help clarify model behaviour during the overall growing cycle. For example, with a consistent overestimation of weight gain it may be easier to identify the cause and effect response, whereas both over- and underestimations make it difficult to identify the cause.

Robustness and flexibility

Robustness refers to the ability of the model to adapt to perturbations (Sauvant and Martin, 2010). A robust model should therefore not

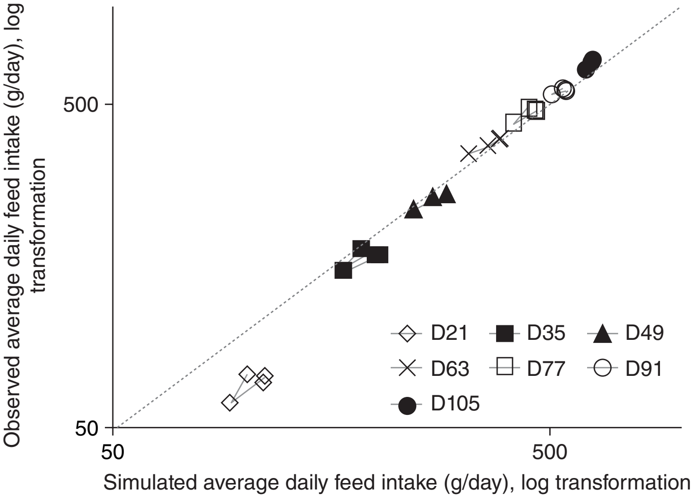


Fig. 8.2. Observed and simulated average daily feed intake (g/bird/day) of male turkeys as a function of age (day 21 to 105, D21 to D105). Values below the dotted line refer to an overestimation of the model outputs, while values on the dotted line are in agreement with the observations.

deviate from realistic values when challenging the outputs with extreme inputs (e.g. deficient levels of amino acids, unbalanced amino acid to energy ratio). By understanding the robustness of a model the user is capable of defining the limitations for its application. For example, low density diets are expected to result in greater feed intake, but a robust model should also account for feed intake limitation due to feed bulk and intake capacity. Although robust concepts have been developed in broiler chicken models (EFG Software, 1995) to account for perturbations such as heat dissipation capacity and feed intake capacity, no estimate of such equation parameters has yet been proposed in turkeys.

Robustness can be evaluated by performing sensitivity analyses, which consist of identifying the parameters that have a major impact on model outputs. Sensitivity analysis enables a better understanding of the behaviour of the model depending on the parameter values. The value of the sensitive parameters should be as accurate as possible, while adjusted parameters should not be sensitive to changes. Also, scientists and users should identify the sensitive parameters of the model to ensure an appropriate interpretation of the outputs. Some of the most sensitive parameters in turkey models are the parameters associated with energy and nutrient requirements. Rivera-Torres *et al.* (2011a) showed that energy requirements for maintenance (i.e. per kilogramme of metabolic weight) were 16% lower in females than in males. Because energy requirement regulates feed intake when no nutrient is limiting in the diet it is important that turkey models account for gender-based differences in maintenance requirements as they strongly impact feed intake and, therefore, weight gain. Also, an accurate estimate of the relationship between water and protein mass is key to estimating body weight and feed intake. Indeed, as water mass represents close to two-thirds of the whole body mass, an overestimate of the water-to-protein ratio may result in an overestimate of body weight as a result of the excessive estimation of water retention (Rivera-Torres *et al.*, 2011c).

Application

Conditions for success

Before training users in model application, documentation should be prepared to: (i) present model theory for a basic understanding of the science by the user (e.g. definition of genetic potential, feed intake regulation); (ii) provide a user manual on the model; and (iii) advise on the methodology for running simulations, optimizations or predictions. Appropriate documentation should facilitate technology transfer while enabling the user to run simulations frequently and rapidly on their own and maintain their skills in model application.

One of the major concerns of users relates to the parameters that define genetic potential and environmental conditions. Indeed, in most cases the same feed is allocated to several flocks and there is a limited number of feeds that are manufactured by the feed mill for production efficiency reasons. The difficulty faced by users is their ability to describe the genetic potential and the average environmental conditions of every flock of birds depending on their performance. Also, the user may not have all the information needed to define accurately the genetic potential and environmental conditions in every flock. As an alternative to simulating the performance of every flock a database of genetic potentials and environmental conditions could be generated and used as inputs. This approach may help the user to generate simulations easily and rapidly with no need to identify the performance of every flock.

Application process

The virtuous circle of model application in both research and industry is presented in Fig. 8.3. An efficient model application strategy relies on the definition of one single objective of improvement prior to running simulations. This pre-defined objective should refer to either a technical growth performance objective (e.g. feed conversion, live weight at a given age), an economic objective (e.g. feed cost per kilogramme of live weight, production cost per kilogramme of breast meat) or an environmental objective (e.g. phosphorus excretion) and should be quantifiable (e.g. three-point improvement in feed conversion, 2% improvement in live weight in 17 weeks of age in male turkeys). The user and other stakeholders must be aware that some trade-offs must be made because improving one output (e.g. feed conversion) may negatively affect other

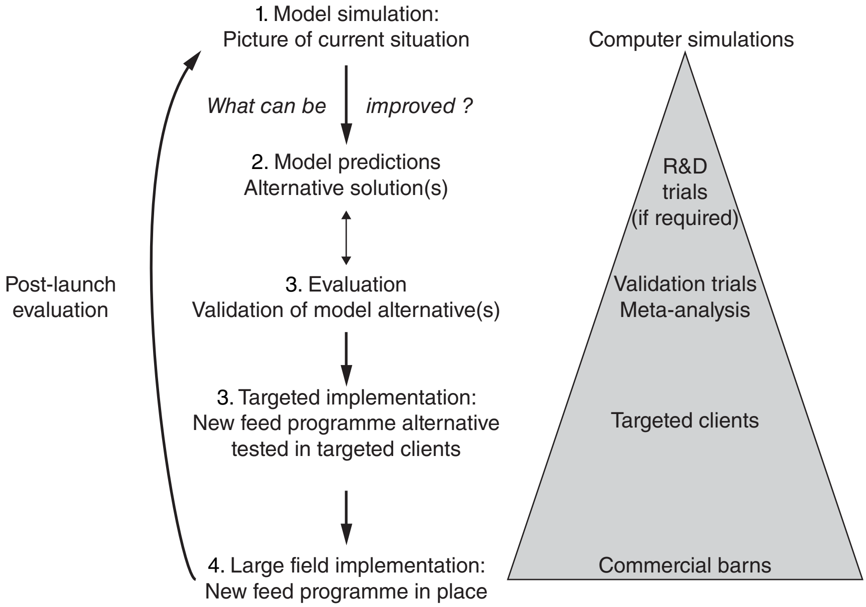


Fig. 8.3. Illustration of the continuous improvement process with animal growth models.

outputs (e.g. feed cost). It is recommended that the pre-defined objective remains reasonable and achievable. Iterative processes of improvement usually represent the most appropriate means of attaining the pre-determined objective with no negative impact on other outputs. In the present section an example is taken where we consider that reducing feed cost by US$0.03/kg of live weight is the pre-defined objective for 6 kg live weight mixed medium turkeys.

Description of present situation and alternatives for improvement

The adjustment of user-defined parameters makes it possible to represent the present situation. The user-defined parameters refer to parameters that define the genetic potential, the environmental conditions and the feed programme (feed sequence and nutrient profile). Adjustments may be performed either manually or through an optimization procedure. Based on the designed situation/simulation the user is capable of evaluating opportunities for improvement through 'what-if' scenarios that explore alternative strategies to reach the pre-defined objective.

In the example above, an alternative to reducing feed cost may be to decrease nutrient levels, although this may negatively affect performance (e.g. feed conversion ratio (FCR)). To quantify the outcomes of alternative solutions 'what-if' simulations may be run to examine the effect of reducing the amino acid levels on weight gain and feed conversion, and thus on feed cost (i.e. three alternative feed programmes; Fig. 8.4).

Validation of model alternatives

Although turkey research studies take several months before completion, validating the model alternatives is recommended before implementing new recommendations. The research trial should consist of a control diet that corresponds to the reference programme, while the other alternative diets constitute the test treatments. Model simulations can therefore be directly compared to the trial results. In Fig. 8.5 the model simulations are compared to observations from a research trial in which different levels of metabolizable energy were tested. While accuracy was moderate (i.e. 10% difference) relative model precision was satisfactory when predicting average daily gain at 49 days and 105 days of age at energy levels varying from 92% to 108% of standard levels (i.e. constant amino acid levels).

As mentioned above, random error may result in differences between simulated and

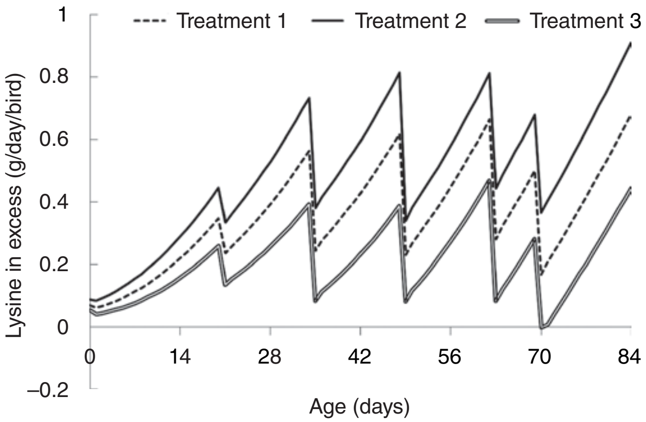


Fig. 8.4. Simulation of excess lysine depending on three commercial feed programmes that vary in dietary amino acid density.

observed values. To avoid this bias the research studies may be replicated to validate the applicability of alternatives for different locations, breeds and genders. As a result of these studies a meta-analysis may be performed to compare the results and validate the selected alternative (Fig. 8.6).

Research studies should be performed along with model simulations until the model has been fully evaluated. Over time, fewer validation trials will be required as model simulations will progressively substitute for research studies, while the model's advantages and limitations will be more clearly understood and precision and accuracy improved.

Implementation

Once the simulated alternative has been selected and validated it can be commercially implemented. A reasonable strategy would

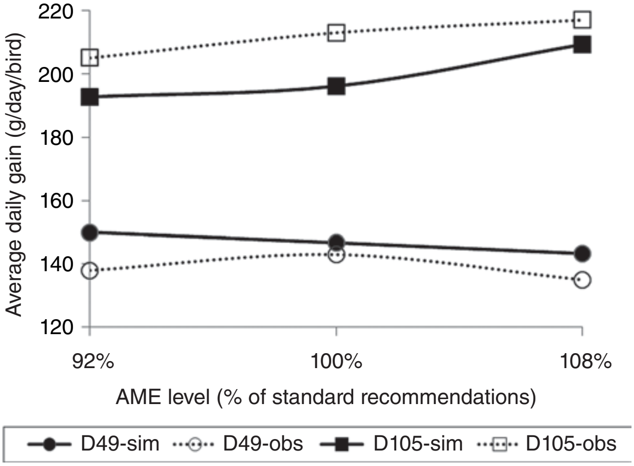


Fig. 8.5. Simulated and observed average daily gains of male turkeys subjected to different metabolizable energy contents (AME, % standard recommendations).

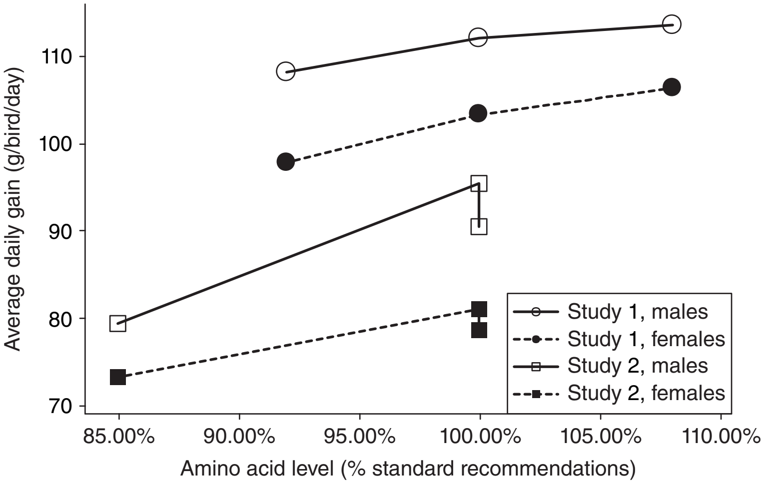


Fig. 8.6. Meta-analysis of the effect of amino acid levels on average daily gain in male and female growing turkeys (i.e. two studies × two genders).

consist of targeting some barns that are well managed and documented so that performance results can be recorded and further used to improve the power of the validation. On the basis of the results from this field validation the new alternative feeding programme may be implemented more generally or as needed in other operations.

Finally, the new alternative programme can be used to run further simulations and evaluate other performance objective improvements. This iterative process is a strategic means for companies to respond rapidly to commercial needs and adapt feed programmes to the growth performance observed in the field while advancing faster in research by testing and validating new recommendations with less need for performing experimental trials.

References

Danfaer, A. (1991). Mathematical modelling of metabolic regulation and growth. *Livestock Production Science* 27, 1–18.

EFG Software (1995) EFG software. Available at: www.efgsoftware.net (accessed May 2013)

Emmans, G.C. and Fisher, C. (1986). Problems in nutritional theory. In: Fisher, C. and Boorman, K.N. (eds), *Nutrient Requirements of Poultry and Nutritional Research*. Butterworths, London, pp. 6–39.

Ferguson, N.S. (2006). Basic concepts describing animal growth and feed intake. In: Gous, R.M., Morris, T.R. and Fisher, C. (eds) *Mechanistic Modelling in Pig and Poultry Production*. CAB International, Wallingford, UK, pp. 22–53.

Kang, C.W., Sunde, M.L. and Swick, R.W. (1985) Characteristics of growth and protein turnover in skeletal muscle of turkey poults. *Poultry Science* 64, 380–387.

Murawska, D. (2013) Age-related changes in the percentage content of edible and nonedible components in turkeys. *Poultry Science* 92, 255–264.

Rivera-Torres, V. and Ferket, P.R. (2012) Recent modeling approaches to simulate turkey growth dynamics as affected by genotype, nutrition and environment. *World Poultry Congress August 5–9, 2012*, Salvador, Bahia, Brazil.

Rivera-Torres, V., Noblet, J., Dubois, S. and van Milgen, J. (2010) Energy partitioning in male growing turkeys. *Poultry Science* 89, 530–538.

Rivera-Torres, V., Noblet, J., Dubois, S. and van Milgen, J. (2011a) Dynamics of energy utilization in male and female turkeys during growth. *Animal* 5, 202–210.

Rivera-Torres, V., Noblet, J. and van Milgen, J. (2011b) Changes in chemical composition in male turkeys during growth. *Poultry Science* 90, 68–74.

Rivera-Torres, V., Ferket, P.R. and Sauvant, D. (2011c) Mechanistic modeling of turkey growth response to genotype and nutrition. *Journal of Animal Science* 89, 3170–3188.

Sauvant, D. and Martin, O. (2010) Robustness, Rusticity, flexibility, plasticity... the quality new criteria of farm animals: systemic and biological definitions of the various concepts. *INRA Productions Animales* 23, 5–10.

Tedeschi, L.O. (2006) Assessment of the adequacy of simulation models. *Agricultural Systems* 89, 225–247.

9 INAVI: A Practical Tool to Study the Influence of Nutritional and Environmental Factors on Broiler Performance

B. Méda,[1]* M. Quentin,[2] P. Lescoat,[3] M. Picard[1] and I. Bouvarel[4]
[1]*INRA, Nouzilly, France;* [2]*Maïsadour, Mont-de-Marsan, France;*
[3]*AgroParisTech, Paris, France;* [4]*Institut Technique de l'Aviculture,*
Nouzilly, France

Abstract

The technical and economic results of a broiler flock depend on complex interactions between the animal and nutritional and environmental factors. It is possible to approach this complexity by considering the animal as a component of a mechanistic model, which can represent the diversity of genotypes and farming practices. INAVI simulates broiler growth as a function of nutritional and environmental parameters. The animal is represented by a simplified diagram of its energy balance with few parameters including physical activity expenditures. INAVI is first calibrated with user data (reference curves for feed intake and growth) associated with 'optimal' nutritional and environmental conditions. At each time step (1 h), the actual feed intake is estimated from the comparison (thermostat) between calculated and reference heat production. Inputs change the energy flows inside the simulation submodel using accessible response laws. A user is therefore able to adapt the model to their own data by changing these laws. Simulations illustrating the potential use of INAVI by different stakeholders of the poultry supply chain are presented in this chapter. In that sense, INAVI could be helpful to design new and more sustainable poultry production systems. However, this will require further improvements to the model, and thus stresses the never-ending process of modelling.

Introduction

Dealing with poultry production is a combination of coordinated actions (from bird selection to final product transformation) needed to obtain the relevant final animal product in a given context to answer consumer and citizen demands. Sustainability issues (such as environmental impacts, farmer income or animal welfare) should therefore be taken into account all along the supply chain.

Combining the three sustainability pillars (environment, economic, social) and the complex environment surrounding farming systems leads to strong challenges regarding poultry production. These three pillars call into question broiler management and highlight the key role of understanding broiler growth in the poultry chain. Growth is a key phenomenon since it results from the combination of numerous nutritional, environmental and animal factors. Therefore, improving

---

*E-mail: bertrand.meda@tours.inra.fr

Nutritional Modelling for Pigs and Poultry (eds N.K. Sakomura *et al.*)

broiler production requires understanding of most of the mechanisms leading to a given level of production within a poultry shed. The model described in this chapter, called INAVI (as a contraction of INRA (research institute) and ITAVI (extension services)), to stress its double purpose (i.e. to be useful for both practitioners and researchers), is proposed below to contribute to this aim.

In a nutshell, INAVI is a mechanistic, dynamic and deterministic model that attempts to integrate at the broiler scale a large set of biological mechanisms and response laws to nutritional and environmental parameters. It aims to simulate broiler growth in contrasted conditions for a large range of broiler breeding lines. However, as for most models, INAVI has to be seen more as a tool to enhance the thinking of researchers and practitioners rather than as a prediction tool. The team (M. Quentin, M. Picard, I. Bouvarel; Quentin, 2004) that developed INAVI chose the simplest possible representation to allow both iteration steps and the possibility for every stakeholder to cope with the whole model and therefore to implement new ideas on their own. The description and examples given below illustrate this aspect of an 'open to change by the user' model and underline the never-ending process of modelling broiler growth.

Broiler Growth in INAVI: An Energetic Point of View

The broiler models of Hurwitz *et al.* (1978) and Emmans (1981) use body composition for predictions of both resource requirements and feed intake. The main objective of INAVI (Fig. 9.1) is the simultaneous adaptation of intake and growth with energy use as the main driving force. The aim of the energy model is not to calculate requirements but rather to describe the use of ingested energy for growth.

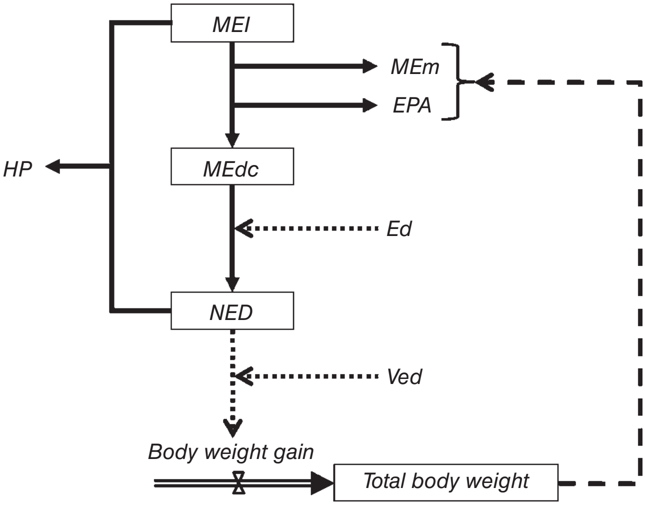


Fig. 9.1. Simplified energy model of INAVI. Ingested metabolizable energy (*MEI*, in kcal) becomes energy available for growth (*MEdc*, in kcal) after withdrawing maintenance requirements (*MEm*, in kcal) and losses for physical activity (*EPA*, in kcal). A fraction of MEdc is deposited, as net energy deposited (*NED*) transformed in body weight gain (in grammes) accumulated in total body weight. Body weight is used to determine *MEm* and *EPA*. The fraction of *MEdc* deposited as *NED* is defined as the efficiency of energy deposition (Ed). Body weight gain is determined from *NED* as a function of the energy content of the weight gain deposited (*Ved*, in kcal/g). Heat production (*HP*) is calculated by difference between *MEdc* and *NED*.

General diagram of energy utilization

INAVI has to remain as simple as possible to remain user-friendly. The representation adopted (Fig. 9.1) by INAVI is based on the use of the metabolizable energy (ME). Feed intake is the main input of the model and is used to calculate metabolizable energy intake (*MEI*, kcal) (defined as the product of feed intake (grammes) by ME dietary content (kcal/kg)). A part of *MEI* is used for maintenance requirements (*MEm*, kcal) and physical activity (*EPA*, kcal). The remaining energy is then defined as the metabolizable energy available for growth (*MEdc*, kcal):

$$MEdc = MEI - MEm - EPA \qquad (9.1)$$

A fraction of *MEdc* is deposited in tissues, the net deposited energy (*NED*, kcal), while the remaining part corresponds to the production of heat associated with these depositions. *NED* is estimated with *MEdc* and a deposition efficiency coefficient (*Ed*):

$$NED = MEdc \times Ed \qquad (9.2)$$

NED is the energy of lipids and proteins deposited, and represents a fraction of the weight gain. The transformation of *NED* into weight gain (Gain, grammes) is estimated by the energetic value of weight gain; that is, the number of calories corresponding to 1 g of weight gain (*Ved*, kcal/g):

$$\text{Gain} = NED/Ved \qquad (9.3)$$

Total body weight (BW) is then calculated from weight gain:

$$\text{Total body weight} = \text{Initial body weight} + \int \text{Gain} \qquad (9.4)$$

Estimation of *MEm*, *Ed* and *Ved*

*Energy for maintenance (*MEm*)*

Maintenance is widely dependent on genotype, feed composition, physical activity and the environment (Van Milgen *et al.*, 1998). It is likely that considering *MEm* as a single function of metabolic weight in broilers of very different growing speeds can be a mistake. To better take into account the potential of every genotype, *MEm* can be considered as a function of body proteins (Whittemore, 1976; Emmans and Fisher, 1986). Some authors even go further by introducing a factor dependent on body weight gain (Black *et al.*, 1986). However, none of these methods can actually represent a real situation. Therefore, in INAVI, the problem related to the determination of *MEm* led to a simplification of the system by considering *MEm* as a function of metabolic weight, which can be adjusted by the user. *MEm* is thus defined as the product of metabolic weight by an index of maintenance (*IM*), an adjustable parameter related to the broiler 'growing shape' (see 'Step 2: calibration of the model'):

$$MEm = IM \times BW^{0.75} \qquad (9.5)$$

*Energy deposition efficiency (*Ed*)*

Ed controls the efficiency of use of *MEdc*. A single parameter does not allow differentiation of the specific efficiency of protein or lipid deposition. Nevertheless, the coefficients of efficiency of deposition of lipid and protein can vary from 0.6 to 0.8 and from 0.4 to 0.6, respectively (De Groote, 1974; Emmans and Fisher, 1986). The use of a single parameter has the advantage of simplifying the system and reducing the number of model parameters, but it can be less flexible. Since the objective of the first version of INAVI was not the prediction of body composition, the use of two coefficients was not required.

An *Ed* value of 0.6 is frequently suggested in the literature as an average (De Groote, 1974). Beyond an oversimplification, *Ed* represents a global metabolic parameter describing the global state of syntheses. We consider that the regulations of these syntheses are probably less sensitive to the feed characteristics, environmental conditions or age than *MEm*, especially in the young growing animal. Therefore, in INAVI, the value of *Ed* is considered to be constant (0.6).

*From *NED* to weight gain in INAVI, the energetic value of weight gain (*Ved*)*

With a variable value of *MEm* and a nearly constant *Ed*, the description of growth is strongly dependent on *Ved*, thus on deposition of protein and lipid. The work of Hancock *et al*. (1995) followed by that of Gous *et al*. (1999) and Sakomura *et al*. (2011) showed that body composition of broilers for a given body weight is comparable from one genotype to another because of a very high pressure of genetic selection. Based on the data of Gous *et al*. (1999), we used Eqn 9.3 to estimate the value of *Ved*. The result of linear regression ($R^2 = 0.998$) of *Ved* according to the body weight (kilogrammes) power 0.6 is described by Eqn 9.6:

$$Ved = 1.56 + 0.63\ BW^{0.6} \qquad (9.6)$$

Nevertheless, as fattening, feathering and protein deposition potential are subject to genetic variations, a factor (*Feg*) was introduced into this equation to allow a modification of *Ved* by the user for a genotype with a very different body composition:

$$Ved = Feg \times (1.56 + 0.63\ BW^{0.6}) \qquad (9.7)$$

Importance of physical activity in energy partitioning

Physical activity (*PA*) can represent from 7% to 15% of the *MEI* in broilers (Wenk and Van Es, 1980). Other behaviours besides movement can be costly from an energetic point of view, such as engaging in social behaviour, eating or perching. Notably, the slow-growing chickens are known to be more active than fast-growing chickens (Bizeray *et al*., 2000; Bokkers and Koene, 2003).

PA represents a cost for the animal but it can also have positive effects. An increase in *PA* of broilers induced by high ventilation rate from 6 to 41 days improves growth without changing feed conversion. Increases in breast meat yield and feed efficiency, and a decrease in fattening were also measured in active animals compared to less active ones (Lei and Van Beek, 1997). A positive correlation between feed conversion and the 'standing' behaviour was clearly demonstrated by Skinner-Noble *et al*. (2003).

In most models, energy related to the physical activity (*EPA*) is included in maintenance requirements, so it is impossible to represent the evolution of *EPA* and modulate it according to the situations. *EPA* can be strongly modified by nutritional or environmental conditions of production. For example, physical characteristics of feed (Savory, 1974) and temperature strongly influence the physical activity of chickens. INAVI has the objective of representing the largest possible number of production systems and conditions. It seems relevant to separate the part of *MEI* used for *PA* from the part used for maintenance to improve the adaptability of the model.

Modelling of the level and the energy cost of the physical activity (*EPA*)

In INAVI, the activity of the animal is represented as the percentage of time during which the animal is standing up. This measure is made by scan-sampling (Picard *et al*., 1999) at the beginning of a period. It defines the initial activity (Initial *PA*) of animals. In INAVI, we consider that the physical activity level (*PAL* in %, i.e. the percentage of time of activity) decreases linearly with time from initial *PA*, using a constant, the activity factor (*AF*, %) (Eqn 9.8). The observation of fast-growing broilers in experimental pens from 4 to 6 weeks of age supports this view (Fig. 9.2).

$$PAL = \text{Initial } PAL - AF \qquad (9.8)$$

The main challenge in the modelling of *PA* is to transform the level of activity (*PAL*) into energy. Baker and Gleeson (1999) considered that the heavier the animal is, the higher the energy cost of *PA*. Therefore, to model this approach in a simple way, we consider the energy cost of *PA* (*EPA*, kcal) as a function of *PAL* and *BW*, using an activity unit (*AU*, kcal/%*PAL*/g *BW*) that represents the energy cost of 1% of *PAL* per gramme of body weight.

$$EPA = PAL \times AU \times BW \qquad (9.9)$$

To estimate *AU*, we used the data from an experiment carried out in the Poultry Research Unit (INRA Nouzilly, France) and the data used for the study of *Ed* and *Ved* (see above). The initial *PA* was 30% for standard broilers of 28 days with an *AF* of 0.8%/day. According

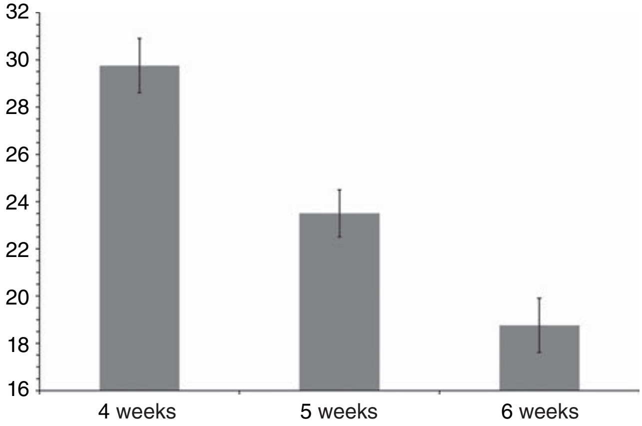


Fig. 9.2. Proportion of fast-growing broilers (12 pens, 25 chickens) observed standing at 4, 5 and 6 weeks of age. Values were obtained by scan-sampling from five observations during four periods (8:00, 12:00, 16:00 and 20:00) of day time. (From Quentin, 2004.)

to Wenk and Van Es (1980), *PA* represents 7% to 15% of *MEI* in fast-growing broilers (from 20 to 40 days of age) in normal measurement conditions in respiratory chambers. We therefore fixed *AU* at a value of 1.5 kcal/% *PAL*/g *BW* so that *EPA* represented 10% of *MEI*. However, this parameter is considered as a constant, independent of *BW*, *PAL* and the age of the animal. The current determination of AU lacks precision but this value can be modified by the user (according to new research or calculations).

Feed Intake Regulation: The Notion of a Thermostat

The main hypothesis regarding feed intake in the current model is based on the adaptation of the animal to its requirements under optimal production conditions. The calculation of energy requirements from body composition and the description of the energy balance of the animal is the classical way to predict feed intake in broilers (Emmans and Fisher, 1986). Even if this approach is successful in ‘optimal’ conditions, predictions are not always fully accurate in ‘non-optimal’ ones. In practice, there is always at least one constraint. The thermolysis capacity of the animal seems to be a factor regulating feed intake, representing a major limit on its metabolic capacities for adaptation.

Are the limits on feed intake physical or physiological?

A decrease in dietary energy content as well as changes in the physical characteristics of the diet (e.g. pellets vs meal) tend to increase feed intake in relatively large proportions, before the physical limit of the animal is reached. This seems to indicate that broilers are almost always physically capable of ingesting more feed. On the other hand, the range of physiological adaptation may be more limiting. Body temperature is never constant, but since broilers are homoeothermic animals, body temperature variations cannot exceed 2–3°C without jeopardizing the survival of the animal (De Basilio *et al.*, 2001). Fast-growing broilers produce more heat than laying hens or slow-growing broilers, and are also more sensitive to the temperature of their environment. Therefore, a major problem for these animals is to dissipate the heat produced by feed intake and their metabolism (Yalcin *et al.*, 1997).

Modelling feed intake regulation

In order to regulate energy intake, we introduced the concept of the ‘thermostat’, which compares the thermal balance in simulation conditions and reference ones.

Two submodels of similar architecture are included: the first for the reference conditions and the second for the simulation conditions (Fig. 9.3). The simulation submodel is the only one connected to the response laws, taking into account the effects of environmental or nutritional factors on the parameters controlling the energy flows in INAVI. The reference submodel is only used to describe reference conditions, considered as 'optimal' by the user, and to calibrate the two parameters *IM* and *AF* described previously.

In reference conditions, we consider that heat production (*HP*) is the expression of an optimal thermal balance. The principle of homeostasis implies that the animal will modify its metabolism in order to maintain this balance. In INAVI, the optimal thermolysis capacity of the animal is defined as the reference *HP* (HP_{ref}) per unit of metabolic weight (kcal/kg$^{0.75}$):

$$HP_{ref} = MEI_{ref} - NED_{ref} \quad (9.10)$$

$$\text{Thermolysis capacity} = HP_{ref}/BW_{ref}^{\;0.75} \quad (9.11)$$

Similarly in the simulation submodel, *HP* is calculated as:

$$HP = MEI - NED, \text{ if } MEI > MEm + EPA$$
$$HP = MEm + EPA, \text{ if } MEI \leq (MEm + EPA) \quad (9.12)$$

The thermostat is the expression of the thermal balance of the animal with regard to an optimal situation. It quantifies 'the energy excess' to be eliminated or the 'energy deficit' to be filled, that is, the difference between thermolysis capacity and simulated *HP*, calculated as

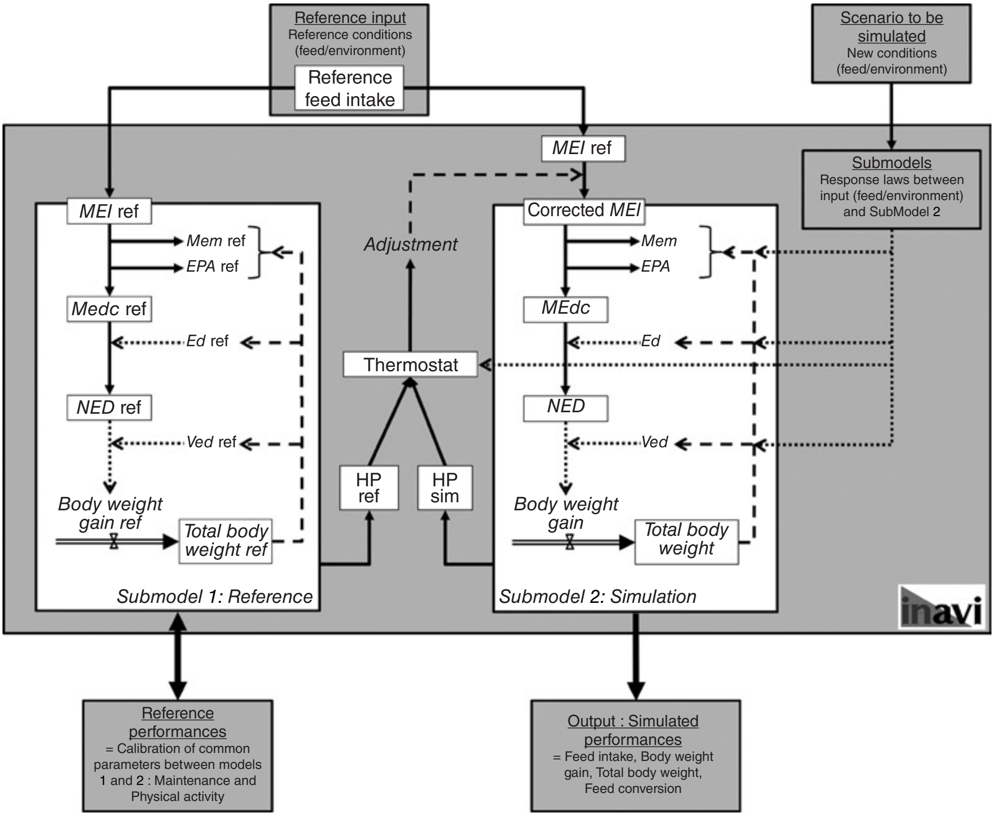


Fig. 9.3. Simplified diagram of INAVI dynamic behaviour. INAVI includes two submodels (1 reference and 2 simulation) allowing the adjustment of performances to the reference taking into account the simulation scenario (set of parameters), which acts on the simulation model thanks to specific response laws. The feed intake adjustment of the reference submodel uses a retroactive thermostat loop that corrects the metabolizable energy intake (*MEI*).

thermolysis capacity multiplied by the simulated metabolic weight (Eqn 9.13). In a dynamic model, it is represented as an accumulation variable for the duration of the simulation:

$$\text{Thermostat} = \int(HP - \text{Thermolysis capacity} \times BW^{0.75}) \quad (9.13)$$

A positive or negative balance of the thermostat induces, respectively, a decrease or an increase in *MEI* at the next time step of the simulation. The correction (Eqn 9.14) is determined by a modifiable factor (Adaptation level) that translates the calories of heat produced into *MEI* calories. Its value is set to 1.5 kcal *EMI*/kcal *HP* but can be modified by the user. Corrected *MEI* is then calculated as the difference between MEI_{ref} and *MEI* correction as shown in Eqn 9.15 (Fig. 9.3).

$$MEI\ \text{correction} = \text{Adaptation level} \times \text{Thermostat} \quad (9.14)$$

$$\text{Corrected}\ MEI = MEI_{ref} - MEI\ \text{correction} \quad (9.15)$$

Mobilization of the reserves

In some cases, the animal has no more access to the feed (e.g. at night). The thermal balance becomes negative and body reserves become the only source of energy for maintenance requirements. In that case, *MEI* is equal to 0 and *MEdc* becomes negative, representing the energy deficit related to the maintenance. In this situation, NED does not represent the deposited energy anymore, but rather the energy needed to cover the maintenance requirements. The efficiency of deposition (*Ed*) becomes meaningless and thus *NED* is defined according to Eqn 9.16:

$$NED = MEdc, \text{ if } MEdc < 0 \quad NED = MEdc \times Ed, \text{ if } MEdc \geq 0 \quad (9.16)$$

In such conditions, weight gain actually represents weight loss related to the use of the body reserves. The energetic value of deposition (*Ved*) is no longer bound to the lipid:protein ratio of growth, but takes the value of 7.4 kcal/g of weight loss per calorie of *NED* (i.e. raw energy of 1 g of lipid (9.3) multiplied by efficiency of use (0.8)) since body lipids are considered as the only source of energy.

Maximum feed intake

The thermostat approach is limited because the quantity of feed ingested by the animal cannot be infinite. The quantity of feed consumed (grammes) is limited by a maximum consumption (grammes) defined as the reference consumption (grammes) multiplied by a physical capacity (Eqn 9.17), an adjustable value, set to 2 in INAVI, which means that in 1 h (time step of the model), the animal cannot ingest more than twice the reference feed intake. This value of 2 corresponds to a practical situation in periods of starvation. It might be adjusted for more restrictive systems.

$$\text{Maximum consumption} = \text{Physical capacity} \times \text{Reference consumption} \quad (9.17)$$

The simulated *MEI* is thus defined in the following way:

$$\begin{aligned} MEI &= \text{Corrected}\ MEI, \text{ if Corrected}\ MEI \leq \text{Maximum consumption} \\ MEI &= \text{Maximum consumption, if Corrected}\ MEI > \text{Maximum consumption} \end{aligned} \quad (9.18)$$

The architecture shown here defines the base of INAVI functioning. It is a simplified energy model with two versions (submodels). The first one establishes the reference energy balance (heat production, thermolysis capacity), which is calibrated with the reference data (growth, feed intake) provided by the user. The second is the simulation submodel, which takes into account nutritional and environmental factors and their consequences for the energy balance. To maintain this balance, feed intake is regulated through a control loop, the thermostat (Fig. 9.3).

Taking into Account Nutritional and Environmental Factors and their Effects on Energy Balance

General approach

In the conceptual approach of INAVI, simulation conditions (i.e. environmental and nutritional factors) influence energy flows within the animal, thus inducing an adaptation of feed intake. One or several factors can influence variables such as *Ed*, *Ved*, etc. Therefore, in order to study the respective effects of these factors on a variable, we defined specific response laws; that is, the relationship between an influencing factor (e.g. ME content) and the variation of this variable, represented by a dimensionless weighting coefficient (variation factor, *VF*). Except for two factors (limiting amino acid level and fine particle level), *VF* values are always expressed as a function of the difference between simulation and reference values of the factors. Furthermore, this approach allows users to modify existing laws or implement new ones in the model.

The variable in the simulation is then calculated as the variable value in the reference conditions multiplied by the product of all *VF* values as shown in Eqn 9.19:

$$\text{Variable} = \text{Variable} \times \prod VF \qquad (9.19)$$

Feed characteristics

Dietary ME content

Several authors have reported an increase in carcass fattening with the increase in dietary ME content (Jackson *et al.*, 1982; Leeson *et al.*, 1996). In our approach, this fattening is connected with an increase in *Ved* of 13% for an increase in ME content of 1000 kcal/kg (in comparison with the reference ME content) as shown in Fig. 9.4a. However, when simulating an increase in ME content from 2900 to 3400 kcal/kg, *BW* was decreased by 7%, which is not realistic. The adjustment of *Ed* was thus necessary to remove this paradoxical effect from INAVI. The regulation of *Ed* according to ME content was based on the data of Jackson *et al.* (1982), with an increase or a decrease of *Ed* of 7% and 6% for an increase or a decrease in ME content of 1000 kcal/kg, respectively (Fig. 9.4a). This balance between *Ed* and *Ved* might be connected to the ME origin, which could be composed of more digestible nutrients.

Dietary crude protein content

In the model, dietary crude protein (CP) content was segregated from essential amino acids (EAA) requirements *sensu stricto*. In practice, feed formulation is generally carried out with minimum levels of EAA and a minimum level of protein. However, CP content (%) was taken into account in the function of ME content by calculating an ME:CP ratio.

The increase in CP content (i.e. decrease in the ME:CP ratio) of the feed is associated with a decrease in fattening and an increase in protein deposition, thus decreasing the value of *Ved*. To calculate these variations, the body composition of broilers fed with regimes of protein content varying from 16% to 36% were used to measure the variations of *Ved* from 0 to 49 days of age (Jackson *et al.*, 1982). A linear relationship between ME:CP and *Ved* was found, and we therefore considered that an increase of 100 units of ME:CP resulted in a 20% increase in *Ved* (Fig. 9.4b).

The effect of the ME:CP ratio on *Ed* was estimated by adjusting *Ed* in order to fit simulated performances to measured performances from Sklan and Plavnik (2002). The increase in CP content from 18% to 24% (ME:CP values of 178 and 133, respectively) induced a decrease of 7% in feed consumption and an increase in growth of 5.5%. The authors also measured a 6% decrease in feed conversion. After adjustment, the effect of ME:CP was estimated to be linear, with an improvement in deposition efficiency (*Ed*) of 10% for an increase of 100 units in the ME:CP ratio (Fig. 9.4b), which could be explained by a higher proportion of lipids deposited in total weight gain. The articulation of *Ed* and *Ved* in connection with the ME:CP ratio emphasizes the importance of examining the intermediary metabolism and consequently the gain content according to the supplied nutrients and the tested bird lines.

Dietary amino acid content

The EAA content of the feed is not taken into account in absolute values but by considering the level of the first limiting EAA. In INAVI,

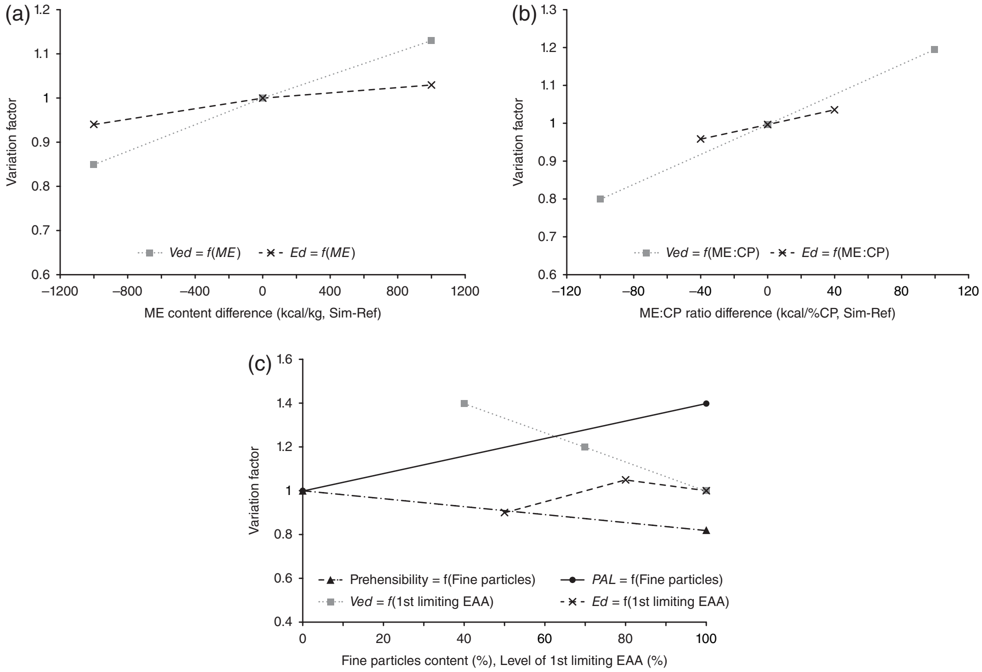


Fig. 9.4. Responses of *Ed* (ME deposition efficiency), *Ved* (energy value of the body weight gain), prehensibility (ease of feed intake), *PAL* (physical activity level) to interacting parameters: (a) changes in *Ed* and *Ved* according to ME dietary content; (b) changes in *Ed* and *Ved* according to ME:CP ratio; (c) *Ed* and *Ved* changes according to the first limiting essential amino acid (EAA), prehensibility and *PAL* according to fine particle levels in the diet.

it is expressed as a percentage (e.g. a value of 80% corresponding to a level equivalent to 80% of requirements).

A deficiency in an EAA has consequences at different levels. First of all, *Ed* is reduced because the protein syntheses are limited by the first limiting EAA. This decrease in protein syntheses is associated with an ME excess, which is converted into lipids (Quentin *et al.*, 2005), thereby inducing an increase in *Ved*.

Sibbald and Wolynetz (1986) measured the response of young broilers (10 to 18 days of age) to the content of lysine in the regime. *NED* and *Ved* were recalculated from body composition data. By indexing *Ved* and the level of lysine as 100 for the optimal regime, the linear increase of *Ved* up to 120% of the initial *Ved* value was observed for between 100% and 70% of the optimum lysine level. It was extrapolated to reach 140% of the *Ved* value for the reference for 40% of the lysine requirement (Fig. 9.4c).

The effect of the EAA level on *Ed* values is more difficult to quantify due to the complexity of experimental measurement. Nevertheless, the *Ed* value is essential in the adaptation of feed intake due to its effect on the energy balance and the thermostat. *Ed* was therefore estimated by adjusting simulated feed conversion to the measurements of Mack *et al.* (1999) for different levels of first limiting EAA. Two situations may be distinguished in the evolution of *Ed* with the changing levels of first limiting EAA: first, there is a slight improvement of *Ed* between 100% and 80% of requirements; second, there is a decrease in *Ed* at between 80% and 50% of requirements (Fig. 9.4c). The improvement in *Ed* observed in sub-deficiency conditions can be explained by the adaptation of the animal. A slight overconsumption of feed is generally observed in these conditions. In the model, the same phenomenon can be observed because production of heat is reduced (in relation to the lower protein synthesis). Yet, the adaptation capacities of the animal are quickly exceeded, explaining the decrease in *Ed* in real EAA deficiency conditions.

Diet particle size

Results from experiments by Quentin *et al.* (2004) were used to represent the influence of levels of fine particles on feed intake (through a variable called 'prehensibility' directly modulating feed intake both in reference and simulation submodels) and *PAL*. The performances of broilers (15–35 days of age) were compared by feeding them with pellets (0% fine particles) or meal (100% fine particles). In broilers fed with meal, feed intake decreased by 18% and *PAL* was estimated to be 140% of that on the pelleted diet. Between these values, the evolution of *PAL* and prehensibility were both considered to be linear as shown in Fig. 9.4c, even if the fine level could also fit a linear-plateau model, that is, if the proportion of fine particles is lower than 30%, they have no effect on *PAL* (Quentin *et al.*, 2004).

Environmental factors: the notion of perceived temperature

Estimation of perceived temperature

The environment strongly influences the heat loss of the chicken, specifically the combination of several parameters such as indoor temperature (T_{indoor}); air relative humidity (%) and air speed (m/s) above the animals (Yahav, 2000). Animal density (birds/m²) also modulates the actual perception of heat. The combination of these factors determines a 'perceived temperature' (noted *Tp*), actually felt by the animal, which influences the balance between thermogenesis and thermolysis. In INAVI, *Tp* is calculated as the sum of T_{indoor} with additive effects of these factors ($E_{density}$, $E_{humidity}$ and $E_{airspeed}$):

$$Tp = T_{indoor} + E_{density} + E_{humidity} + E_{airspeed} \tag{9.20}$$

An increase in animal density is associated with a decline in the performances (Feddes *et al.*, 2002). The influence of density on *Tp* was taken into account by adjusting the model results according to the data of Feddes *et al.* (2002). In INAVI, we therefore considered there to be an increase in temperature of 0.18°C per supplementary kg/m² (Fig. 9.5a). However, when simulation stocking rate was below 20 kg/m² or lower than the reference, the influence of animal density was considered to be negligible.

From 4 to 8 weeks of age, the growth of the broilers exposed to a temperature of 35°C is a parabolic function of relative humidity, with an optimum between 60% and 65% (Yahav *et al.*, 1995). Indeed, under high temperatures (greater than 28°C), the main method of thermolysis is hyperventilation (panting), thus heat losses are mainly latent. A relative humidity that is too high reduces the efficiency of thermolysis and the animal quickly becomes hyperthermic, with a decrease in feed intake and growth. In contrast, when relative humidity is lower than the optimum, thermolysis is easier but water losses due to hyperventilation cannot be totally compensated for and quickly lead to a respiratory alkalosis, also affecting growth (Teeter *et al.*, 1985). Based on the data of Yahav (2000), we therefore considered an influence of +0.095°C per % of relative humidity higher or lower than the optimum as shown in Fig. 9.5b.

Air speed (m/s) above the animals reduces the sensation of heat by convection, which increases the feeling of coolness. The effect of air speed (from 0.5–3 m/s) on growth was measured by Yahav *et al.* (2001) at high temperatures (35°C). The adjustment of the INAVI results based on the results of Yahav *et al.* (2001) led to a decrease in *Tp* of 3.3°C between 0 and 2.5 m/s, while for an air speed over 3 m/s, *Tp* was only reduced by 2.2°C (Fig. 9.5c). This relationship is only valid for T_{indoor} values below 26°C. Above 26°C, we considered there to be a linear decrease (empirical estimate) of 5°C for an increase in air speed of 1 m/s as shown in Fig. 9.5c.

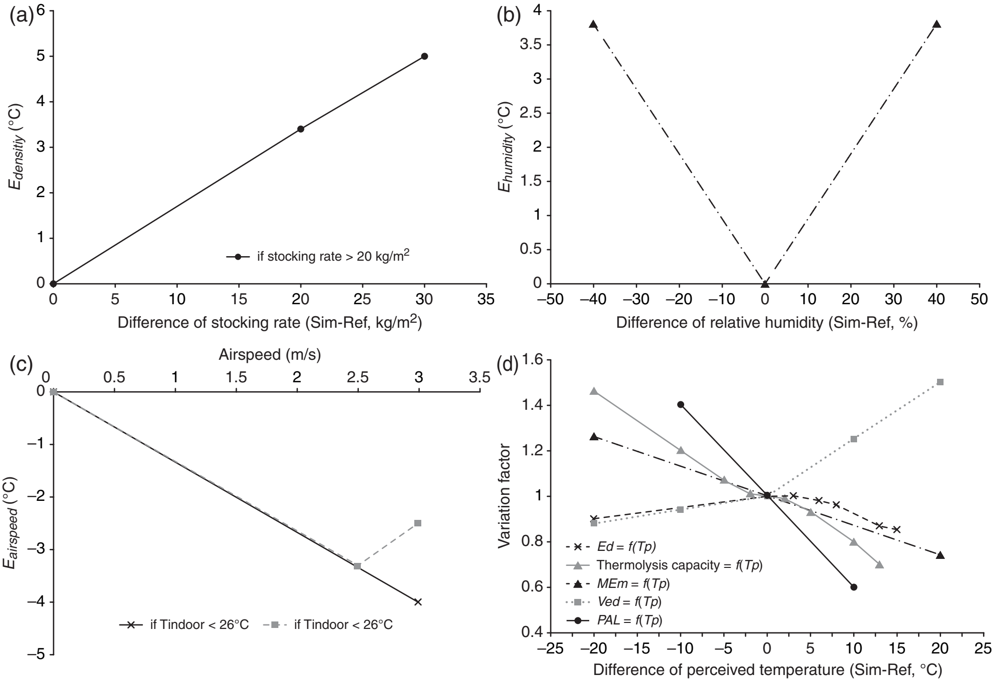


Fig. 9.5. Responses of bird-perceived temperature (*Tp*, °C) to various parameters: (a) stocking rate; (b) relative humidity; (c) air speed (ventilation); and (d) impact of *Tp* on various parameters – *Ed*, Thermolysis capacity, *Ved*, *PAL* and *MEm* (ME for maintenance).

Influence of perceived temperature on Ed, Ved, *heat production, physical activity and* MEm

Many mechanisms are involved in regulating broiler metabolism and thus maintaining homeostasis. In INAVI, we took into account only five of them. Furthermore, two situations can be distinguished according to the value of simulated *Tp*, in comparison with an 'optimal' temperature that we considered as the reference (i.e. *Tp* lower or higher than 'optimum').

ED. Below 'optimal' temperature, the efficiency of synthesis mechanisms as well as growth is considered to change little (Howlider and Rose, 1987). Therefore, in INAVI we considered that *Ed* is decreased by 1% when the temperature is 2°C below the 'optimal' temperature (Fig. 9.5d).

To represent the changes in *Ed* above the 'optimal' temperature, *Ed* was adjusted so that the simulated results fitted to the observations of Geraert *et al.* (1996), which resulted in a decrease in the *Ed* value with increasing temperature difference between the simulation and reference conditions as shown in Fig. 9.5d.

VED. Below 'optimal' temperature, Howlider and Rose (1987) measured an increase in fattening of 0.8% per supplementary °C associated with a growth decrease of 0.12%. From these results, we estimated there to be a decrease in *Ved* of 0.6% for a decrease of 1°C below the reference temperature. Above the 'optimal' temperature, the results from Geraert *et al.* (1996) showed that protein deposition decreased by 8% when comparing broilers reared at 22°C and 32°C, which corresponds to an increase in *Ved* of 2.5% per supplementary °C (Fig. 9.5d).

HEAT PRODUCTION. Koh and Macleod (1999) measured *HP* without physical activity in commercial broilers of 28 days of age between 15°C and 32°C. They showed that a decrease of 1°C in temperature resulted in an increase of 2.3% in *HP* (Fig. 9.5d). Equation 9.10 is then multiplied by this *VF* to estimate the thermolysis capacity in simulation conditions.

PHYSICAL ACTIVITY. When reared in cold conditions (i.e. below 'optimal' temperature), broilers spend more time feeding, which increases their physical activity (and helps to produce heat). Because data were missing, the effect of cold on physical activity was adjusted from the equations of Howlider and Rose (1987). In INAVI, a decrease of 10°C below 'optimal' temperature induced an increase in physical activity of 40%. Above 'optimal' temperature, we considered that the decrease in physical activity with increasing temperature was of the same order of magnitude (Fig. 9.5d).

Hurwitz *et al*. (1980) measured the effect of the ambient temperature on maintenance requirements of broilers from 4 to 9 weeks of age. The influence was found to be linear with a decrease in *MEm* of 1.32% when temperature is increased by 1°C (Fig. 9.5d).

From the Conceptual Model to a Practical Tool: Evaluation of Performances in New Conditions, a Three-step Simulation

Step 1: description of reference and simulation conditions

A Microsoft Excel® sheet is used to describe the reference conditions. The studied age period and the reference physical activity (%), which is considered to be representative of the genotype, are first described.

Three tables are then filled out to describe, on a daily basis, the reference conditions:

Daily performances: feed consumption (g) and weight gain (g).

Feed characteristics: ME content (kcal/kg), crude protein content (%), fine particles (<0.5 mm) content (%), level of primary limiting amino acid (%).

Environmental conditions: average indoor temperature (°C), average indoor relative humidity (%), animal density (birds/m^2) and air speed (m/s).

Step 2: calibration of the model

The calibration step is essential in the use of INAVI in order to fit two parameters (index of maintenance, *IM*, and the activity factor, *AF*) according to the reference performances observed by the user. These two parameters are considered to be representative of the genotype and will be used to calculate reference heat production, which is necessary for the adaptation of feed intake by the thermostat.

The calibration is carried out with VENSIM®, whereby the user modifies the values of *IM* and *AF* manually with cursors in order to fit the reference performances calculated by the model to the reference performances observed by the user (Fig. 9.6). After that, obtained values of *IM* and *AF* must be manually noted in the Excel sheet to be used later for the simulations.

Step 3: simulations

The simulation process requires the description of the simulation conditions in the same Excel sheet. To that purpose, the user must fill out two tables containing feed characteristics and environmental conditions of the simulation (with the same variables as for the description of reference conditions). The simulation is then launched from VENSIM® and takes only a few seconds.

Examples of Simulations

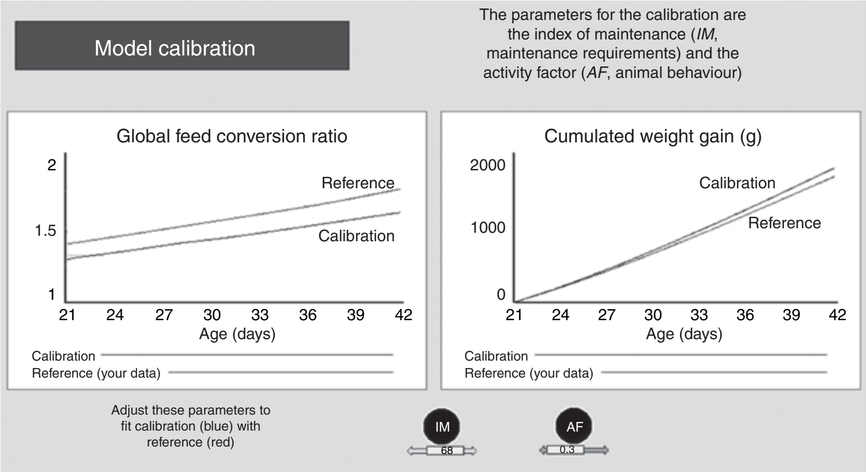
Two examples are given to illustrate how INAVI might be used to assess the impact of nutritional and environmental factors on broiler performances (growth, intake). In order to easily compare these simulations, the reference scenario will be identical for each simulation, and only one factor will differ among them.

Reference scenario

The reference scenario (Ref.) simulates the performances of fast-growing broilers (Ross PM3) reared at an animal density of 15 birds/m² between 21 and 41 days of age. During this period, birds were given two successive diets (3175 kcal ME/kg, 21% CP from day 21 to day 28; 3225 kcal ME/kg, 20% CP from day 29 to day 41) as shown Table 9.1.

Effect of indoor temperature

To show the influence of the temperature on broiler performances through the regulation of feed intake (see 'Feed intake regulation: the notion of a thermostat'), we investigated a scenario (T+6) in which we simulated the effect of chronic exposure to higher temperatures



Model calibration

The parameters for the calibration are the index of maintenance (*IM*, maintenance requirements) and the activity factor (*AF*, animal behaviour)

Adjust these parameters to fit calibration (blue) with reference (red)

Fig. 9.6. Calibration curves of the INAVI simulation model. *IM* (maintenance requirements coefficient) and *AF* (activity factor, slope of change in physical activity with age) should be moved up to a strict recovery of the calibration and reference curves of global feed conversion ratio and cumulative weight gain.

Table 9.1. Scenarios tested by INAVI simulation model.

Scenario	Feed ME content	Feed CP content	Indoor temperature	Fine particle level in feed (<0.5 mm)
Reference (Ref.)	21–28 days: 3175 kcal/kg 29–41 days: 3225 kcal/kg	21–28 days: 21% 29–41 days: 20%	21–24 days: 24°C 25–28 days: 23°C 29–32 days: 22°C 33–41 days: 21°C	0%
T+6	Ref.	Ref.	+6°C compared to Ref.	Ref.
Fine100%	Ref.	Ref.	Ref.	21–34 days: Ref. 35–41 days: 100%

ME: metabolizable energy; CP: crude protein; Ref.: reference scenario; T+6: constant heat stress of 6°C; Fine100%: 100% fine particles (<0.5 mm) instead of pellets for 7 days.

(+6°C in comparison to Ref. scenario) throughout (i.e. from 21 to 41 days).

When broilers are reared in hot conditions (+6°C compared to Ref.) with no nutritional changes, growth performances are reduced by about 20% for the two periods corresponding to the two successive diets (days 21–28, days 29–41, respectively), with average daily gain of 58.9 g/day (vs 71.6 g/day for Ref.) and 70.3 g/day (vs 87.4 g/day for Ref.) for these two periods (Fig. 9.7). These differences in average daily gain (*ADG*) can be explained by a lower feed intake, with average daily intake (*ADI*) of 106 g/day (vs 118 g/day for Ref., –10%) and 142 g/day (vs 168 g/day for Ref., –16%), respectively for the two periods (Fig. 9.8). This lower feed intake can be explained by a lower thermolysis capacity (i.e. the capacity of the animal to evacuate heat) in the T+6 scenario (–17% on average between day 21 and day 41). As a consequence, the animal has to reduce its feed intake in order to adapt its heat production to its thermolysis capacity. Thus, *NED* is reduced by about 8% and, combined with an increase of *Ved* (+15%) leads to a higher *FCR* (feed conversion ratio) of about 6% in T+6 compared with Ref. (1.93 vs 1.81 g/g, respectively) (Fig. 9.9).

Effect of feed level of fine particles

This scenario (Fine100%) presents the influence of physical form of diet (i.e. particle size) on the performance of a broiler between 21 and 41 days of age, in comparison to the Ref. scenario. We simulate a transition from a full-pelleted diet with no fine particles (<0.5 mm) to a meal diet with 100% fine particles (e.g. after the delivery of feed that has not been well processed) from 35 days until 41 days of age.

The transition from a full-pelleted diet to a meal diet with 100% fine particles decreased growth performances by 31% over the period days 35–41, with *ADG* values of 61.9 and 89.9 g/day, respectively, for Fine100% and Ref. scenarios (Fig. 9.7). This can be explained mainly by the lower *ADI* during this period (–21%, 142 vs 180 g/day, respectively, for Fine100% and Ref.), in relation to poor prehension of diet by the animal (–18% compared to Ref., Fig. 9.8). At the same time, the animal uses more energy in physical activity (*EPA*) to catch the same amount of feed (+40% compared to Ref.), which cannot be therefore used for growth.

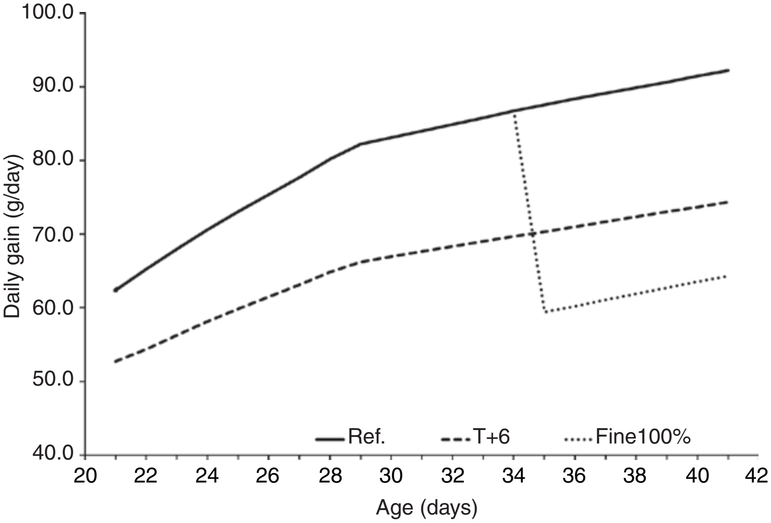


Fig. 9.7. Evolution of daily gain from 21 to 41 days of age in four simulations compared to the reference scenario (Ref.). T+6: reference indoor temperatures + 6°C compared to Ref. Fine100%: at 35 days, transition from a diet without fine particles (<0.5 mm) to a diet with 100% fine particles.

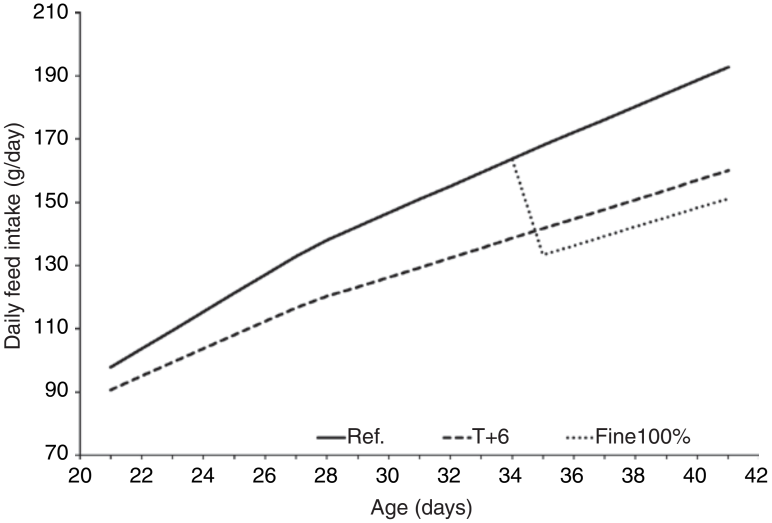


Fig. 9.8. Evolution of daily feed intake from 21 to 41 days of age in four simulations compared to the reference scenario (Ref.). T+6: reference indoor temperatures + 6°C compared to Ref. Fine100%: at 35 days, transition from a diet without fine particles (<0.5 mm) to a diet with 100% fine particles.

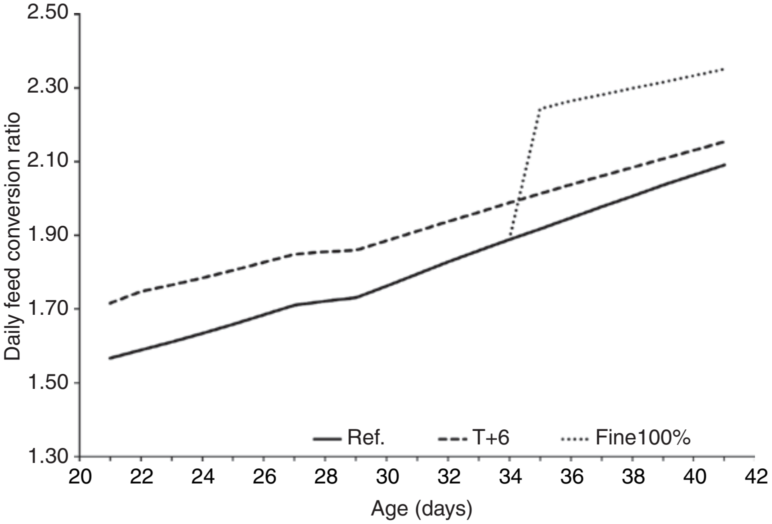


Fig. 9.9. Evolution of daily feed conversion ratio from 21 to 41 days of age in four simulations compared to the reference scenario (Ref.). T+6: reference indoor temperatures + 6°C compared to Ref. Fine100%: at 35 days, transition from a diet without fine particles (<0.5 mm) to a diet with 100% fine particles.

As a consequence of this decrease in feed intake and daily gain, *FCR* for the 35–41-day period is higher in Fine100% (2.30 g/g) than in Ref. (2.01 g/g) as shown in Fig. 9.9. This simulation underlines the importance of taking into account the physical characteristics of diet in order to maintain animal performance, especially during feed transition as recommended by Quentin *et al.* (2004).

Discussion and Perspectives

Previously most authors have considered growth performance from an energetic standpoint. They usually took for granted that feed intake was the consequence of growth, as the means to achieve their growing potential. However, many factors (i.e. nutritional and environmental ones) are known to be involved in the regulation of feed intake, making it difficult to predict feed intake precisely by considering only nutritional requirements. We chose to consider growth as a consequence of energy intake. To regulate feed intake, INAVI is based on the thermostat concept, which computes the energy balance between a reference model in 'optimal' conditions and a simulation model in 'non-optimal' ones. This concept stresses that thermal balance is a key issue for the animal, and it could be considered as the homeostatic regulating mechanism, since the animal will try to adapt its heat production according to its capacity to evacuate it on a short-term scale (less than 1 h). However, since energy balance is not the only key to the regulation of feed intake, INAVI also takes into account regulations based on feed characteristics (composition, size of particles). It could be asked what the threshold is above which the bird would be unable to maintain its internal temperature, and what crisis mechanisms should be added to the model.

Despite the underlying complex biological mechanisms (regulations loops, energy balance, metabolic efficiencies, etc.) included in the model, INAVI has a simplified architecture. It includes a low number of parameters in order to remain both user-friendly and biologically relevant. Our approach is the result of conflicting issues: a mechanistic process is required to model broiler growth, but models have to be simple and useful tools for multiple stakeholders, who are not always used to the underlying concepts. This simplification led us to take some shortcuts, for which we are fully open to criticism, such as a constant basic efficiency of deposition (*Ed*) (even though it is modified by response laws) and a global energetic value of deposition (*Ved*). INAVI also led to us renewing the concept of maintenance by separating physical activity from basic metabolism for maintenance even though the measurement of the energy cost of physical activity remains difficult. The use of a simple behavioural quantification and an energy transformation is consistent with data from the literature but requires additional validation.

Taking into account body composition in the representation of weight gain

In INAVI, growth is considered as a consequence of the global use of ME by the animal (i.e. the difference between ME intake – heat production) with the introduction of two parameters describing the use efficiency of ME (*Ed*) and the energetic value of deposition (*Ved*), which converts energy into body weight gain. Total growth can also be seen as the sum of the growth of several compartments (protein, fat, ash, water) as proposed by Emmans (1995). Both approaches (intake or growth as driving forces) could be assumed to be relevant, specifically under a push–pull representation.

A precise description of body composition, especially protein and ash weight therefore could be used for the prediction of nitrogen and phosphorus excretion by a mass balance approach between ingestion (feed intake) and retention (deposition). Nutritional strategies could be thus evaluated both on economical (growth, feed intake) and environmental (nitrogen and phosphorus excretions) bases. Moreover, body composition could also be used in order to evaluate the quality of carcasses, mainly by considering carcass fattening and the weight of physical parts with an economic interest such as breast or drumstick (Danisman and Gous, 2011).

Future improvements concerning growth and intake regulation

Temperature effects

The perceived temperature described previously takes into account several environmental factors in a single intermediate variable 'informing' the bird and therefore impacting its behaviour and metabolism. However, this variable should be improved with new data from the literature and expertise for the different impacts it is involved in. As an example, the influence of this variable on energy partitioning should be more precisely taken into account since new knowledge is now available (Sakomura *et al.*, 2009).

Amino acid requirements

In INAVI, amino acid requirements were considered through the use of a synthetic variable taking into account the level of the first limiting essential amino acid. However, the effects on growth of an amino acid deficiency can be different according to the considered amino acid. Many studies have focused on lysine and sulphur amino acid requirements (Mack *et al.*, 1999; Conde-Aguilera *et al.*, 2013), but the experiments carried out to assess those requirements are mostly based on factorial approaches. In that sense, the development of new response laws describing the effect of each essential amino acid level on growth and feed intake could be helpful to investigate further the ideal protein concept proposed by Mack *et al.* (1999), though a ranking between amino acids should be proposed, since the multiplication of response laws might bias the model behaviour through lack of consistent data for some amino acids.

Influence of phosphorus and calcium dietary content on growth performances

In INAVI, performances are modified by environmental conditions and feed characteristics. Diet composition is taken into account, with a specific focus on energy and protein metabolisms, while several other nutrients are known to have a meaningful influence on broiler performance, such as phosphorus. However, the studies of Rousseau *et al.* (2012) and Létourneau-Montminy *et al.* (2010) showed that the influence of dietary phosphorus content on performances has to be studied simultaneously with dietary calcium and microbial phytase levels. Modelling of the combined influence of these factors is therefore a main future development to be considered for INAVI.

Conclusions

As stated in the introduction, the audience for INAVI is both researchers and practitioners. The 'open to change by the user' approach developed in INAVI induces new issues that should be investigated in the future by experimental trials carried out both in the laboratory and the field. Since the start of the INAVI project, new knowledge has been obtained from the biomolecular up to batch management scale. Therefore, the improvement of our model requires the ranking of the mechanisms and laws regulating growth that should be implemented. This has to be done through continuous discussion between stakeholders both on the research and production sides. To date, this discussion has led to the following improvements:

1. Growth prediction connected with body composition.
2. Prediction of N and P excretion.
3. Growth regulation with P–Ca nutrition.
4. Digestibility of nutrients.
5. Connection of INAVI with a diet formulation tool (combining nutritional, economic and environmental constraints).

Moreover, performances variability is not taken into account in INAVI, though this aspect is a key issue for the sustainability of poultry production systems. However, INAVI is a deterministic animal-centred model, aimed at integrating knowledge at the animal scale, which does not cope with variability. Since the development of new and more sustainable production systems requires the development of models at the upper scales (farms, territories), the role of INAVI in these multi-scale approaches should be anticipated.

References

Baker, E.J. and Gleeson, T.T. (1999) The effects of intensity on the energetics of brief locomotor activity. *Journal of Experimental Biology* 20, 3081–3087.

Bizeray, D., Leterrier, C., Constantin, P., Picard, M. and Faure, J.M. (2000) Early locomotor behaviour in genetic stocks of chickens with different growth rates. *Applied Animal Behaviour Science* 68, 231–242.

Black, J.L, Campbell, R.G., Williams, I.H., James, K.J., and Davies, G.T. (1986) Simulation of energy and amino acid utilisation in the pig. *Research and Development in Agriculture* 3, 121–145.

Bokkers, E.A.M and Koene, P. (2003) Eating behaviour, and preprandial and postprandial correlations in male broiler and layer chickens. *British Poultry Science* 4, 538–544.

Conde-Aguilera, J.A., Cobo-Ortega, C., Tesseraud, S., Lessire, M., Mercier, Y. and van Milgen, J. (2013) Changes in body composition in broilers by a sulfur amino acid deficiency during growth. *Poultry Science* 92, 1266–1275.

Danisman, R. and Gous, R.M. (2011) Effect of dietary protein on the allometric relationships between some carcass portions and body protein in three broiler strains. *South African Journal of Animal Science* 41, 194–208.

De Basilio, V., Vilarino, M., Yahav, S. and Picard, M. (2001) Early age thermal conditioning and a dual feeding program for male broilers challenged by heat stress. *Poultry Science* 80, 29–36.

De Groote, G. (1974) Utilisation of metabolisable energy. In: Morris, T.R. and Freeman, B.M. (eds) *Energy Requirements of Poultry*. British Poultry Science Ltd, Edinburgh, UK, pp. 113–133.

Emmans, G.C. (1981) A model of the growth and feed intake of ad libitum fed animals, particularly poultry. *Computer in Animal Production*, Occasional Publication No. 5., British Society of Animal Production, Edinburgh, UK, pp. 103–110.

Emmans, G.C. (1995) Problems in modelling the growth of poultry. *World's Poultry Science Journal* 51, 77–89.

Emmans, G.C. and Fisher, C. (1986) Problems in nutritional theory. In: Fisher, C. and Boorman, K.M. (eds) *Nutrient Requirement of Poultry and Nutritional Research*. Butterworths, London, pp. 9–39.

Feddes, J.J.R., Emmanuel, E.J. and Zuidhoft, M.J. (2002) Broiler performance, body weight variance, feed and water intake, and carcass quality at different densities. *Poultry Science* 81, 774–779.

Geraert, P.A., Padilha, J.C. and Guillaumin, S. (1996) Metabolic and endocrine changes induced by chronic heat exposure in broiler chickens: growth performance, body composition and energy retention. *British Journal of Nutrition* 75, 195–204.

Gous, R.M., Moran, E.T. Jr, Stilborn, H.R., Bradford, G.D. and Emmans, G.C. (1999) Evaluation of the parameters needed to describe the overall growth, the chemical growth, and the growth of feathers and breast muscles of broilers. *Poultry Science* 78, 812–821.

Hancock, C.E., Bradford, G.D., Emmans, G.C. and Gous, R.M. (1995) The evaluation of the growth parameters of six strains of commercial broiler chickens. *British Poultry Science* 36, 247–264.

Howlider, M.A.R. and Rose, S.P. (1987) Temperature and the growth of broilers. *World's Poultry Science Journal* 43, 228–237.

Hurwitz, S., Sklan, D. and Bartov, I. (1978) New formal approaches to the determination of energy and amino acid requirements of chicks. *Poultry Science* 57, 197–205.

Hurwitz, S., Weiselberg, M., Eisner, U., Bartov, I., Riesenfeld, G., Sharvit, M., Niv, A. and Bornstein, S. (1980) The energy requirements and performance of growing chickens and turkeys as affected by environmental temperature. *Poultry Science* 59, 2290–2299.

Jackson, S., Summers, J.D. and Leeson S. (1982) Effect of dietary protein and energy on broiler carcass composition and efficiency of nutrient utilization. *Poultry Science* 61, 224–2231.

Koh, K. and Macleod, M.G. (1999) Effects of ambient temperature on heat increment of feeding and energy retention in growing broilers maintained at different food intakes. *British Poultry Science* 40, 511–516.

Leeson, S., Caston, L. and Summers, J.D. (1996) Broiler response to diet energy. *Poultry Science* 75, 529–535.

Lei, S. and Van Beek, G. (1997) Influence of activity and dietary energy on broiler performance, carcase yield and sensory quality. *British Poultry Science* 38, 183–189.

Létourneau-Montminy, M.P., Narcy, A., Lescoat, P., Bernier, J.F., Magnin, M., Pomar, C., Nys, Y., Sauvant, D. and Jondreville, C. (2010) Meta-analysis of phosphorus utilisation by broilers receiving corn-soybean meal diets: influence of dietary calcium and microbial phytase. *Animal* 4, 1844–1853.

Mack, S., Bercovici, D., De Groote, G., Leclercq, B., Lippens, M., Pack, M., Schutte, J.B., and Van Cauwenberghe, S. (1999). Ideal amino acid profile and dietary lysine specification for broiler chickens of 20 to 40 days of age. *British Poultry Science* 40, 257–265.

Picard, M., Plouzeau, M. and Faure, J.M. (1999) A behavioural approach to feeding broilers. *Annales de Zootechnie* 48, 233–245.

Quentin, M. (2004) Une approche dynamique de la croissance des poulets de chair. Conception d'un modèle pratique: INAVI. PhD Thesis, Ecole Nationale Supérieure Agronomique de Rennes, Rennes, France.

Quentin, M., Bouvarel, I. and Picard, M. (2004) Short- and long-term effects of feed form on fast- and slow-growing broilers. *Journal of Applied Poultry Research* 13, 540–548.

Quentin, M., Bouvarel, I. and Picard, M. (2005) Effects of the starter diet, light intensity, and essential amino acids level on growth and carcass composition of broilers. *Journal of Applied Poultry Research* 14, 69–76.

Rousseau, X., Létourneau-Montminy, M.P., Même, N., Magnin, M., Nys, Y. and Narcy, A. (2012) Phosphorus utilization in finishing broiler chickens: effects of dietary calcium and microbial phytases. *Poultry Science* 91, 2829–2837.

Sakomura, N.K., Fernandes, J.B.K, Resende, K.T., Rabello, C.B.V., Longo, F. and Neme, R. (2009) Modelling energy utilization in poultry. In: Sauvant D., Van Milgen J., Faverdin P., and Friggens N. (eds) *Modelling Nutrient Digestion and Utilisation in Farm Animals*. Wageningen Academic Publishers, Wageningen, The Netherlands, pp. 297–305.

Sakomura, N.K., Gous, R.M., Marcato, S.M. and Fernandes, J.B.K. (2011) A description of the growth of the major body components of 2 broiler chicken strains. *Poultry Science* 90, 2888–2896.

Savory, C.J. (1974) Growth and behaviour of chicks fed on pellet or mash. *British Poultry Science* 15, 281–286.

Sibbald, I.R. and Wolynetz, M.S. (1986) Effects of dietary lysine and feed intake on energy utilization and tissue synthesis by broiler chicks. *Poultry Science* 65, 98–105.

Skinner-Noble, D.O., Jones, R.B. and Teeter, R.G. (2003) Components of feed efficiency in broiler breeding stock: is improved feed conversion associated with increased docility and lethargy in broilers? *Poultry Science* 82, 532–537.

Sklan, D. and Plavnik, I. (2002) Interactions between dietary crude protein and essential amino acid intake on performance in broilers. *British Poultry Science* 43, 442–449.

Teeter, R.G., Smith, M.O., Owens, F.N., Arp, S.C., Sangiah, S. and Breazile, J.E. (1985) Chronic heat stress and respiratory alkalosis: occurrence and treatment in broiler chicks. *Poultry Science* 64, 1060–1064.

Van Milgen, J., Bernier, J.F., Lecozler, Y., Dubois, S. and Noblet, J. (1998) Major determinants of fasting heat production and energetic cost of activity in growing pigs of different body weight and breed/castration combination. *British Journal of Nutrition* 79, 509–517.

Wenk, C. and Van Es, A.J.H. (1980) Studies on the energy metabolism and the protein and fat deposition of growing chickens with special reference to physical activity. *Zeitschrift für Tierphysiologie Tierernahrung und Futtermittelkunde* 43, 241–254.

Whittemore, C.T. (1976) A study of growth responses to nutrient inputs by modelling. *Proceedings of the Nutrition Society* 35, 383–391.

Yahav, S. (2000) Relative humidity at moderate ambient temperatures: its effect on male broiler chickens and turkeys. *British Poultry Science* 41, 94–100.

Yahav, S., Goldfeld, S., Plavnik, I. and Hurtwitz, S. (1995) Physiological responses of chickens and turkeys to relative humidity during exposure to high ambient temperature. *Journal of Thermal Biology* 20, 245–253.

Yahav, S., Straschnow, A., Vax, E., Razpakovski, V. and Shinder, D. (2001) Air velocity alters broiler performance under harsh environmental conditions. *Poultry Science* 80, 724–726.

Yalcin, S., Testik, A., Ozkan, S., Settar, P., Celen, F. and Cahaner, A. (1997) Performance of naked neck and normal broilers in hot, warm, and temperate climates. *Poultry Science* 76, 930–937.

10 Model Applications in Poultry Production and Nutrition

E.O. Oviedo-Rondón*
North Carolina State University, Raleigh, North Carolina, USA

Abstract
Mathematical models have been developed in the past few decades to aid in decision making, management, research and teaching in many aspects of animal and poultry production. These are very useful tools that can offer a wide vision of complex problems common in enterprise process management, processing, live production and nutrition of animals to assist in developing solutions. Despite the advantages of using modelling approaches, many factors have limited their broad application in commercial poultry production. Currently, very few poultry companies and nutritionists worldwide use biological models on a daily basis. Modelling techniques are not even taught in animal and poultry nutrition classes in all universities. Because of this, it is very difficult for these excellent tools to advance sufficiently to benefit the poultry industry. This chapter will enumerate some of the main advances that have been made in the different categories of mathematical modelling that have been developed for poultry nutrition, production and processing. These include applications developed to model growth and egg production of birds and the whole poultry enterprise. Additionally, some of the limitations in terms of common knowledge, training and data availability needed to apply modelling to commercial conditions will be discussed. The objectives of this chapter are: (i) to highlight the importance of modelling for advancing the acquisition of information for decision making related to the intricate and critical problems often observed in poultry production and nutrition; (ii) to list and briefly describe some of the current applications; and (iii) to identify factors that need to be improved to enable greater use under commercial conditions and in research. This author does not intend to criticize any of these models, since most have not yet been fairly evaluated.

Introduction

Modelling is conducted to better understand, quantify and optimize systems. Modelling can be conducted at different levels, from cells to organs, animals to flocks, flocks to farms, farms to companies. At each one of these levels, different modelling techniques could be applied and, in fact, very few tools have been used. Mathematical modelling includes a very broad set of tools that have not yet been completely explored for use in poultry nutrition, production and processing (Roush, 2001, 2006; Render *et al.*, 2011). The following is a list of the mathematical methods that could be utilized as modelling techniques:

- Statistical analysis.
- Decision analysis.

---

*E-mail: eooviedo@ncsu.edu

Nutritional Modelling for Pigs and Poultry
(eds N.K. Sakomura *et al.*)

- Inventory control.
- Linear programming.
- Non-linear programming.
- Goal programming.
- Integer programming.
- Dynamic programming.
- Time series analysis.
- Queuing analysis.
- Risk analysis.
- Simulation.
- Neural networks.
- Genetic algorithms.
- Fuzzy logic theory.
- Chaos theory.
- Game theory.
- Data mining.

Several of these techniques could be applied to common problems in poultry production. This includes areas such as resource distribution and allocation, planning and orientation, scheduling and routing, market forecasting, inventory control, optimization and replacement and maintenance.

Among the techniques listed, artificial neural networks are interesting mathematical tools that have been used in poultry production in many areas. There are several publications that reference the multiplicity of applications of this methodology, which is an output of artificial intelligence technology. Artificial neural networks have been evaluated to predict biological responses of poultry, such as growth (Roush *et al.*, 2006; Ahmad, 2009; Ahmadi and Golian, 2010; Mottaghitalab *et al.*, 2010), egg production in layers (Savegnago *et al.*, 2011; Wang *et al.*, 2012), or in breeders (Salle *et al.*, 2003; Faridi and Golian, 2011) and hatchability (Bolzan *et al.*, 2008). Artificial neural networks have also been applied to estimate nutrient composition in feed (Cravener and Roush, 2001; Perai *et al.*, 2010; Ebadi *et al.*, 2011) and manure (Chen *et al.*, 2009), traits of carcasses (Faridi *et al.*, 2012) or eggs (Patel *et al.*, 1998), and forecast market behaviours (Huang *et al.*, 2009), among other applications. It is known that neural networks do not help to understand the systems under study, but it is impossible to deny the high accuracy, precision and lack of prediction bias of these algorithms.

The theory and other applications of neural networks is discussed in another chapter of this book (see Ferraudo, Chapter 7, this volume). However, this author suggests that this tool should be integrated into traditional biological modelling to advance further their application to commercial conditions of poultry production where mechanistic or empirical models have failed to provide the accuracy of predictions demanded by the industry. Nowadays, many statistical software packages offer this tool and the algorithms could be integrated into existing poultry modelling software, making it easier to apply with the right set of data (Roush, 2006).

The reader will notice that meta-analyses, frequently used to summarize published information in poultry science, were not included in this list. Although meta-analyses can be used to explore the tendencies of biological responses when appropriate statistical methods are used, most of the time the sources of data are extremely variable, do not have similar treatment levels and are affected by many unknown variables, which may not be mentioned in the publications. This problem in statistics is often called study heterogeneity (Nordmann *et al.*, 2012). Ideally, the studies whose results are being combined in the meta-analysis should all be undertaken in the same way and to the same experimental protocols (Sutton *et al.*, 2000), but this hardly ever occurs in the meta-analyses conducted with poultry data. In almost all meta-analyses, this inconsistency among experimental protocols may make the results of such mathematical exercises inaccurate and misleading, and the resultant equations should probably not be used as simulation, prediction or optimization tools. Meta-analyses are still valuable as they help researchers to better understand the factors that may cause variability in the responses observed when similar treatments are applied, but they always should lead to controlled experiments and mechanistic models. Consequently, meta-analyses themselves should not be considered directly as a modelling methodology.

Advances in Modelling Applications for Poultry Nutrition and Production

In poultry nutrition the most common approach has been to model growth or egg production of a single bird and, on a very few occasions, generate small populations. Based on the mathematical description of the biological system constituted by the animal biology, the feed composition and the environmental factors involved and all their interactions, such models are able to simulate diverse conditions, and estimate outputs of the system.

The modelling techniques employed so far may vary from empirical to mechanistic. Models that have been developed for poultry are deterministic. Stochastic models are not currently available for modelling the biological responses of poultry. Unfortunately, the intrinsic variability of data, which is natural in all biological systems, is oftentimes disregarded for both experimental and commercial conditions. The availability of such data is, however, extremely important for detecting the problems and inefficiencies in any system to be modelled. New computer modelling advancements could make it possible for such stochasticity to be incorporated into more efficient models that are able to repeatedly simulate all the natural variability and detect the critical limits that cause some of the issues often observed in commercial poultry production.

From a couple of published reviews that this author has been involved with on models developed for poultry nutrition (Oviedo-Rondón and Waldroup, 2002; Oviedo-Rondón *et al.*, 2002a, 2013), it can be concluded that each modeller has taken different approaches, but almost all models have very similar outputs. The majority of these models are able to determine body weight (BW), BW gain, feed conversion ratio (FCR), and energy, protein and amino acid needs, or other biological responses, such as tissue, chemical component accretion or egg output of broilers, turkeys, layers or breeders to different dietary nutrient levels or environmental conditions. Most of the models have low accuracy in predicting feed intake (FI), and base their predictions of FI on theoretical energy needs for an expected genetic potential for growth and some environmental constraints to FI and growth, or on regulation of thermogenesis and thermolysis. Very few models include effects of stocking density, diet presentation and bird activity influenced by light or space availability. The low accuracy of FI predictions has resulted in issues with regard to observations when predicting other traits. This problem is mainly due to lack of equations to estimate the effects of other factors also known to affect FI. Very few models include the interactive effects of ambient temperature, relative humidity and wind speed, which determine the effective body temperature of birds, as well as minor factors such as air quality, lighting or effects of dietary calcium levels. The widely spread utilization of phytases and other enzymes has resulted in more variability in dietary levels of calcium and phosphorus, and in the levels of energy used. This generates more unevenness in FI and animal responses related to the effects of other nutrients.

The growth models developed to date for broilers and turkeys employ very similar functions to describe growth. All models basically have used the Gompertz (1825) function to describe growth or development of body components at the tissue (viscera, carcass and feathers) or the chemical components (ash, protein, lipid and water). After these components are described, nutrients needed to either maintain or deposit more energy or nitrogen are estimated using efficiency factors for dietary nutrient utilization, body component allometry and ratios among nutrients such as ideal protein profiles to estimate all amino acids involved with the animal's lysine needs. However, lysine is not the main limiting amino acid for poultry and other presumptions of the ideal protein concept are not applicable to poultry. Consequently, many ideal protein profiles are observed worldwide. Growing birds respond to increasing levels of crystalline lysine, while other amino acids can remain constant (Si *et al.*, 2001). It would be useful if biological models allowed users to modify the ideal protein profile that they desire to use. On the other hand, other nutrients such as minerals or vitamins are kept constant in the diets, ignoring their effects and interactions with other nutrients as levels of dietary energy and amino acids are modified.

In reviewing the history of computerized model development to determine poultry nutrient needs or estimate responses of birds to those nutrient levels, it can be observed that many of these tools have been abandoned without being extensively used or even fairly evaluated by the poultry industry. For instance, at present models such as FORTEL™ (Emmans, 1981, 1989, 1994; Emmans and Fisher, 1986), CHICKOPT™ (Hurwitz *et al*., 1978; Talpaz *et al*., 1986, 1991), IGM® (Harlow and Ivey, 1994), OmniPro® II (Fancher, 1999; Ivey, 1999) or the ones proposed by Pesti *et al*. (1986), Liebert *et al*. (2000), King (2001) and Guevara (2004) are not currently used by nutritionists or they are not presently available to the industry.

Models Used in Commercial Poultry Production and Nutrition

A few groups are, however, currently developing and using models for decision making by the poultry industry. Among these modeller groups, we can spotlight the work done by EFG Software from Natal, South Africa (Gous, 2006, 2007, 2012), Aviagen (Alabama, USA) with LIDM Software from Israel (De Beer, 2009, 2010; Talpaz *et al*., 2013); Fee2Gain (Frank Ivey, Missouri, USA); Roland Consulting (Economic Feeding and Management of Commercial Leghorns), Cargill Animal Nutrition (Minnesota, USA) and Nutreco (Canada) modelling divisions; Danisco Animal Nutrition (UK); and INRA (France). Companies such as AGROINFO TI (São Paulo, Brazil); CyberAgra (Virginia, USA); M-Tech Systems (Georgia, USA); UniSoma (São Paulo, Brazil); and The Wala Group (Minnesota, USA) offer business models and other data analysis tools that generate mathematical models for decision making in poultry enterprises. It is relevant to mention that the majority of developments observed currently in poultry modelling come from private companies, and there is very little work that is currently being developed in public institutions.

EFG Software

EFG Software (www.efgsoftware.net/) has developed models for broilers, turkeys, broiler breeders and swine. EFG Software also offers the Reading Model for table egg layers within its products (Fisher *et al*., 1973). These models and their applications will be explained in detail in this book (see Fisher, Chapter 1, this volume and Gous, Chapters 3 and 13, this volume). The broiler growth model has been the one with the most evaluations or applications published (Oviedo-Rondón *et al*., 2002b,c; Gutierrez *et al*., 2008; Chrystal, 2009).

Aviagen and LIDM development of models for application in the poultry industry

The poultry breeding company Aviagen Inc. (Huntsville, Alabama, USA), cooperating with LIDM Software Systems, Ltd (Israel), has been developing several tools to model poultry growth and behaviour in an effort to provide poultry companies with information targeted to improving the efficiency of poultry meat and hatching egg production. Aviagen has embraced biological models as a means to enhance their technical guidance efforts with their client base. Biological models are helping Aviagen to better understand the optimal nutrient requirements for different genotypes under varying economic conditions.

With the vision of creating models for commercial application in the poultry industry, Bryan Fancher, Hovav Talpaz and Michael Cohen have worked closely together since 2000 to pursue this objective. Further development and implementation of these systems continues with the combined efforts of Fancher and his colleagues at Aviagen and Talpaz and Cohen at LIDM Software Systems, Ltd. The following list describes the comprehensive software and prediction tools developed by this group:

1. *Broiler Economics for Energy and Protein* (BEEP) aims to determine optimal dietary energy and amino acid density, subject to composition and costs of available ingredients, target product mix and market prices, and projected biological response. Aviagen has conducted numerous trials using a wide range of nutrient density and measured bird ages (i.e. diets ranging from 2723 to 3386 kcal ME/kg, 0.89% to 1.65% digestible lysine with all essential amino acids being indexed to lysine, and BW 1.09–4.70 kg). Results from these trials were utilized to build this model to estimate biological responses, such as live performance and carcass component yield to nutrient density changes, and determine dietary levels of energy and amino acid requirements that maximize margin over feeding cost (MOFC) on a per broiler or per broiler annualized basis. The effects of incrementally changing feed or meat prices on optimal energy and amino acid levels is evaluated via parametric analysis. The model can be exploited to enhance decision making under volatile market conditions.

2. *Broiler Lighting Design* is designed to predict the optimal lighting programme schedule for broiler production. Based on experimental data developed by Aviagen and the University of Saskatchewan, Canada (Hank Classen), the model estimates the effects of lighting regimes on broiler live and processing performance and, similar to BEEP, optimizes MOFC for live bird or processed meat markets.

3. *Business Process Analysis (BPA) – Broiler* analyses broiler flock settlement records from corporate databases. The time span typically used for analysis is a rolling average of 3 years of data. Flock record data are utilized to estimate the pure effects of numerical variables (e.g. dietary energy or amino acid density, temperature; down-time between flocks, stocking density) and class variables (e.g. genotype, sex, drinker type, feeder type). Pure effects are estimated for objective variables (FCR; BW, mortality, condemnations and MOFC). Proprietary 'ideal adjustment' procedures are applied on FCR and BW to ensure comparability among flocks harvested at various ages. *BPA – Breeder* analyses breeder flock records from corporate databases. The flock records data are utilized to estimate the pure effects of numerical variables during rearing and laying periods, as well as class variables. Pure effects are estimated for objective variables (e.g. egg production, hatchability, mortality and number of chicks produced). The optimal BW trajectory is estimated via orthogonal function transformations specifically designed for the task.

4. A collection of prediction tools have been developed which can be utilized independently or integrated into comprehensive software like the aforementioned two. These prediction tools include:

(i) *Curve* estimates BW or specific carcass components via a modified Gompertz equation.

(ii) *Adjustment* estimates BW trajectory via a modified Gompertz equation, FCR via a proprietary approach, and adjusts FCR to a selected BW by a proprietary 'ideal adjustment' approach.

(iii) *Energy Requirement* estimates the energy requirement of broilers and broiler breeders. The model takes a unique approach by utilizing a time age-variant maintenance energy function, which is estimated via a proprietary non-linear optimizer.

(iv) Multi-parameter age-variant function tools to estimate, from partial datasets of breeder flocks, egg production, hatchability, fertility, livability, egg weight and hatch emergence rate.

5. *Uniformity Prediction* is a multi-parameter prediction tool that estimates the live BW distribution of a flock and quantifies the number of birds per cohort weight range subject to uniformity constraints and defined weight interval boundaries.

6. *Experimental Design* estimates the required number of replicate pens and birds per pen to achieve a successful trial at a desired level of probability.

Development of a new broiler management programme is currently underway to simulate broiler growth under various conditions subject to dietary nutrient density. Model parameters will be estimated similarly to BEEP using the same experimental information and diet formulation procedure. A calibration process is conducted to reflect localized user conditions. A proprietary non-linear algorithm is applied to maximize the user specified objective function.

Feed2Gain products

Feed2Gain, LLC is a small company (www.feed2gain.com) with two broiler modelling software products. One is called *BroilerOpt*™ and is a full blown modelling program with least cost formulation and cost optimization ability. The second is a simplified model that can evaluate the outcome of trials, called *Estudy*™. Both models are based on the considerable work of Hurwitz, Talpaz and their associates (Hurwitz *et al.*, 1978, 1980; Talpaz *et al.*, 1986) with significant modifications, and adaptations supplied by Feed2Gain, LLC (Ivey and Harlow, 1994).

The founder of Feed2Gain, LLC is Frank Ivey, who, while at Novus International Inc., developed and worked with several model concepts. The greatest benefit of these models is the increased confidence in making a change in the field that the models provided. The benefits of a model can easily be expressed, and precision in decision making is the first. Mr Ivey (F. Ivey, Missouri, 2013, personal communication) indicated that a revealing moment in using models came when one of the first nutritionists he worked with said that the FCR they had obtained in the first week of a change was 1½ points poorer than predicted. He then laughed and said that he had never before known what the FCR should be after a change. Exactly the kind of benefit a model can bring. Several papers have been published on the subject (Ivey and Harlow, 1991, 1992; Harlow and Ivey, 1994).

The two products that Feed2Gain has made use of employ the same growth prediction model. However, their focus is very different. The Estudy™ program evaluates the outcome of a feeding trial where single changes in diet are made. This is done by calibrating the growth of the animals to the growth of animals on the control diet. That is to say that the model assumes that the growth of the broilers is the result of the nutrient contents of each diet. It then evaluates the new ingredient, such as an enzyme, a different energy source or medication, and computes the nutritional change attributed to the change in diet.

The BroilerOpt™ program is much more extensive and includes a least cost feed formulation program because it will find those feeding programmes where the ingredient usage is optimized. The program then calibrates itself to current results using the restrictions in the least cost programme and restrictions on feed conversion, so growth rate or other desirable parameters of the organization can identify the feeding prescription that is the least cost feeding programme with the ingredients that are at hand. Because ingredient prices vary from location to location and growth conditions vary, such precise identification of the best feeding programme is impossible without an accurate model.

Econometric feeding and management of commercial leghorns, 'EF&M'

The EF&M is a model for layers developed by Dr David A. Roland (Professor Emeritus at Auburn University). This software is currently used as part of the services of Ridley Feed Ingredients (http://www.ridleyfeedingredients.com/index.html). This model is based on many feeding trials that evaluated the responses of layers to nutrient levels (Roland *et al.*, 1999; Ahmad and Roland, 2001, 2003a,b; Sohail *et al.*, 2003). The EF&M has four parts: (i) a least cost feed formulation programme; (ii) a traditional feeding programme; (iii) a record keeping module; and (iv) a model for econometric simulation of conditions and estimation of optimums depending on the business objective. This software is used successfully by several layer companies in the USA.

Model development and use at Cargill Animal Nutrition, Danisco and Nutreco

Large grain, feed and feed additive providers, such as Cargill Animal Nutrition (www.cargill.com/feed), Danisco Animal Nutrition, Dupont Industrial Biosciences (www.biosciences.dupont.com/industries/animal-nutrition) and Nutreco (www.nutreco.com/), have developed their own mathematical models and use them as either internal tools or as an aid in service for their clients. These companies either shared information or agreed to allow the author to make a few comments about the details of their software so as to inform the public that in reality their modelling programs are useful tools for decision making in nutrition.

Cargill has a strong modelling platform called *MAX*® for swine, dairy and beef that is currently being used, and which is being further developed for wider applications. Cargill's MAX® software enables distinctive nutrition solutions for an animal producer. The software enables better nutrition decisions by providing access to Cargill nutrition know-how, fitting to the local market and enabling value-based nutrition for producers of meat, milk and eggs. The system provides a practical way to connect nutrient supply, nutrient demand and projected animal performance for practical decisions on diet or ration formulation, so that nutrition decisions can be defined based on cost or profitability. The system was architected on intake-based and performance-based nutrition for the best local value. The current system is available in various languages to support dairy cattle, beef cattle, pork and chicken broiler producers worldwide. The system has evolved since 1986 where it is currently supported by US and EU patents.

Additionally, Cargill has the *Panorama Service Model*, originally developed by PROVIMI. Panorama is a model based on an empirical approach to maximize the economic return of a poultry company in a period of 1 year. Therefore, in addition to optimizing diets' energy and ideal protein levels, the model represents the entire production environment of typical broiler integration, and a complete description of fixed and variable costs and selling prices of products. The model is calibrated with data from the companies themselves, increasing its adherence and reliability. Analysis of client production database is very important to define the so-called current scenario, which will then be subject to optimization. The model takes into account impacts of any changes in the composition of the diets on carcass, cuts and condemnations in abattoirs. Due to the high number of variables (more than 200) and relationships among them (nearly two million relations) involved, the model uses a powerful mathematical solver able to compute complex linear and non-linear problems.

Danisco Animal Nutrition service consists of laboratory analyses of various ingredients to directly determine substrates, and their levels and types for feed enzymes action. This step is followed by employing various software models such as *Avicheck*® *Corn*, *Avicheck*®, *Phycheck*®, *Porcheck*® and *DuPont Optimize Feed*™ to take advantage of the ingredient substrate information but also by including inputs specific to a customer's situation. The variables will vary depending on the enzyme, for example, phytate for phytase, viscosity for xylanase/beta-glucanase in wheat/barley, starch digestion for carbohydrases in corn. The outcomes of the models provide poultry and swine feed producers with a tailored recommendation of how much the energy, phosphorus, calcium and amino acid specifications of specific feeds can be reduced according to the quality and quantity of ingredients used in the feed formulation. It can also recommend feed enzyme levels to be used in specific feeds.

In Nutreco, there are currently two models used for poultry. The first one is *Nutri-Opt*, which simulates/predicts the growth response of commercial broilers to energy and amino acids (Nutri-Opt version 2 to be available later in 2014). This model is used by nutritionists and clients to decide the adequate energy and amino acid levels, depending upon the client's performance objective and feed cost. This model is related to the work of Eits *et al.* (2002a,b, 2003, 2005). The second model is a dynamic turkey model called *Darwin*, a derivate of

Rivera-Torres *et al.* (2011a,b,c) used internally only by nutritionists. With this application the user can run different scenarios to compare turkey growth responses and production costs depending on nutrient levels, feeding schedule and growth potential. Both tools work by running simulations of different nutritional strategies to evaluate impacts on growth rate, FCR and production costs. They are used to make informed choices, not as optimization tools, but are aimed at helping the user explain the bird's response to different scenarios. It is important to the company that the users still critically evaluate the outputs and decide which option is more appropriate given the production goals desired.

Model development in Europe

The *INAVI* growth model developed at INRA (France) and described in detail in this book (see Méda *et al.*, Chapter 9, this volume) simulates broiler growth according to the bird's environment, including diet, temperature and genetic lines. Its main driving force could be considered to be its feed intake regulated by the balance between thermogenesis and thermolysis. This model has now evolved by combining INAVI (feed regulated) with the work of Dr Luciano Hauschild (Professor UNESP, Jaboticabal, São Paulo, Brazil, 2013, personal communication), which included concepts described by Emmans (1981, 1989, 1994) and uses genetic potential growth as a driving force.

Other models have been developed from INAVI. For example, *MOLDAVI* is a modelling approach (Méda, 2011) to evaluate the fluxes of various elements coming in and out of poultry houses (greenhouse gas, nitrogen and phosphorus). The purpose of this model was to be able to predict properly the variations in element emissions in order to evaluate the local or global environmental impact of a broiler flock growth. It includes the averaged laws of responses of INAVI and it proposes emissions predictions according to the flock environment (indoor, outdoor, management). Another example is the *CENTRAVI* model (Bignon *et al.*, 2007), which also adapted the INAVI broiler growth simulation and incorporated the impact of physical activity and feed characteristics like pellet hardness, durability, length and fine levels on performance.

Meta-analyses have also been conducted and have helped to determine tendencies of responses; for example, the work of Létourneau-Montminy *et al.* (2010) related to utilization of phosphorus or the work of Nugues *et al.* (2013) on wheat digestibility. Private companies have been developing modelling tools, most of them based on empirical approaches simultaneously with meta-analysis. One example was presented by Mathiaud *et al.* (2013) at the '10th Journées de la Recherche Avicole'. Some of the private developments from European companies could be considered more mechanistic, such as the TECHNA model for turkeys (Rivera-Torres *et al.*, 2011a,b,c).

Poultry business models

Poultry production generally ends up adopting vertically integrated systems. To aid in decision making, planning and programming of multiple activities and resources in each sector of these complex integrated systems, several information technology companies have developed specific software. This software describes and quantifies the complex relationships in enterprise systems. Consequently, by definition these tools should be also considered as models of production systems.

This new generation of business models enables managers to assess the direct impact of traditional operating variables such as FCR, flock density, strain, diet formulation and many others on bottom-line business objectives and determine the optimal values of various operating parameters which will maximize the objectives of the integrated system. In order to succeed in the most common volatile and competitive markets, it is critical that poultry companies focus on bottom-line business objectives, which maximize measures such as profitability, return on investment and net income of the whole production system and not just each one of its parts. It should be expected that these models arrive at non-traditional management strategies because the models are looking at the enterprise on an integrated (linked) basis instead of a dis-integrated (de-linked) basis, which is common in the industry today. This section will list alphabetically some of the companies providing these poultry business models and their services that are currently being used by the poultry industry worldwide.

AgroInfo TI

This company based in Campinas, São Paulo, Brazil, has offered services to the poultry industry since the year 2000 (www.agroinfoti.com.br). Its tools and services are focused into two groups, the *WOVO System* and *Artificial Intelligence* analyses. The WOVO system is a tool for the egg production industry. It is a management tool that includes factors from pullet chicks to egg production, including schedules to manage activities, like health monitoring and vaccinations, until the end of the flocks. From a good track record and parameterization of the system, users can make predictions for egg production, including size classification and the number of eggs expected weekly, and, in this way, they can plan the most appropriate dates for performing activities such as housing and critical management practices. Likewise, with forecasting of egg and hen sale prices the system aids in identifying the best time to sell the flock. The management system also helps to plan feed inventory. Based on records of current and predictions of future flocks, the system guides the purchase of raw materials for feed production. The animal health monitoring system can aid in gaining knowledge about flock immunity. From serological analyses, common to poultry farms, the system quickly generates dispersion curves that allow decision makers to check the level of exposure and optimize disease vaccination programmes, ensuring both flock health condition and that the vaccine programmes save medicines and have improved efficiency. Using artificial intelligence techniques and robust data analysis tools, such as SAS Enterprise Miner and IBM SPSS Data Mining, customized models are generated for each company to identify features that reveal new information applicable and relevant to decision makers. Techniques such as decision trees, neural networks and fuzzy logic have been applied. The decision tree technique has been used, for example, to evaluate the incubation process (Lima and Rodrigues, 2010). The artificial intelligence techniques can also identify factors to reprogramme the electronic controllers in poultry houses to adjust the levels of operation of all devices seeking maximum efficiency with lower energy costs. To estimate the environmental requirements, the analyses use the daily physiological changes of the flocks, fluctuations in weather conditions and the characteristics of the equipment used for environmental control in farms (e.g. fans, exhaust fans, air inlets, heaters, etc.).

CyberAgra

This is a company based in Richmond, Virginia, USA (www.cyberagra.com) that has been offering software to the poultry industry for more than 15 years. For the poultry industry, CyberAgra offers two software packages for integrated layer and broiler companies. The *CyberAgra Egg Layer Enterprise*™ and the *CyberAgra Poultry Enterprise*™ v13.01.0330 are the latest major releases for fully integrated poultry enterprise record keeping systems. They include either production and accounting of pullet, egg layer and feedmill operations, or production and accounting of pullets, breeders, broilers/turkeys, hatchery, processing plant and feedmill operations. New features in this release include several resource optimizations for faster input/output, W3C conformance for all major browsers and a new default intuitive user interface for easy training and implementation. This software uses a based costing method, which directly traces field history costs related to a specific product, thus providing a more accurate margin calculation than Enterprise Resource Planning systems.

M-Tech Systems

A company based in Atlanta, Georgia, USA (www.mtech-systems.com) that has offered software solutions, industry knowledge, experience and consulting for over 20 years. It has poultry company customers on every continent. M-Tech Systems offers completely integrated systems for every aspect of production from planning, management, detailed live costing, key performance index analysis, remote data collection and full traceability. Through each stage of the live process, whether it is the initial genetic/breeder stages through hatchery or rearing or from grow out to harvest, M-Tech Systems transfers information and cost through each stage, providing the ability to perform critical cost analysis as well as the planning tools to provide optimized supply chain and logistical planning. On the food safety sector, M-Tech Systems' information integrations provide one of the most comprehensive information traceability systems available. Any information captured at any stage can be immediately linked to the final product. Remote data capture devices allow for ease of information scanning and uploading directly from farms, hatcheries and feed mills, for immediate analysis, eliminating human error when transferring data. The following are some of their specific applications for the poultry industry:

- *Live Haul Scheduling Assistant (LHS).* This is an optimization module that imports the planned harvest schedule and rates all factors within the process such as distance to farm, catch crew numbers and production times, down times and many more to determine the most efficient solution to provide the most cost-effective plan.
- *The Broiler Planning Assistant Poultry* (BRPA) generates the most effective harvest and replacement schedules for both poultry processing and live production.
- *Feed Mill Automation.* Automatically transfers feed load and ingredient receiving information. The system automatically captures scale weights, transfers information back to management systems, eliminates human error and increases efficiency and profitability.

UniSoma

A company founded in 1984 and based in Campinas, São Paulo, Brazil (www.unisoma.com), UniSoma is a pioneer in and leading provider of supply chain planning and advanced planning and scheduling solutions for the Brazilian poultry market. In 1989, UniSoma started a partnership with SADIA, at the time the largest poultry and swine cooperative producer. The main result of this joint effort was *PIPA, Integrated Poultry Production Planning System*. PIPA consists of a set of modules used in poultry production planning, from strategic and tactical, to operational. This tool provides support for integrating the several areas that make up the supply chain for poultry production: vertical agricultural integration, slaughterhouses, logistics and sales. SADIA calculated a US$50 million benefit during 1992 to 1994 due to PIPA implementation (Taube-Netto, 1996).

Unisoma has a history of successful projects applying mathematical modelling techniques for optimization, production control and scheduling of integrated animal production systems in Brazil. These projects are described in detail on their website (www.unisoma.com.br/en/estudos-de-caso.php). It is important to highlight the Optimized Production Control and Scheduling at Sadia, the Integrated Animal Planning at Aurora Alimentos, the Optimal Chicken Project at Perdigão S.A. and the PLAMES/F at Avicola Paulista Ltda. All these projects have shown benefits, such as discovery of the best production mix, detection of shadow prices of sales constraints, generation of the necessary forecasts for optimized planning and better estimation of slaughter weights, and reduction of FCR despite BW variations. The integrated planning of processes has helped to quickly synchronize egg incubation, chick placement and flock slaughter activities. These plans can be easily visualized and improved over time. All these benefits have led to decreased use of supplies, less final product stock, and improved delivery dates, maximizing companies' net marginal profitability.

Wala Group

This company based in Shoreview, Minnesota, USA (walagroup.com; solve@walagroup.com), is the developer of *CAMERA*® systems, a business model for broiler and turkey operations, and *Layerite*® a business model for egg production. The Wala Group has been developing integrated life sciences and 'supply chain optimization' technologies to enable meat and egg producers and growers to improve their bottom line results for over 30 years. The company also produces and markets EZ-Stats, a poultry live production and processing, monitoring and tracking tool, and CAMERA Vision Egg®, a margin enhancement technology for integrated egg operations. The Wala Group has taken patented Life Science Algorithms to develop the CAMERA® Analytics software for integrated broiler and turkey companies. CAMERA® optimizes the production process with respect to the net income of the operation. This optimization enables production managers to improve their bottom line results by 'fine tuning' the many trade-offs and inter-dependencies of earnings at risk between cost reduction and revenue generation. CAMERA® utilizes the patented growth algorithm to enable managers to achieve a higher level of alignment and integration among hatchery, feed mill, purchasing, grow out and processing business units.

Limitations on Applying Modelling to Commercial Conditions

There are several opinions on the reasons that have prevented modelling in poultry from advancing and being adopted and implemented as it has been for other species. An extension programme called the Poultry Decision Makers Workshop Series has been conducted at North Carolina State University, since 2006 with the objective of promoting mathematical modelling techniques for decision making in commercial poultry production and research (www.poultry.ces.ncsu.edu/the-poultry-decision-makers-workshop-series/). Based on the experiences collected in these workshops in the past 7 years, it is possible to conclude that one of the main limitations for the application of modelling techniques in the poultry industry is knowledge related to statistical concepts for fitting non-linear or multiple linear regression equations, data analyses in general, and training on concepts of growth and development. Additionally, bad experiences with previous models that were offered raising expectations way above their capabilities have caused many problems and an aversion towards the use of these tools.

Many people in the poultry industry were consulted on this topic and the most common reason for scepticism as to their use was related to the lack of knowledge on how each model has been developed, its accuracy, and a lack of familiarity with what potential users called 'black boxes'. Those black boxes often had outputs that were not expected based on the potential user's general knowledge. However, most of the models available are based on concepts that have been published or discussed in many forums. One step that may not be clearly understood by the general public is the way that a model's theory and equations are organized in the software, but this information is often proprietary to the model's developers. The author also discussed this issue with modeller colleagues, and the opinions of Bryan Fancher (Aviagen Inc.), Frank Ivey (Feed2Gain), Greg Page (Nutreco) and Phillipe Lescoat (INRA) are included in the following paragraphs.

Every person involved in this topic indicated that attempts to market biological or even business models in the poultry industry have had multiple challenges. Through the years it has been observed that many poultry producers have invested heavily in transactional accounting, database and supply chain management systems, especially on the processing side of the business, but far fewer have integrated biological models into their information technology systems. This is partially explained by a general lack of familiarity with biological models among poultry producers and even poultry professionals, and hence lack of confidence in the software. However, with increasing volatility in the feed ingredient and meat markets and the demonstrable benefits of biological models, newfound interest has emerged in the poultry industry in improving their operational efficiency and decision making.

Some modellers mentioned that the sense that the nutritionist will be replaced by a model is one of the most detrimental factors for the use of models. However, there is so much more that the nutritionist does, that this is impossible. The prescription for feeding an animal includes the levels of energy, protein, individual amino acids, minerals, vitamins and medications that the animal needs at all stages of growth. Models can help to determine the levels of some of these nutrient categories, but not all. The experience and judgement of the nutritionist in making decisions about ingredients, quality of ingredients, additives, minerals, vitamin sources and levels, medications, etc. cannot be replaced by a model or by a less educated person.

Other professionals using or developing models indicated that the 'failure', relative to applications in other species, in applying poultry models may partially be explained by the fact that poultry nutritionists expect strong accuracy, while they are not capable of providing the amount of data that would be needed to generate such model accuracy. In other words, commercial application requires a lot of understanding of and quantitative information about the growing conditions (i.e. environmental conditions, accurate FI per bird, BW gain at different ages) of every flock that is to be simulated. However, in reality, producers only have mean values that in themselves may not be accurate. Also, because feeding programmes are implemented in several flocks at the same time rather than only one, or one animal as it can be in the dairy or swine industries, it is almost impossible to adapt a feeding programme to the environment and genetic potential for every single flock. In order to at least optimize parameters by groups of farms with similar traits, it is necessary to have all the data about those farms.

Furthermore, poultry model application will be more successful when model developers/scientists and professors have succeeded in teaching a new approach to nutrition. This approach consists of knowing growth, tissue and chemical development of the avian species or strain to work with, the environmental conditions during grow out, and the feed with which one is dealing. It is also necessary to understand and interpret model outputs that show how the bird behaves in such conditions, so that one can finally decide the appropriate nutritional or production strategy to be used while simultaneously understanding the model's limitations and considering individual flock variability and feed quality. Moreover, econometric techniques should be applied in poultry nutrition and production. Applying these techniques should help to understand the impacts of changes in feedstuff costs and prices of poultry products to determine the most adequate nutrient levels for each specific market condition and obtain the maximum profitability.

Another explanation for the lack of use of models in poultry research and production was pointed out as the relatively low experimental cost associated with poultry research, compared with other species such as ruminants. Consequently, very few efforts have been devoted to optimizing the experimental design, with no formal request to make explicit the underlying assumptions tested, leading to a lack of conceptual models. This might change due to the increasing costs and legal requirements attached currently to avian experimentation.

Finally, poultry production chains involve stakeholders who are direct competitors on the market. Therefore, any research that might lead to an economical advantage is, by definition, not shared. As a consequence, systemic modelling, which is a long-term action relying on substantial economical and intellectual supports, is difficult to implement due to the lack of access to some data and to the weakness of human resources available within a given firm. Ways to overcome these problems may be to create consortiums between networks of firms and research institutes to define and develop a shared model, or public research and extension networks aiming at developing models and at building databases usable for meta-analysis or other modelling techniques.

Conclusions

Mathematical models are indeed tools necessary to understand the complex problems common in poultry enterprise management, processing, live production, nutrition and research. Many models have been proposed for the poultry industry and most have been abandoned. Currently, models that have the capability to link live performance with econometric business analyses are still used or being developed in the industry. The interest in poultry modelling is greater in the industry than in academic institutions. Poultry companies invest heavily in tools that allow them to observe transactions, carry out planning, forecasting, estimate optimal production levels and evaluate business strategies. Very few biological models have broad application in the poultry business or are linked to more complex modelling tools for decision making. Mechanistic models, although well known to be more accurate and helpful in gaining knowledge, are indeed less appreciated in the poultry industry than the ones developed based on empirical methodologies. The main limitation to model adoption is knowledge of mathematical methods, growth and development concepts, and understanding of model structure and outputs. The value of these tools is accepted by the industry, but the interest in investing in more mechanistic biological tools is still low. In order to resolve the issues that are limiting application of models in poultry, it is necessary to enhance the interest of the academic community in these approaches and to train future professionals in these techniques and this way of thinking. This may require the collaboration of the private industry that actually owns, develops and uses such models.

References

Ahmad, H.A. (2009) Poultry growth modeling using neural networks and simulated data. *Journal of Applied Poultry Research* 18, 440–446.

Ahmad, H.A. and Roland, Sr, D.A. (2001) Effect of method of formulation and feeding on performance and profitability of laying hens. an econometric approach. *Journal of Applied Poultry Research* 10, 162–171.

Ahmad, H.A. and Roland, Sr, D.A. (2003a) Effect of environmental temperature and TSAA level on performance and profitability of laying hens: an econometric approach. *Journal of Applied Poultry Research* 12, 476–482.

Ahmad, H.A. and Roland, Sr, D.A. (2003b) Effect of method of feeding and feed formulation on performance and profitability of laying hens: an econometric approach. *Journal of Applied Poultry Research* 12, 291–298.

Ahmadi, H. and Golian, A. (2010) Growth analysis of chickens fed diets varying in the percentage of metabolizable energy provided by protein, fat, and carbohydrate through artificial neural network. *Poultry Science* 89, 173–179.

Bignon, L., Llorca, A., Bouvarel, I. and Lescoat, P. (2007). Amelioration de la prise en compte de l'activite physique et de la presentation de l'aliment dans la prevision des performances des poulets de chair. *Proceedings of Actes des 7èmes Journées de la Recherche Avicole*, INRA, Tours, France. CD.

Bolzan, A.C., Machado, R.A.F. and Piaia, J.C.Z. (2008) Egg hatchability prediction by multiple linear regression and artificial neural networks. *Revista Brasileira de Ciência Avícola* 10, 97–102.

Chen, L.J., Xing, L. and L.J. Han (2009) Quantitative determination of nutrient content in poultry manure by near infrared spectroscopy based on artificial neural networks. *Poultry Science* 88, 2496–2503.

Chrystal, P.V. (2009) Maximising broiler profit using the EFG Model: a comparative case study. In: The Poultry Federation, *Proceedings of the Arkansas Nutrition Conference*. Rogers, Arkansas, USA. Available at: www.thepoultryfederation.com/public/userfiles/files/Chrystal%20-%20Maximising%20Broiler%20Profit%20with%20EFG%20a%20Comparative%20.pdf (accessed 5 June 2014).

Cravener, T.L. and Roush, W.B. (2001) Prediction of amino acid profiles in feed ingredients: genetic algorithm calibration of artificial neural networks. *Animal Feed Science and Technology* 90, 131–141.

De Beer, M. (2009) Adjusting nutrient density when faced with volatile markets. In: The Poultry Federation, *Proceedings of the Arkansas Nutrition Conference*. Rogers, Arkansas, USA.

Available at: http://www.thepoultryfederation.com/public/userfiles/files/DeBeer%20-%20Adjusting%20Nutrient%20Density%20when%20Faced%20with%20Volatile.pdf (accessed 5 June 2014).

De Beer, M. (2010) Nutrition for maximum profit – do the math. *Aviagen Brief, Huntsville, Alabama, USA. no. 29*. Available at: http://www.aviagen.com/assets/Uploads/AviagenBriefNutritionForProfitOct2010.pdf (accessed 30 June 2014).

Ebadi, M.R., Sedghi, M., Golian, A. and Ahmadi, H. (2011) Prediction of the true digestible amino acid contents from the chemical composition of sorghum grain for poultry. *Poultry Science* 90, 2397–2401.

Eits, R.M., Giesen, G.W., Kwakkel, R.P., Verstegen, M.W. and Den Hartog, L.A. (2002a) Dietary balanced protein in chickens. 2. An economic analysis. *British Poultry Science* 44, 310–317.

Eits, R.M., Kwakkel, R.P., Verstegen, M.W., Stoutjesdijk, P. and De Greef, K.H. (2002b) Protein and lipid deposition rates in male broiler chickens: separate responses to amino acids and protein-free energy. *Poultry Science* 81, 472–480.

Eits, R.M., Kwakkel, R.P., Verstegen, M.W.A. and Emmans, G.C. (2003) Responses of broiler chickens to dietary protein: effects of early life protein nutrition on later responses. *British Poultry Science* 44, 398–409.

Eits, R.M., Kwakkel, R.P., Verstegen, M.W. and Den Hartog, L.A. (2005) Dietary balanced protein in chickens. 1. A flexible and practical tool to predict growth response curve. *British Poultry Science* 44, 300–309.

Emmans, G.C. (1981) A model of the growth and feed intake of *ad libitum* fed animals, particularly poultry. In: Hillyer, G.M., Whittemore, C.T. and Gunn, R.G. (eds) *Computers in Animal Production*. Animal Production, Occasional Publication No. 5, London, pp. 103–110.

Emmans, G.C. (1989) The growth of turkeys. In: Nixey, C. and Grey, T.C. (eds) *Recent Advances in Turkey Science*. Butterworth, London, pp. 135–166.

Emmans, G.C. (1994) Effective energy: a concept of energy utilization applied across species. *British Journal of Nutrition* 71, 801–821.

Emmans, G.C. and Fisher, C. (1986) Problems in nutritional theory. In: Fisher, C. and Boorman, K.N. (eds) *Nutrient Requirements of Poultry and Nutritional Research*. Butterworths, London, pp. 9–39.

Fancher, B.I. (1999) Use of broiler growth modeling technology in live production strategic planning. *Proceedings of the Maryland Nutrition Conference*. College Park, Maryland, USA, pp. 41–50.

Faridi, A. and Golian, A. (2011) Use of neural network models to estimate early egg production in broiler breeder hens through dietary nutrient intake. *Poultry Science* 90, 2897–2903.

Faridi, A., Sakomura, N.K., Golian, A. and Marcato, S.M. (2012) Predicting body and carcass characteristics of 2 broiler chicken strains using support vector regression and neural network models. *Poultry Science* 91, 3286–3294.

Fisher, C., Morris, T.R. and Jennings, R.C. (1973) A model for the description and prediction of the response of laying hens to amino acid intake. *British Poultry Science* 14, 469–484.

Gompertz, B. (1825) On the nature of the function expressive of the law of human mortality, and on a new mode of determining the value of life contingencies. *Philosophical Transactions of the Royal Society of London* 115, 513–585.

Gous, R.M. (2006) A method for optimising the feeding of commercial broilers. *Proceedings of ASA Conference*. ASA, Manila, Philippines.

Gous, R.M. (2007) Predicting nutrient responses in poultry: future challenges. *Animal* 1, 57–65.

Gous, R.M. (2012) Simulation modeling for predicting responses in broiler breeder and laying hens. In: WPSA (ed.) *Proceedings of World's Poultry Congress*. WPSA, Salvador, Bahia, Brazil. CD-ROM.

Guevara, V.R. (2004) Use of nonlinear programming to optimize performance response to energy density in broiler feed formulation. *Poultry Science* 83, 147–151.

Gutierrez, O., Surbakti, N., Haq, A., Carey, J.B. and Bailey, C.A. (2008) Effect of continuous multiphase feeding schedules on nitrogen excretion and broiler performance. *Journal of Applied Poultry Research* 17, 463–470.

Harlow, H.B. and Ivey, F.J. (1994) Accuracy, precision, and commercial benefits of growth modeling for broilers. *Journal of Applied Poultry Research* 3, 391–402.

Huang, B.W., Shih, M.L, Nan-Hsing Chiu, Hu, W.Y. and Chiu, C. (2009) Price information evaluation and prediction for broiler using adapted case-based reasoning approach. *Expert Systems with Applications* 36, 1014–1019.

Hurwitz, S., Sklan, D. and Bartov, I. (1978) New formal approaches to the determination of energy and amino acid requirements of chicks. *Poultry Science* 57, 197–205.

Hurwitz, S., Plavnik, I., Bartov, I. and Bornstein, S. (1980) The amino acid requirements of chicks: experimental validation of model-calculated requirements. *Poultry Science* 59, 2470–2479.

Ivey, F.J. (1999) Desenvolvimento e aplicação de modelos de crescimento para frango de corte. In: Embrapa (eds) *Proceedings Simpósio internacional ACAV Embrapa sobre Nutrição de Aves*. Concórdia, Santa Catarina, Brazil, pp. 22–35

Ivey, F.J. and Harlow, H.B. (1991) Value of a growth model as a decision making tool. In: NFIA (eds) *Proceedings of Nutrition Institute Amino Acids Symposium*. Rosemont, Illinois, USA.

Ivey, F.J. and Harlow, H.B. (1992) Improvements in broiler production through the use of a growth model. *Novus International Symposium*. Lisbon, Portugal.

Ivey, F.J. and Harlow, H.B. (1994) Application of statistical modelling to predict broiler performance. *Proceedings of 9th European Poultry Conference*. Glasgow, UK, pp. 13–16.

King, R.D. (2001) Description of a growth simulation model for predicting the effect of diet on broiler composition and growth. *Poultry Science* 80, 245–253.

Létourneau-Montminy, M.P., Narcy, A., Lescoat, P., Bernier, J.F., Magnin, M., Pomar, C., Nys, Y., Sauvant, D. and Jondreville, C. (2010) Meta-analysis of phosphorus utilisation by chicks: influence of dietary calcium and microbial phytase supply. *Animal* 4, 1844–1853.

Liebert, F., Rimbach, M. and Peisker, M. (2000) Model for estimation of amino acid utilization and its requirements in growing animals. *Proceedings of Australian Poultry Science Symposium*. Sydney, Australia, pp. 79–92.

Lima, M.G.F. and Rodrigues, L.H.A. (2010) Decision tree applied to hatchery databases of Hy-Line W-36. *Ciência e Agrotecnologia* 34(6), http://www.scielo.br/pdf/cagro/v34n6/28.pdf.

Mathiaud, A., Mougenot, F., Klein S. and Mansuy, E. (2013) Modélisation nutritionnelle et prédiction des performances des poulets de chair. In: INRA (eds) *Proceedings 10e Journées de la Recherche Avicole et Palmipèdes à Foie Gras*. INRA, La Rochelle, France.

Meda, B. (2011) Une approche dynamique des flux d'éléments et d'énergie des ateliers de production avicole avec ou sans parcours: conception et application du modèle MOLDAVI. PhD Thesis, Agrocampus Ouest – Ecole Doctorale VAS Rennes, France, Thèse C-103-2011.23, 238 pp.

Mottaghitalab, M., Faridi, A., Darmani-Kuhi, H., France, J. and Ahmadi, H. (2010) Predicting caloric and feed efficiency in turkeys using the group method of data handling-type neural networks. *Poultry Science* 89, 1325–1331.

Nordmann, A.J., Kasenda, B. and Briel, M. (2012) Meta-analyses: what they can and cannot do. *Swiss Medical Weekly* 142, w13518.

Nugues, M., Métayer, J.-P., Skiba, F., Duyme, F. and Vilarino, M. (2013) Recherche de facteurs explicatifs de la digestibilité de l'amidon et de l'énergie des blés chez le poulet de chair par meta-analyse. In: INRA (eds) *Proceedings 10e Journées de la Recherche Avicole et Palmipèdes à Foie Gras*. La Rochelle, France.

Oviedo-Rondón, E.O. and Waldroup, P.W. (2002) Models to estimate amino acid requirements for broiler chickens: a review. *International Journal of Poultry Science* 1, 106–113.

Oviedo-Rondón, E.O., Murakami, A.E. and Sakaguti, E.S. (2002a) Computer modeling for poultry production and research. *Brazilian Journal of Poultry Science* 4, 199–207.

Oviedo-Rondón, E.O., Fritts, C.A. and Waldroup, P.W. (2002b) Accuracy of OmniPro® predictions for amino acid needs without minimum crude protein requirement. *International Journal of Poultry Science* 2, 178–182.

Oviedo-Rondón, E.O., Fritts, C.A. and Waldroup, P.W. (2002c) Accuracy of Omnipro II estimations for amino acid requirements of broilers. *International Journal of Poultry Science* 1, 119–126.

Oviedo-Rondón, E.O., Pomar, C. and Conceição, L.E.C. (2013) Modelagem na nutrição de monogástricos. In: Sakomura, N.K. and Hauschild, L. (eds) *Nutrição de Monogástricos*. FUNEP, Jaboticabal, São Paulo, Brazil.

Patel, V.C., McClendon, R.W. and Goodrum, J.W. (1998) Color computer vision and artificial neural networks for the detection of defects in poultry eggs. *Artificial Intelligence Review* 12, 163–176.

Perai, A.H., Nassiri Moghaddam, H., Asadpour, S., Bahrampour, J. and Mansoori, G. (2010) A comparison of artificial neural networks with other statistical approaches for the prediction of true metabolizable energy of meat and bone meal. *Poultry Science* 89, 1562–1568.

Pesti, G.M., Arraes, R.A. and Miller, B.R. (1986) Use of the quadratic growth response to dietary protein and energy concentrations in least-cost feed formulation. *Poultry Science* 65, 1040–1051.

Render, B., Stair, R.M. and Hanna, M.E. (2011) *Quantitative Analysis for Management*, 11th edn. Prentice Hall, New Jersey, USA, 667 pp.

Rivera-Torres, V., Ferket, P. and Sauvant, D. (2011a) Mechanistic modeling of turkey growth response to genotype and nutrition. *Journal of Animal Science* 89, 3170–3188.

Rivera-Torres, V., Noblet, J. and Van Milgen, J. (2011b) Changes in chemical composition in male turkeys during growth. *Poultry Science* 90, 68–74.

Rivera-Torres, V., Noblet, J., Dubois, S. and van Milgen, J. (2011c). Dynamics of energy utilization in male and female turkeys during growth. *Animal* 5, 202–210.

Roland D.A. Sr., Bryant, M.M., Zhang, J.X., Rao, S.K. and Roland Jr, D. (1999) Econometric nutrition and management. I: Maximizing profits on Hy-Line W-36 hens by optimizing feeding method, total sulfur amino acid intake and environmental temperature. *Journal of Applied Poultry Research* 7, 401–411.

Roush, W.B. (2001) An operations research approach to leveraging new technology opportunities. *Journal of Applied Poultry Research* 10, 293–302.

Roush, W.B. (2006) Advancements in empirical models for prediction and prescription. In: Gous, R., Morris, T. and Fisher, C. (eds) *Mechanistic Modelling in Pig and Poultry Production*. CAB International, Wallingford, UK, pp. 97–116.

Roush, W.B., Dozier, W.A. and Branton, S.L. (2006) Comparison of Gompertz and neural network models of broiler growth. *Poultry Science* 85, 794–797.

Salle, C.T.P., Guahyba, A.S., Wald, V.B., Silva, A.B., Salle, F.C. and Nascimento, V.P. (2003) Use of artificial neural networks to estimate production variables of broilers breeders in the production phase. *British Poultry Science* 44, 211–217.

Savegnago, R.P., Nunes, B.N., Caetano, S.L., Ferraudo, A.S., Schmidt, G.S., Ledur, M.C. and Munari, D.P. (2011) Comparison of logistic and neural network models to fit to the egg production curve of White Leghorn hens. *Poultry Science* 90, 705–711.

Si, J., Fritts, C.A. and Waldroup, P.W. (2001) Relationship of dietary lysine level to the concentration of all essential amino acids in broiler diets. *Poultry Science* 80, 1472–1479.

Sohail, S.S., Bryant, M.M. and Roland, D.A. Sr (2003) Influence of dietary fat on econometric return of commercial leghorns. *Journal of Applied Poultry Research* 12, 356–361.

Sutton, A.J., Jones, D.R., Abrams, K.R., Sheldon, T.A. and Song, F. (2000) *Methods for Meta-analysis in Medical Research*. Wiley, London.

Talpaz, H., de la Torre, J.R., Sharpe, P.J.H. and Hurwitz, S. (1986) Dynamic optimization model for feeding broilers. *Agricultural Systems* 20, 121–132.

Talpaz, H., Sharpe, P.J.H., Wu, H.I., Plavnik, I. and Hurwitz, S. (1991) Modeling the dynamics of the accelerated growth following feed restriction in chicks. *Agricultural Systems* 36, 125–135.

Talpaz, H., Cohen, M., Fancher, B. and Halley, J. (2013) Applying complex models to poultry production in the future: economics and biology. *Poultry Science* 92, 2541–2549.

Taube-Netto, M. (1996) Integrated planning for poultry production at Sadia. *Interfaces* 26, 38–53.

Wang, B.Y., Chen S.A. and Roan, S.W. (2012) Comparison of regression and artificial neural network models of egg production. *Journal of Animal and Veterinary Advances* 11, 2503–2508.

11 Commercial Application of Integrated Models to Improve Performance and Profitability in Finishing Pigs

N.S. Ferguson*
Nutreco Canada Agresearch, Guelph, Ontario, Canada

Abstract

The current market and economic challenges faced by pork producers are unprecedented and therefore there is a constant need to determine the economically optimal nutrition and management solutions. Simulation models can be used to fulfill this need provided they have the capacity to integrate animal responses, management practices and economics into an optimization process that produces reasonably accurate predictions under a wide range of commercial practices. Some of the key components required to successfully implement an optimization model in commercial practice include: (i) the ability to predict feed intake; (ii) integration of an animal biology model that predicts animal responses to nutrient, management and environmental changes and the financial consequences thereof, with a feed formulation system; (iii) knowing the variation in responses between individual animals and understanding the source of animal variation; (iv) the effect of shipping management on mean performance; and (v) model validation. Such integrated optimization models (e.g. Watson® 2.0 used by Nutreco) can be used strategically to drive significant nutritional or production changes with large economic consequences. For example, based on the findings of a model, a commercial feed company may change the nutrient profile of all their standard nursery diets in response to increasing ingredient prices. Or a model may help a producer to understand the risks, costs and benefits of changing genetics, or provide producers with a reference guide to help decide what is the optimum shipping weight bearing in mind rapidly changing pig and/or feed prices. Just as helpful but on a much smaller scale is using a model to help a producer improve feed efficiency or reduce costs or increase revenue by optimizing the nutrient density of the diet or optimizing when diets should be changed during the grower-finishing period. Fundamental to the successful application of optimization models in commercial practice is the need for an accurate biological model as well as a well-defined commercialization process.

Introduction

Simulation of pig growth for the purpose of predicting the responses of pigs to nutrient inputs has come a long way since the first conceptual frameworks were published by Whittemore and Fawcett (1976) and Emmans (1981). A number of models differing in complexity and application have been reported in the scientific literature, each with their own description of growth and predictive objectives (Black *et al.*, 1986; Pomar *et al.*, 1991; Ferguson *et al.*, 1994; Moughan, 1995; Knap, 1999;

---

*E-mail: neil.ferguson@nutreco.ca

Nutritional Modelling for Pigs and Poultry (eds N.K. Sakomura *et al.*)

Birkett and de Lange, 2001; Green and Whittemore, 2003; Wellock *et al.*, 2003a; van Milgen *et al.*, 2008; NRC, 2012). The successful application of these models in practice has varied owing to a number of factors including complexity, ease of use, ability to integrate into existing business software and the robustness of their scientific theory under commercial application. Despite the limited degree of success, there is no doubt that the integration of a biological growth model with a dynamic feed formulator and optimization capabilities significantly enhances the ability to make well informed decisions in a highly volatile market and a changing production environment. It is for this reason that an integrated pig management system, called Watson®, was developed and applied in commercial practice. The theoretical framework and associated quantitative biology contained within Watson® is based on scientific evidence published over the last 30 years and can be reviewed in previously published papers (Wellock *et al.*, 2003a,c; Ferguson, 2006). Traditionally, pig growth models have been characterized by their ability to partition nutrients (energy and protein or amino acids) into protein and fat tissue, with a strong emphasis on predicting static nutrient requirements and growth responses. However, they have had limited capacity to accommodate dynamic interactions between voluntary feed intake, animal performance and production economics, including raw material costs and pig prices. Without the ability to predict the effects of interactions between the animal, the feed and the physical and social environment on voluntary feed intake and subsequent body tissue growth, pig growth models will continue to receive minimal commercial attention. The current market and economic challenges faced by pork producers are unprecedented and therefore there is a constant need to determine the economically optimal nutrition and management solutions. In addition to financial sustainability, there is increasing demand for socially responsible pork production including improved animal welfare or social interactions, and reductions in carbon footprint, eutrophication and acidification. With this in mind, the expectation and role of simulation models in commercial practice is evolving such that they are required to: (i) simultaneously focus on nutrient, economic and environmental sustainability responses through optimization procedures integrating animal biology, least cost feed formulations and economics; (ii) be more context orientated by providing solutions to rapidly changing market conditions and improve problem solving capabilities; (iii) incorporate intelligent user interface processes to improve the accuracy and reliability of critical input data as well as simplifying the process, such as describing the genotype or quantifying the health status; (iv) provide a more diverse user base such as business leaders, sales managers, technical advisors and not just nutritionists; (v) become part of the company's 'DNA' or an integral part of the value proposition provided to their customers; and (vi) provide accurate predictions across a wide range of commercial conditions. This chapter will focus on certain key components identified as being important in the process of successfully applying an integrated pig model to commercial practice.

Animal Biology

For a detailed description of the biological theory refer to papers by Emmans (1981) and Ferguson (2006). However, one of the key biological components necessary for commercialization of a growth simulation model is the prediction of voluntary feed intake. Without the ability to predict feed intake, it is not possible to incorporate optimization and particularly stochastic optimization because it is the link between animal performance and economics (Gous and Berhe, 2006). However, predicting feed intake is also very challenging because of the complexity of feed intake regulation. It is for this reason that in most models feed intake is either an input (Pomar *et al.*, 1991; TMV, 1994; Moughan, 1995; Birkett and de Lange, 2001), or empirical feed intake curves are used (NRC, 2012). Despite the challenges, there are models that predict feed intake with varying degrees of success (Black *et al.*, 1986; Ferguson *et al.*, 1994; Knap, 1999; Wellock *et al.*, 2003b). Watson® predicts feed intake by considering both what the animal would need to eat to satisfy the requirement for the most limiting nutrient under non-limiting conditions (i.e. desired feed intake), and what it is constrained to eat by gut capacity, the diet, social stressors and environmental factors (i.e. constrained feed intake). With this approach it is possible to predict the voluntary feed intake with a reasonably high degree of accuracy (<5% deviation from actual) (Wellock *et al.*, 2003b; Ferguson, 2006). This approach to predicting feed intake allows for changes in animal definition, nutrient profile and supply, social and physical environment and health status to be reflected in the amount of feed consumed and in the subsequent growth of the animal. It is also important to note that these responses will differ between individuals within a population (Ferguson *et al.*, 1997; Knap, 2000; Wellock *et al.*, 2004; Brossard *et al.*, 2009; Hauschild *et al.*, 2010).

Optimization

Given the unprecedented challenges pork producers are facing, not to mention the volatility in the ingredient commodity market, only financially optimal nutrition and management solutions are sustainable. Running a single simulation will not provide an optimal solution; rather it is necessary to run multiple simulations simultaneously to achieve the optimum solution for a given objective (e.g. maximum margin over feed cost (MOFC) or minimum feed:gain). Optimizing nutritional strategies based on economic returns or animal performance rather than least cost formulation for a defined set of nutrient requirements is the most appropriate method for improving performance and profitability at the farm level. Gous and Berhe (2006) defined the criteria required for optimization as: (i) feed costs at defined nutrient levels; (ii) animal responses to changing nutrient profiles; (iii) fixed and variable costs associated with the production system; and (iv) definition of revenue generating processes. Figure 11.1 illustrates the conceptual relationship between animal biology, optimization and animal variation.

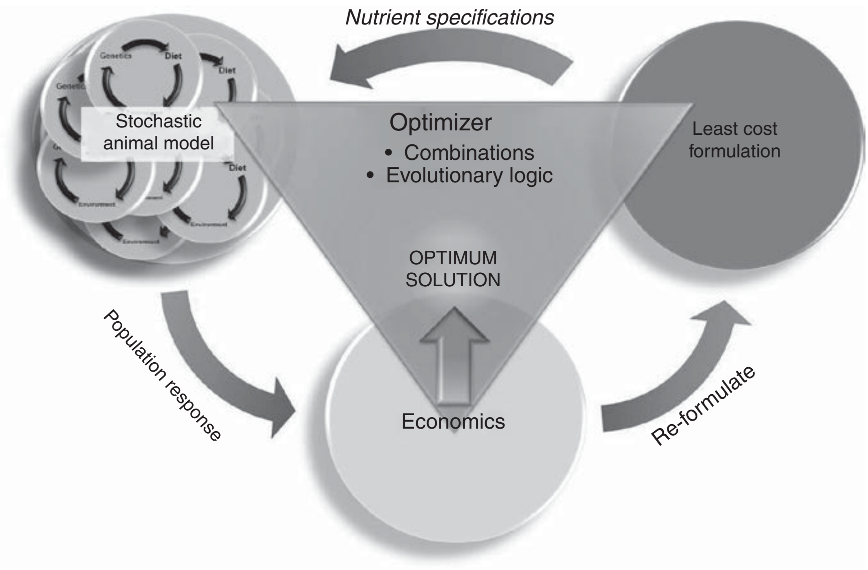


Fig. 11.1. The main components of the optimization process.

The optimization process is started by passing initial specifications (Nutrients) to a feed formulator to determine the ingredient composition at the least cost (Formulation). These diets are made available to the animal in the biology component to produce a specific animal response, including feed intake, growth, feed costs and carcass characteristics. From these data the financial outcomes (Economics) can be generated, which are then forwarded to the optimizer to complete the cycle. This process is repeated before identifying the 'best' solution to meet the optimization objective. Currently in Watson® 2.0 the processes to be optimized include energy content, nutrient density, amino acid responses, carcass weights and feeding phases, while the optimization objectives include maximizing growth rates, margin over feed costs, net profit per pig and minimizing feed:gain, cost/kilogramme gain, and nutrient excretion. There will be different optimum solutions depending on the objective. For example, the incremental cost of increasing the dietary amino acid level may not be offset by the increase in revenue generated from improved feed efficiency and/or higher carcass lean, resulting in differences in the optimum amino acid requirements between minimizing feed:gain and maximizing margin over feed cost objectives. The results of the optimization process always provide three possible solutions including: (i) the single best solution (e.g. highest MOFC or lowest feed:gain) called the Optimum solution; (ii) a solution that can meet the objective (e.g. improve MOFC by CAN$0.50/pig) but does not deviate too much from the current nutrition programme, called the Minimum solution; and (iii) a programme that represents the average of all solutions that meet the objective (e.g. improve MOFC by $0.50/pig), called the Average solution.

As individual pigs will have different optimum performance and economic responses to amino acid intakes, it is necessary to incorporate this between-animal variation into the optimization process. Gous and Berhe (2006) summarized the importance of this issue as follows:

> Models of individuals may be adequate for an understanding of the theory of growth and feed intake, as well as for 'what-if' scenario planning. However, for purposes of optimization, it is imperative to account for the variation inherent in the system if a realistic assessment of the population response is to be simulated.

Within a batch of finishing pigs there is sufficient between-animal variation in protein and fat deposition, feed intake and subsequent efficiency of nutrient utilization to ensure differences in the optimum nutrient response between the single average individual and the batch mean (Pomar *et al.*, 2003; Brossard *et al.*, 2009; de Lange *et al.*, 2012). The challenge for commercial models used across functional areas is how to introduce stochasticity into the optimization process without generating excessively large amounts of redundant data that take up unnecessary time and computing resources.

Animal Variation

Most integrated pig growth models are deterministic by nature and assume that the response of the 'average' individual is a good representation of the population response. In most practical cases this assumption may hold true, but there are cases when the mean response can differ significantly from the average individual response due to the variation in growth potential between individual animals (Pomar *et al.*, 2003; Brossard *et al.*, 2009). The extent of these differences will depend on: (i) the extent of the differences between individuals within the population; (ii) the correlation between the genetic parameters defining the genotype; and (iii) the individual animal's ability to cope with social stressors (Wellock *et al.*, 2003c, 2004). The more individuals vary within a population (e.g. the larger the variation in initial starting weight), the more inappropriate it is to use the average individual response as a means of predicting the population response. For example, predicting nutrient requirements for a population based on the single deterministic response will introduce a bias against individuals with a higher nutrient requirement. These errors can be magnified during the optimization process, which is dependent on the herd nutrient responses. Not only is the introduction of animal genetic variation essential for more accurate nutritional optimization but, according to Knap (1995), it also influences financial outcomes through the subsequent variation in production characteristics (feed intake, growth rate, backfat, hot carcass weight, lean yield and gross profit). Further reasons for considering between-animal variation in pig modelling are: (i) to predict more accurately the optimum strategy for shipping pigs to market to increase the proportion of 'full-value' pigs per close-out; and (ii) to enhance production through better utilization of space and minimizing performance failures. There are other sources of variation (feed and physical environment) that influence the individual's response but these will not be addressed in this chapter. In general, variation is introduced into the model by randomly generating a value around the mean and standard deviation of: (i) the genetic potential parameters; (ii) initial size; (iii) ability to cope with social stress; and (iv) health score.

Genetic potential

As described in a previous paper (Ferguson, 2006) and other similar models (Knap 2000; Pomar *et al.*, 2003; Wellock *et al.*, 2003a), the genetic potential growth of an individual pig can be defined in principle by three components: (i) potential rate of maturing (B) or its uncorrelated with Pm equivalent ($B^* = B \times Pm^{0.27}$); (ii) mature protein weight (Pm); and (iii) inherent fatness or desired fat level relative to protein weight (LPm). Data for these parameters and their variability are limited and confined to a generic estimate for the genotype irrespective of gender. Typical coefficient of variation (CV) values are 0.01–0.03 for B^*, 0.05–0.07 for Pm and 0.10–0.15 for LPm.

Initial size (body weight for a given age)

Individuals within a population are likely to have different starting body weights for a given age, and therefore different amounts of protein, lipid, water and ash. Assuming a fixed starting age, initial body weight will vary according to the population mean weight and standard deviation. This variation at the start of the growing period will be a significant factor affecting the variation in body weights at slaughter. Wellock *et al.* (2004) modelled the effect of varying the standard deviation of initial body weight from 0 kg to 12 kg and concluded that this variation would substantially affect the subsequent population mean growth response. Based on previous grower-finisher trials at Nutreco Canada, the coefficient of variation of feeder pigs (initial weights close to 25 kg) varied from 0.06–0.17 with an average of 0.11. Part of the variation in starting weight will be derived from the individual's potential growth rate, and therefore start weight will be correlated with the genetic parameters (Wellock *et al.*, 2004). Individuals with the highest growth potential will tend to have the highest initial weight.

Ability to cope with social stress

Earlier studies have clearly demonstrated that individual pigs within a pen interact differently with each other, and these interactions can affect individual performances (Tindsley and Lean, 1984). Data from Giroux *et al.* (2000) indicate that social interactions can account for 9% of the variation in average daily gain (ADG) in growing pigs. Socially dominant individuals, often larger individuals, are less affected by social stresses and tend to perform better than their subordinates when exposed to suboptimal production conditions (e.g. high stocking density, inadequate feeder space) (Botermans, 1999). Wellock *et al.* (2003c) proposed a modelling approach to incorporate social interactions between individuals and the effects these have on subsequent performance. The authors introduced a genetic parameter (A2C) to describe 'the ability of an individual pig to cope when exposed to social stressors'. The mechanism by which A2C exerts its influence on performance involves both the animal's ability to attain potential growth and its effect on feeding behaviour. Socially stressed animals (low A2C) will have a lower capacity to achieve potential (protein) growth and their normal feeding behaviour is disrupted, resulting in subsequent reduced performance. The main social stressors that interact with A2C include stocking density, feeder space and health status (Fig. 11.2).

The A2C parameter will accommodate the noticeable variation between individuals in how they respond to social stressors. Because of the strong correlation between size and dominance (Tindsley and Lean, 1984; D'Eath, 2002) it is reasonable to assume that there is a strong positive correlation between live weight and A2C. Turner *et al.* (2002) observed a greater reduction in growth rates in smaller pigs than larger pigs when grown under more stressful conditions (low feeder space and large group size). There is likely to be an increase in within-pen body weight variation when the level of stress increases. This was observed by Anil *et al.* (2007) when pigs kept at acceptable stocking density levels (>0.74 m^2/pig) had body weight standard deviations of 7.6–14.9 kg compared to those pigs with less space (0.64 m^2/pig) of 11.7–16.6 kg Although these differences were not statistically different, they do highlight the possibility that the weight differences between the small and large pigs in a pen may increase with higher levels of stress. Tindsley and Lean (1984) noted that dominant pigs were generally the heaviest pigs and that the variation in ability to dominate may be responsible for live weight variations.

Health

Not only are there differences in growth potential, initial body weight and A2C between individuals within a group, there are also genetic differences in immune-competence (Knap and Bishop, 2000; Flori *et al.*, 2011).

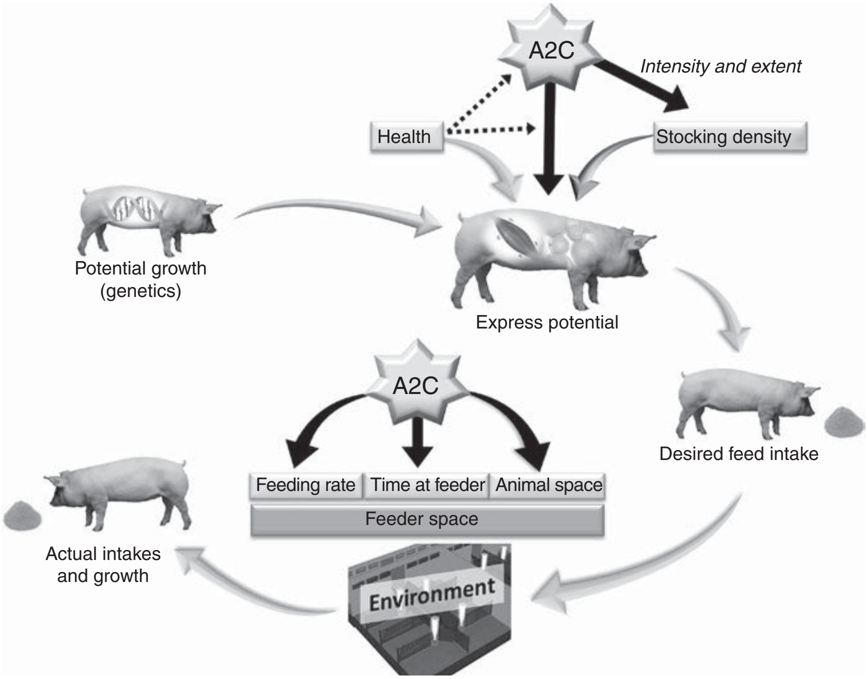


Fig. 11.2. Interactions between an animal's ability to cope (A2C) with social stressors and subsequent effects on performance.

Clapperton *et al.* (2009) observed substantial genetic variation in immunity traits in pigs and therefore it can be assumed that individual pigs in a population will have different abilities to respond to a health challenge. To accommodate this phenotypic variation in health, it is assumed that the variation in health status (or score) will not be constant, but in a population of very healthy pigs (e.g. population mean health score = Optimal) there will be less variation than in a population that has a health challenge. In a population with a mean low health status there is likely to be more individual variation with some pigs with a strong immune-competency effectively having a higher health status. Flori *et al.* (2011) observed a range of phenotypic variation (CV) values in immune traits between 0.01 and 0.039, therefore it can be assumed that the CV of an 'Average' health status herd will be somewhere in between (0.017–0.020). Within a significantly health-challenged herd the CV for health will increase to 0.04, whereas under 'Optimal' health conditions the CV will be close to 0. There is also likely to be some interaction between A2C and health status, as healthier individuals are better able to cope with stress than challenged pigs.

Shipping Strategies

When considering economic optimization (e.g. maximize MOFC), one of the most important factors is the revenue per pig carcass and therefore the higher and less variable the revenue generated per batch of pigs, the more profitable the operation. For this reason it is important to know when individual pigs should be shipped to maximize their revenue based on the method of payment the producer receives (e.g. index or bonus/discount systems). Table 11.1 illustrates the potential opportunity of models to predict the outcomes of different shipping strategies. The data were from pigs shipped over a 5-week period based on a shipping weight of close to 119 kg (Nutreco Canada, 2012, unpublished data). Using a modified differential evolutionary algorithm the optimum shipping strategies can be defined. Table 11.2 illustrates an example of such an optimization process and the potential to improve gross profit by selecting the optimum weekly shipping pattern. The actual levels of improvement will depend on the grading system used for determining payment per pig.

Commercial Applications

When models are used to drive significant policy, nutritional, production and/or manufacturing changes with potentially large economic consequences, this process can be defined as strategic model utilization. The other commercial application of models is more incremental by nature, where attention is given at the local (producer-specific) level to improve performance or profitability or assist in the day-to-day decision making processes. Typically there will be an external stimulus that will trigger a response for change. The magnitude of the expected response will define whether the model is used strategically or incrementally. For example, if there is an increase in the price of one or more important ingredients that will have a significant effect on feed costs either for the feed manufacturer and/or the pig producer, this will invoke a strategic response such as running multiple optimizations to determine the formulation change, notifying manufacturing of the pending changes and then communicating to the relevant stakeholders (sales team, producers, etc.). Typical incremental use of the model would be to optimize performance or profit for a specific producer, e.g. to determine the optimum slaughter weight when the price per kilogramme of hot carcass changes.

Strategic use

The following are some commercial examples of strategic model usage.

High feed costs and associated changes to the nursery feeding programme

In 2012 most of the main cereal grains and high protein ingredients exhibited significant

Table 11.1. Summary of the predicted (Watson) and actual (trial data) number of pigs shipped weekly over a 5-week period and their respective performances as well as the average performance for the whole batch of pigs (cumulative) (From Nutreco Canada, 2012, unpublished data.)

Week	%	Farm gate weight (kg)			ADG (kg/day)			ADFI (kg/day)			FG		
Shipped	Shipped	Actual	Predicted	% Difference	Actual	Predicted	% Difference	Actual	Predicted	% Difference	Actual	Predicted	% Difference
12	16	118	119	1.1	1.08	1.09	1.0	nd	3.10		nd	2.83	
13	30	119	119	0.4	1.04	1.03	–0.7	nd	2.57		nd	2.49	
14	32	119	117	–1.8	0.98	0.96	–2.7	nd	2.40		nd	2.51	
15	0												
16	22	122	123	1.2	0.89	0.90	0.3	nd	2.26		nd	2.52	
Cumul. average		119	119	0.0	1.00	0.99	–0.9	2.544	2.53	–0.4	2.58	2.56	–0.8

ADG = average daily gain; ADFI = average daily feed intake; FG = ADFI/ADG price increases, in most cases over 50%. This resulted in large increases in feed prices and it was therefore necessary to re-examine whether the current nursery feeding programme was providing the maximum financial return for the producer. This process entailed running multiple optimizations using different feed pricing and pig payment scenarios. The outcome of the optimization process was to feed diets higher in amino acids (9% and 12%, Phase 3 and 4, respectively) to improve feed efficiency and reduce overall feed costs. Table 11.3 summarizes the predicted and actual performance and economic responses associated with the change.

The optimization process predicted that by the end of the nursery phase, the producer should have a reduction of 0.09 in feed:gain and $0.031/kg in cost/kg gain. In reality the producer returned a 0.08 reduction in feed:gain and a $0.024/kg reduction in feed costs/kg gain.

Production system change (health and genetics)

A producer was having significant health challenges and was unhappy with the growth performance of his current genetics. He wanted to know what performance he could expect if he improved the health status of the herd by depopulating the barn, leaving this empty for a period of time and then repopulating the barn with pigs from

Table 11.2. The predicted potential improvements in margin over feed cost (MOFC) for different shipping strategies, identified by the optimization process, relative to the shipping pattern used in a commercial trial. (From Nutreco Canada, 2012, unpublished data.)

	% of pigs shipped each week					Improvement
	Week 12	Week 13	Week 14	Week 15	Week 16	in MOFC ($)[a]
Trial	16	30	32	0	22	
Optimum 1	0	16	50	0	34	+$2.60
Optimum 2	0	32	30	0	38	+$2.57
Optimum 3	0	24	40	0	36	+$2.54
Optimum 4	0	40	30	0	30	+$2.52

[a] Improvement in MOFC relative to trial shipping strategy – actual improvement values will depend on the grading payment system.

Table 11.3. Summary of the predicted (Watson) and actual (on-farm) performance and economic responses for the whole nursery period, to changes in Phase 3 and 4 nursery diets derived from the optimization process. (From Simard, 2012, unpublished data.)

	Watson simulations			On-farm results		
	Original	Optimized	Difference	Original	Optimized	Difference
Phase 3 diets only (8–12 kg)						
End weight, kg	28.5	29.3	+0.75	28.6	29.0	+0.38
ADG, g/day	450	468	+18	449	458	+9
Feed:gain	1.51	1.49	–0.02	1.56	1.54	–0.02
Cost/kg gain, $/kg	0.99	0.98	–0.01	0.99	0.99	–0.01
Phase 4 diets only (12–28kg)						
End weight, kg	28.3	28.1	–0.20	28.5	29.1	+0.61
ADG, g/day	444	440	–4	447	460	+13
Feed:gain	1.57	1.50	–0.07	1.58	1.52	–0.06
Cost/kg gain, $/kg[a]	0.872	0.848	–0.024	0.997	0.980	–0.017

[a] There was a large increase in feed ingredient prices between the time of simulation and on-farm feeding, which caused the differences in cost/kg.

ADG = average daily gain.

a different source of genetics. This was a significant investment for the producer and he wanted to be reasonably certain that the improvement in animal performance would, in the long term, cover the costs and help to justify the decision. Simulations were performed to illustrate the expected outcomes. Table 11.4 summarizes the comparison between predicted and actual performance before and after the changes.

It was evident that the predictions were within ±5% of actual results, and the model was effective in estimating the changes in performance when genotype and health status were improved.

Changing market environment

One of the biggest challenges for pig producers is to manage effectively the volatility in the market, especially when pig prices are fluctuating and feed costs are high. In these situations it is critical to know what the optimum shipping live weight should be for a specific slaughter plant. Watson® was used to derive a reference guide for producers to help in their decision making process (Table 11.5).

The guide is a quick and easy reference for the producer to identify the target shipping live weight that will provide the highest gross profit per pig under different pig price and feed cost scenarios. It is readily used by sales teams because it is simple, easy to read and provides a more objective assessment when dealing with rapidly changing market conditions. It has been reported to have saved producers up to $1.50/pig (Perron, 2011).

Sustainability

Most animal nutrition service providers are stakeholders in the pig industry and therefore need to support producers in their compliance with nutrient management regulations, as well as encourage responsible pork production. Models are an excellent tool to facilitate the reduction of their carbon footprint, and nutrient excretion, especially nitrogen (N) and phosphorus (P). This includes: (i) meticulous assessment of total and digestible protein (Nx6.25) and P content of feed ingredients in order to eliminate unnecessary safety margins; (ii) using Watson® to determine the optimal ideal protein and P requirement for each phase of feeding; (iii) optimizing the feed formulations to minimize N and P losses; and (iv) monitoring the magnitude of change associated with new feeding strategies. In addition, the power of optimization allows producers to decide between reducing their environmental impact (e.g. CO_2 per kg pork, N and P excretion) or continuing to use financial and performance orientated objectives. For example, by allocating a CO_2 output value for each ingredient and therefore for the complete feed it is possible to formulate diets that will optimize financial gains while at the same time reducing the CO_2 per kg pork of the production system.

Table 11.4. Summary of the predicted (Watson) and actual (on-farm) performances before and after changing the health status and genotype. (From Shur-Gain field trial, 2007.)

	Before changes			After changes		
	Watson	On-farm	% Difference	Watson	On-farm	% Difference
ADG (g/day)	847	866	+2.2	970	934	+3.7
Feed conversion	2.70	2.64	–2.2	2.44	2.42	–1.0
Days to market	94.5	95.0	+0.5	98.0	99.0	+1.0
ADFI (kg/day)	2.50	2.60	+4.0	2.36	2.26	–4.3
Market weight (kg)	112.7	113.7	+0.9	114.4	113.5	–1.0
Carcass weight (kg)	90.2	91.1	+1.0	92.6	92.5	–0.1
Lean yield (%)	60.6	59.8	–1.3	60.9	61.1	+0.3
Backfat (mm)	18.6	18.9	+1.6	18.4	18.1	–1.6

ADG = average daily gain; ADFI = average daily feed intake.

Table 11.5. An example of a reference guide to identify the target shipping live weight that will maximize the profit per pig under different pig price and feed cost scenarios. (From R. Mercier, personal communication, 2011.)

Pig price	Average feed cost/MT ($/MT)									Target
($/kg)	300	310	320	330	340	350	360	370	380	Live weight (kg)
1.5	(9.93)	(12.4)	(14.8)	(17.2)	(19.6)	(22.0)	(24.5)	(26.9)	(29.3)	118
	(7.98)	(10.5)	(13.0)	(15.5)	(18.0)	(20.5)	(23.1)	(25.6)	(28.1)	120
	(6.83)	(9.43)	(12.0)	(14.6)	(17.2)	(19.9)	(22.5)	(25.1)	(27.7)	122
	(6.82)	(9.52)	(12.2)	(14.9)	(17.6)	(20.3)	(23.0)	(25.7)	(28.4)	125
	(7.66)	(10.5)	(13.3)	(16.1)	(18.9)	(21.7)	(24.5)	(27.3)	(30.1)	127
	(9.10)	(12.0)	(14.9)	(17.8)	(20.7)	(23.6)	(26.5)	(29.4)	(32.3)	130
1.6	(1.86)	(4.29)	(6.71)	(9.13)	(11.6)	(14.0)	(16.4)	(18.8)	(21.2)	118
	0.40	(2.11)	(4.63)	(7.14)	(9.65)	(12.2)	(14.7)	(17.2)	(19.7)	120
	1.81	(0.80)	(3.40)	(6.00)	(8.61)	(11.2)	(13.8)	(16.4)	(19.0)	122
	2.06	(0.65)	(3.35)	(6.05)	(8.75)	(11.5)	(14.2)	(16.9)	(19.6)	125
	1.40	(1.40)	(4.20)	(7.00)	(9.80)	(12.6)	(15.4)	(18.2)	(21.0)	127
	0.11	(2.79)	(5.68)	(8.58)	(11.5)	(14.4)	(17.3)	(20.2)	(23.1)	130
1.7	6.20	3.77	1.35	(1.07)	(3.49)	(5.91)	(8.34)	(10.8)	(13.2)	118
	8.78	6.26	3.75	1.23	(1.28)	(3.79)	(6.31)	(8.82)	(11.3)	120
	10.44	7.84	5.23	2.63	0.03	(2.58)	(5.18)	(7.78)	(10.4)	122
	10.93	8.23	5.53	2.83	0.13	(2.57)	(5.27)	(7.97)	(10.7)	125
	10.47	7.67	4.87	2.07	(0.73)	(3.53)	(6.33)	(9.13)	(11.9)	127
	9.32	6.43	3.53	0.63	(2.26)	(5.16)	(8.06)	(10.96)	(13.9)	130
1.8	14.26	11.8	9.41	6.99	4.57	2.15	(0.27)	(2.70)	(5.12)	118
	17.2	14.6	12.1	9.61	7.10	4.58	2.07	(0.44)	(2.96)	120
	19.1	16.5	13.9	11.3	8.66	6.06	3.45	0.85	(1.75)	122
	19.8	17.1	14.4	11.7	9.00	6.30	3.60	0.90	(1.80)	125
	19.5	16.7	13.9	11.1	8.33	5.54	2.74	(0.06)	(2.86)	127
	18.5	15.6	12.7	9.84	6.95	4.05	1.15	(1.74)	(4.64)	130

MT = metric tonnes.

Incremental use

When the model is used at a local level to help a customer, there is a general approach that is adopted. Typically this process would involve: (i) identifying the customer's objective(s) and decide whether Watson® is the appropriate tool; (ii) collecting as much production and farm specific data as required; (iii) initializing Watson®, including simulations to define the baseline farm performance; (iv) diagnosing opportunities for improvement by simulating appropriate scenarios; (v) deriving solutions to defined objective(s); and (vi) if possible, validating solutions with on-farm testing. The following examples illustrate the incremental usage of Watson® to derive optimum nutritional solutions for specific scenarios.

Improve feed efficiency

A large customer wanted to improve feed efficiency and reduce feed costs to improve their profit margin. To address this issue, Watson® was used first as a diagnostic tool to identify possible causes, and second to highlight the opportunity for improvement. The main causes of reduced feed efficiency were incorrect feed budget, diets too low in nutrient density, too much feed wastage, health concerns and various combinations of these causes. A summary of the solutions associated with each possible constraining factor is shown in Table 11.6.

Changing the health status and/or feed wastage required either long-term adjustments to their biosecurity programme or purchasing new feeders, which were then considered by the producer to be out of scope. Attention was focused on manipulating the feed budget and increasing the amino acid to energy ratio of the diets to meet the goal of improving feed efficiency and reducing feed costs. Watson® predicted an improvement in feed:gain of –0.05 g/g and a potential reduction in feed costs of $0.80/pig when changing both the nutrient composition and amount of each phase diet. These predicted changes were validated in a controlled study where the existing nutrition programme (diet and feed budget) was compared with two alternative treatments (same diets, different budget, and different diet, different budget). The results are shown in Table 11.7.

Table 11.6. Predicted relative improvements in performance and feed costs after changing certain production characteristics (from Nutreco Canada, 2007, unpublished data).

	Factors that were changed (gains relative to current programme)					
	Actual	Predicted	Feed budget	Diet + budget	Reduce feed waste	Improve health
ADG, g/day	767	769	+2	+8	0	+50
ADFI, kg/day	2.29	2.28	–0.01	–0.02	–0.03	+0.05
Feed:gain	2.29	2.96	–0.02	–0.05	–0.02	–0.08
Cost/kg gain ($/kg)	0.61	0.61	0	–0.01	–0.01	–0.02
Feed costs ($/pig)	52.5	52.8	–0.21	–0.80	–0.49	–0.80

ADG = average daily gain; ADFI = average daily feed intake.

Table 11.7. Actual vs predicted relative improvements to performance and feed costs after changing the feed budget and diet + feed budget. (From Nutreco Canada, 2007, unpublished data.)

	Predicted (commercial conditions)		Actual (research conditions)	
	Feed budget	Diet + budget	Feed budget	Diet + budget
ADG, g/day	+2	+8	+1	+8
ADFI, kg/day	–0.01	–0.02	–0.05	–0.05
Feed:gain	–0.02	–0.05	–0.06	–0.07
Cost/kg gain ($/kg)	0	–0.01	–0.07	–0.09
Feed costs ($/pig)	–0.21	–0.80	–0.51	–0.66

ADG = average daily gain; ADFI = average daily feed intake.

Despite some variances in actual vs predicted responses which were expected given the better management and health status of the research facility compared to the average commercial barn, the improvements were consistent. For the producer, feeding higher amino acid:energy ratio diets on a different feed budget improved feed efficiency and reduced feed costs.

Optimum nutrition strategy

Where there are strong business relationships with large customers, models are of particular benefit because predicting small cost savings or increased revenue can translate into significant monetary gains. However, customers require time to build up a level of trust in the accuracy of model predictions. Should the model consistently prove itself to be reliable and accurate, then larger customers will integrate the model into their decision making process, frequently requesting simulations to be made and the outcomes analysed before implementing any nutrition or production changes. In 2010, a large farrow to finish operation (>15,000 sows) in Canada that has utilized the services of Watson® for the past 5 years, wanted to 'maximize the margin over feed cost (MOFC) without sacrificing biological performance'. The key to addressing this, and any, issue with an established customer is being able to utilize a proven description of the current production environment already in the model. Running a series of optimizations for an established customer is a quick and efficient process. The results of the optimization analysis yielded two significant recommendations that would achieve the desired objective: (i) change the nutrient density (amino acids and energy) of the diets; and (ii) add another phase in the grow-finish programme. The end result was an improvement in MOFC of $2.38/pig without sacrificing performance (Table 11.8).

Table 11.8. Summary of the performance predictions between the original programme and the proposed Optimum programme based on optimizing for margin over feed costs (MOFC). (From At a Glance (an internal publication of Nutreco that is distributed to their customers), February 2010.)

	Original	Optimum
ADG, g/day	892	890
ADFI, kg/day	2.23	2.25
Feed:gain	2.50	2.51
Carcass weight, kg	95.4	95.4
MOFC improvement, $/pig		+2.38

ADG = average daily gain; ADFI = average daily feed intake.

Optimum nutrient density

A large integrator wanted to re-evaluate the nutrient specifications of their grower-finisher diets because of increasing feed ingredient prices using Watson® and then validate within a controlled research facility. The optimization objective was to reduce MOFC by at least $0.50/pig through changes in the energy and/or amino acid levels of the diets. The recommendation from the optimization process was to change the amino acid levels. A validation trial with Current, Optimum and Average feeding programme treatments was conducted using eight replications per treatment (Nutreco Canada, 2010, unpublished data). All simulations used to design these programmes were based on the current genetics, health status, physical environment and costs specific to the farm and time of year. The predicted and actual trial results are shown in Table 11.9.

The differences between the actual and predicted performance results were <4%. The close alignment between the actual (1.3%) and predicted (1.1%) improvement in the producer's MOFC confirms the validity of using the optimization process in commercial practice.

Conclusions

For successful commercial application of growth models it is not only imperative to have an accurate biological model, but also a well-defined commercialization process that includes: (i) involving all stakeholders (e.g. technical advisors, sales managers, business leaders and the various beneficiaries of the technology) in

Table 11.9. Comparison between Actual vs Predicted treatment performance results for the Whole Test Period (31–118 kg) and carcass results at 122 kg. (Control represents the existing feeding programme while Optimum and Average represent the optimum amino acid levels for each phase that provided the highest MOFC and the average amino acid levels for all optimum solutions that met the minimum improvement in MOFC, respectively.) (From Nutreco Canada, 2010, unpublished data.)

	Control		Optimum		Average	
	Actual	Watson	Actual	Watson	Actual	Watson
ADFI, kg/day	2.52	2.46	2.54	2.48	2.49	2.44
ADG, kg/day	0.946	0.917	0.946	0.921	0.931	0.914
Feed:gain	2.67	2.68	2.73	2.70	2.70	2.67
Feed cost, $	65.0	65.3	63.8	63.2	62.8	62.3
Cost/kg, $/kg	0.73	0.74	0.73	0.73	0.73	0.73
Slaughter weight, kg	123	123	121	122	121	121
Hot carcass weight, kg	99.1	99.0	97.6	97.7	97.1	97.3
Backfat, mm	19.7	20.3	19.3	20.1	19.7	19.8
Lean yield, %	60.4	60.0	60.6	60.1	60.4	60.2
MOFC difference, $[a]			+0.69	+0.74	+0.49	+0.41
MOFC improvement			+1.3%	+1.4%	+0.9%	+0.8%

[a]Standardized to 99 kg HCW, including additional feed costs based on (99 – HCW)/Dressing% × FG × Cost/MT.

ADG = average daily gain; ADFI = average daily feed intake; HCW = hot carcass weight; MOFC = margin over feed costs.

the design and development stages; (ii) fostering a modelling culture within the organization; (iii) a biological framework that is sufficiently robust to allow for easy and rapid changes and inclusion of new technologies; and (iv) the strategic utilization of the models to drive the decision making process through all levels of production, but particularly when it comes to profit optimization.

References

Anil, L., Anil, S.S. and Deen, J. (2007) Effects of allometric space allowance and weight group composition on grower-finisher pigs. *Canadian Journal of Animal Science* 87, 139–151.

Birkett, S. and de Lange, C.F.M. (2001) A computational framework for a nutrient flow representation of energy utilization by growing monogastric animals. *British Journal of Nutrition* 86, 661–674.

Black, J.L., Campbell, R.G., Williams, I.H., James, K.J. and Davies, G.T. (1986) Simulation of energy and amino acid utilisation in the pig. *Research and Development in Agriculture* 3, 121–145.

Botermans, J.A.M. (1999) Feeding environment for growing-finishing pigs. Effects of competition for feeding frequency on performance, behavior, injuries, plasma cortisol and exocrine pancreatic secretion. *Acta Universitatis Agriculturae Sueciae – Agraria* 192, 1–45.

Brossard, L., Dourmad, J.-Y., Rivest, J. and van Milgen, J. (2009) Modelling the variation in performance of a population of growing pigs as affected by lysine supply and feeding strategy. *Animal* 3, 1114–1123.

Clapperton, M., Diack, A.B., Matika, O., Glass, E.J., and Gladney, C.D. (2009) Traits associated with innate and adaptive immunity in pigs: heritability and associations with preference under different health status conditions. *Genetic Selection Evolution* 41, 54–61.

D'Eath, R.B. (2002) Individual aggressiveness measured in a resident-intruder test predicts the persistence of aggressive behavior and weight gains of young pigs after mixing. *Applied Animal Behaviour Science* 77, 267–283.

De Lange, C.F.M, Levesque, C.L. and Kerr, B.J. (2012) Amino acid nutrition and feed efficiency. In: Patience, J. (ed.) *Feed Efficiency in Swine*. Wageningen Academic Publishers, Wageningen, The Netherlands. pp. 81–100.

Emmans, G.C. (1981) A model of the growth and feed intake of *ad libitum* fed animals, particularly poultry. In: Hillyer, G.M., Wittemore, C.T. and Gunn, R.G. (eds) *Computers in Animal Production*. Animal Production Occasional Publication No. 5, London, pp. 103–110.

Ferguson, N.S. (2006). Basic concepts describing animal growth and feed intake. In: Gous, R.M., Fisher, C. and Morris, T. (eds) *Mechanistic Modelling in Pig and Poultry Production*. CAB International, Wallingford, UK, pp. 22–53.

Ferguson, N.S., Gous, R.M. and Emmans, G.C. (1994) Preferred components for the construction of a new simulation model of growth, feed intake and nutrient requirements of growing pigs. *South African Journal of Animal Science* 24, 10–17.

Ferguson, N.S., Gous, R.M. and Emmans, G.C. (1997) Predicting the effects of animal variation on growth and food intake in growing pigs using simulation modeling. *Animal Science* 64, 513–522.

Flori, L., Gao, Y., Laloe, D., Lemonnier, G., Leplat, J.-J., Teillaud, A., Cossalter, A.-M., Laffitte, J., Pinton, P., de Vauriex, C., Bouffaud, M., Mercat, M.-J., Lefevre, F., Oswald, I.P., Bidanel, J.-P. and Rogel-Gaillard, C. (2011) Immunity traits in pigs: substantial genetic variation and limited covariation. *PLoS ONE* 6, 1–11.

Giroux, S., Martineau, G.P. and Roberts, S. (2000) Relationships between individual behavioural traits and post-weaning growth in segregated early-weaned piglets. *Applied Animal Behaviour Science* 70, 41–48.

Gous, R.M. and Berhe, E.T. (2006) Modelling populations for purposes of optimization, In: Gous, R.M., Fisher, C. and Morris, T. (eds) *Mechanistic Modelling in Pig and Poultry Production*. CAB International, Wallingford, UK, pp. 76–96.

Green, D.M. and Whittemore, C.T. (2003) Architecture of a harmonized model of the growing pig for the determination of dietary net energy and protein requirements and of excretions into the environment (IMS Pig). *Animal Science* 77, 113–130.

Hauschild, L., Pomar, C. and Lovatto, P.A. (2010) Systematic comparison of the empirical and factorial methods used to estimate the nutrient requirements of growing pigs. *Animal* 4, 714–723.

Knap, P.W. (1995) Aspects of stochasticity: variation between animals. In: Moughan, P.J., Verstegen, M.W.A. and Visser-Reyneveld, M.I. (eds) *Modelling Growth in the Pig*. EAAP publication no. 78, Wageningen Agricultural University, Wageningen, The Netherlands, pp. 165–172.

Knap, P.W. (1999) Simulation of growth in pigs: evaluation of a model to relate thermoregulation to body protein and lipid content and deposition. *Animal Science* 68, 655–679.

Knap, P.W. (2000) Stochastic simulation of growth in pigs: relations between body composition and maintenance requirements as mediated through protein turnover and thermoregulation. *Animal Science* 71, 11–30.

Knap, P.W. and Bishop, S.C. (2000) Relationships between genetic change and infectious disease in domestic livestock. In: Hill, W.G., Bishop, S.G., McGuirk, B., McKay, J.C., Simm, G and Webb, A.J. (eds) *The Challenge of Genetic Change in Animal production*. British Society of Animal Production Occasional Publications No. 27, Edinburgh, UK, pp. 65–80.

Moughan, P.J. (1995) Modelling protein metabolism in the pig – critical evaluation of a simple reference model. In: Moughan, P.J., Verstegen, M.W.A. and Visser-Reyneveld, M.I. (eds) *Modelling Growth in the Pig*. EAAP publication no. 78, Wageningen Agricultural University, Wageningen, The Netherlands, pp. 103–112.

National Research Council (NRC) (2012) *Nutrient Requirements of Swine*, 11th edn. National Academy Press, Washington, DC.

Perron, M. (2011) Une journee de transfert technologique a la ferme: quoi de plus payant. *Coup d'oeil* Spring 2011, pp. 6.

Pomar, C., Harris, D.L. and Minvielle, F. (1991) Computer simulation of swine production systems. 1: Modeling the growth of young pigs. *Journal of Animal Science* 69, 1468–1488.

Pomar, C., Kyriazakis, I., Emmans, G.C. and Knap, P.W. (2003) Modeling stochasticity: dealing with populations rather than individual pigs. *Journal of Animal Science* 81(E Suppl. 2), E178–E186.

Technisch Model Varkensvoeding Werkgroep (TMV) (1994) Informatiemodel TMV. Report P1.117. Research Institute for Pig Husbandry, Rosmalen, The Netherlands.

Tindsley, W.H. and Lean, I.J. (1984) Effects of weight range at allocation on production and behavior in fattening pig groups. *Applied Animal Behavioural Science* 12, 79–92.

Turner, S.P., Dahlgren, M., Arey, D.S. and Edwards, S.A. (2002) Effect of social group size and initial liveweight on feeder space requirement of growing pigs fed *ad libitum*. *Animal Science* 75, 75–83.

Van Milgen, J., Valancogne, A., Dubois, S., Dourmand, J.Y., Seve, B. and Noblet, J. (2008) InraPorc: a model and decision support tool for the nutrition of growing pigs. *Animal Feed Science and Technology* 143, 387–405.

Wellock, I.J., Emmans, G.C. and Kyriazakis, I. (2003a) Modelling the effects of thermal environment and dietary composition on pig performance: model logic and concepts. *Animal Science* 77, 256–266.

Wellock, I.J., Emmans, G.C., and Kyriazakis, I. (2003b) Modelling the effects of thermal environment and dietary composition on pig performance: model testing and evaluation. *Animal Science* 77, 267–276.

Wellock, I.J., Emmans, G.C. and Kyriazakis, I. (2003c) Predicting the consequences of social stressors on pig food intake and performance. *Journal of Animal Science* 81, 2995–3007.

Wellock, I.J., Emmans, G.C. and Kyriazakis, I. (2004) Modeling the effects of stressors on the performance of populations of pigs. *Journal of Animal Science* 82, 2442–2450.

Whittemore, C.T. and Fawcett, R.H. (1976) Theoretical aspects of a flexible model to simulate protein and lipid growth in pigs. *Animal Production* 22, 87–96.

12 Estimating Real-time Individual Amino Acid Requirements in Growing-finishing Pigs: Towards a New Definition of Nutrient Requirements in Growing-finishing Pigs?

C. Pomar,[1]* J. Pomar,[2] J. Rivest,[1,3] L. Cloutier,[4]
M.-P. Letourneau-Montminy,[1] I. Andretta[1] and L. Hauschild[5]
[1]Agriculture and Agri-Food Canada, East Lennoxville, Quebec, Canada; [2]Universitat de Lleida, Lleida, Espagne; [3]Centre de Développement du Porc du Quebec inc., Sainte-Foy, Quebec, Canada; [4]Université Laval, Quebec, Canada; [5]Universidade Estadual Paulista, Jaboticabal, São Paulo, Brazil

Abstract

Energy, amino acids, minerals, vitamins and water are essential nutrients that must be provided to animals in adequate amounts to live (maintenance), grow and produce (reproduction, lactation, etc.). For a given growing animal and at a given time during its development, the daily nutrient requirements can be estimated as the sum of the requirements for maintenance and growth. These requirements are estimated for each nutrient or its precursor taking into account the efficiency with which each nutrient is used for each metabolic function. However, pigs are raised in groups and, within each group, animals significantly differ in body weight and growth potential and consequently nutrient requirements vary greatly among them. Phase-feeding is widely used in growing-finishing pig operations and, in this context of feeding populations, nutrition requirements are rather defined as the amount of nutrients needed for specified production purposes, which in farm animals consist of optimal production outputs (e.g. maximal growth rate, optimal feed conversion, etc.). Unfortunately, the optimal population responses are obtained with levels of nutrients that satisfy the requirements of the most demanding pigs, with the result that most of the pigs in the population receive more nutrients than they need to express their growth potential. Precision farming or precision agriculture is an agricultural management concept that relies on the existence of in-field variability. Precision feeding allows the feeding of individual pigs with daily tailored diets, the composition of which is determined in real time using the available information from the farm, which in the context of precision feeding is daily feed intake and body weight measurements. The real-time individual pig nutrient requirement estimated using each pig pattern of feed intake and growth represents a fundamental paradigm shift in pig nutrition because pig nutrient requirements are no longer a population attribute estimated from data collected in previous trials, but a dynamic process that evolves independently for each animal and is regulated by its own intrinsic (e.g. genetics, health, nutritional status, etc.) and extrinsic (e.g. environmental and social stressors, management, etc.) modulating factors. Precision feeding is being proposed to alleviate the limitations of group-feeding systems in which optimal dietary

---

*E-mail: candido.pomar@agr.gc.ca

Nutritional Modelling for Pigs and Poultry (eds N.K. Sakomura *et al.*)

nutrient levels are determined *a priori* and served to heterogeneous populations over specified periods of time. It is demonstrated that feeding pigs individually with diets tailored daily to their individual lysine requirements made it possible to obtain similar intake and growth results to conventional feeding systems. Precision feeding reduced lysine intake by more than 25% and feeding costs by more than 8%. Precision feeding is an effective approach to improve nutrient utilization efficiency, to reduce nutrient excretion and feed costs, and thus it is proposed to the swine industry as an essential tool to enhance sustainability and competitiveness.

Introduction

Precision livestock farming is an innovative and integrated production approach based on the utilization of advanced technologies and up-to-date scientific knowledge in animal sciences (Berckmans, 2004), with the objective of optimizing animal production and the management of the productive processes (Groot Koerkamp *et al.*, 2007) by controlling the variability that exists among farm animals (Wathes *et al.*, 2008; van Milgen *et al.*, 2012). A relevant contribution in this regard is the development of precision feeding systems (Niemi, 2006; Pomar *et al.*, 2009b; Pomar and Pomar, 2012). Precision feeding lays the groundwork for addressing key issues in today's intensive livestock farming, which are: (i) reducing feeding cost by improving feed and nutrient efficiencies; (ii) improving production system sustainability by increasing profitability and reducing environmental footprints; and (iii) increasing food safety through traceability.

In group-fed pigs, precision feeding requires defining feeding programmes that closely meet but without excess, the nutrient requirements of the group (Patience, 1996). Since in young pigs their appetite (i.e. in kilogrammes of feed per day) increases faster than their daily nutrient requirements (i.e. g/day), the optimal dietary concentration of nutrients (i.e. in g/kg of feed) progressively decreases during the growing period (NRC, 2012). Indeed, nutrient efficiency can be improved by the concomitant adjustment of the dietary concentration of nutrients to the estimated requirements of the herd (Bourdon *et al.*, 1995) using multi-phase feeding systems (Letourneau Montminy *et al.*, 2005). However, the requirements of the individuals within a herd show large variation (Pomar *et al.*, 2003; Brossard *et al.*, 2009) and, therefore, feeding pigs with daily tailored diets using individual precision feeding techniques may be an effective approach to improving feed and nutrient efficiencies, and reducing feeding costs and the excess of the most economically and environmentally detrimental nutrients (Pomar *et al.*, 2010). However, the proper implementation of precision feeding in livestock production systems is challenged by the reliability of the numerical methods estimating in real time the requirements for each individual nutrient, the devices collecting real-time information from the farm and the individual animals, and the feeder device that provides the right feed to each pig within the herd in the right amount at the right time. The objective of this chapter is to describe the key elements of precision feeding with special emphasis on the real-time estimation of nutrient requirements in growing-finishing pigs. Preliminary experimental results comparing individual precision feeding with conventional group feeding systems are also presented.

Precision Feeding

Feed cost is by far the greatest input cost in pork production and improving feed efficiency has a great impact on farm profitability. In growing-finishing pig operations, feeding programmes are proposed to optimize population responses at minimal feed costs. However, nutrient requirements vary greatly among the pigs of a given population (Pomar *et al.*, 2003; Brossard *et al.*, 2009; Quiniou *et al.*, 2013; Vautier *et al.*, 2013) and for each pig these requirements change over time following individual patterns (Pomar *et al.*, 2010). In order to optimize population responses, nutrients are provided on farms at levels that satisfy the requirements of the most demanding pigs and, therefore, most of the pigs receive more nutrients than they really need to express their growth potential (Hauschild *et al.*, 2010). This is because for most nutrients, underfed pigs will exhibit reduced growth performance, while the overfed ones will exhibit near optimal performance. Providing growing animals with excess nutrients to avoid reducing herd performance has become a common, if not a universal practice in commercial swine operations. The use of these safety margins has to be seen as an admission of our inability to precisely estimate the animal's nutritional requirements and the factors that may modulate them (Patience, 1996). Nonetheless, in the context of feeding populations of pigs, nutrient requirements should be seen as the balance between the proportion of pigs that are going to be overfed and underfed (Brossard *et al.*, 2009; Hauschild *et al.*, 2010), acknowledging that this proportion will change within each feeding period.

Precision farming or precision agriculture is an agricultural management concept that relies on the existence of in-field variability. Precision feeding is based on the fact that animals within a herd differ from each other in terms of age, weight and production potential and, therefore, each pig has different nutrient requirements. The precision feeding concept herein proposed is applied to individual animals and concerns the use of feeding techniques that provide each pig of the herd with a daily diet that contains the optimal concentration of nutrients. To provide these daily and individually tailored diets, precision feeding needs to include the following essential elements (Pomar *et al.*, 2009b):

- The precise evaluation of the nutritional content of feed ingredients.
- The real-time determination of individual nutrient requirements.
- The formulation of balanced diets limiting the amount of excess nutrients.
- The concomitant adjustment of the dietary supply of nutrients that will match the evaluated requirements of each individual within the herd.

New developments in the real-time determination of nutrient requirements along with some preliminary results comparing individual precision feeding with conventional group feeding systems are described in the following sections.

Estimating Nutrient Requirements in Growing Animals

Body growth results from the net synthesis of body components and depends on an adequate supply of energy and essential nutrients used by producing animals for body maintenance, growth, reproduction and lactation. Growing pigs must be provided with these essential feed resources in adequate amounts and in forms that are palatable and efficiently utilized for optimal growth (NRC, 1998). These nutrients are provided by feed ingredients the nutritive value of which is estimated based on their nutritive composition, digestibility, metabolic availability and fate, taking into consideration the addition of enzymes, feed physical treatments and other factors (Noblet and van Milgen, 2004; Stein *et al.*, 2007; NRC, 2012). The precise evaluation of the nutritional potential of feed ingredients is an essential element for livestock precision feeding.

For specific nutrients (e.g. essential amino acids), and when all other nutrients are provided at adequate levels, nutrient requirements can be defined as the amount of nutrients needed for specified production purposes, which in farm animals are production outputs such as growth rate, protein deposition, milk yield, etc. (Fuller, 2004). Depending on the production purpose and the nutrient, this required nutrient amount can be considered as the minimum amount that will prevent signs of deficiency and allow the animal to perform its necessary functions in a normal manner. Nutrient requirements are modulated by factors that are related to the animal (e.g. genetic potential, age, weight and sex), the feed (e.g. nutrient composition, digestibility and anti-nutritional factors) and the environment (e.g. temperature and space allowance) (Noblet and Quiniou, 1999), and they are estimated for a given animal at a given point in time as the sum of the requirements for maintenance and production. When applied to pig populations, however, the requirements for a nutrient should rather be defined as the amount needed for specified production purposes such as optimal growth rate, protein deposition, feed efficiency, etc. (Hauschild *et al.*, 2010). That is, the concept of nutrient requirements when applied to populations should be considered in the context of nutrients provided to heterogeneous populations over long periods of time (Ferguson *et al.*, 1997; Knap, 2000; Leclercq and Beaumont, 2000; Pomar *et al.*, 2003; Vautier *et al.*, 2013). An individual animal's response to dietary nutrient levels may differ in magnitude and pattern from the response of a population (Pomar *et al.*, 2003) and, as indicated before, population nutrient requirements should be seen as the desired balance between the proportion of pigs that are going to be overfed and underfed acknowledging that this proportion will change over time.

In practice, there are two methods used to estimate the nutrient requirements of domestic growing animals: the empirical and the factorial methods (Patience *et al.*, 1995). In the empirical method, nutrient requirements are estimated by feeding groups of pigs with increasing levels of the nutrient under evaluation and measuring one or several sets of performance parameters (e.g. growth rate) at given time intervals. In this empirical method, the nutrient level at which the optimal population response is observed within a given growing period is identified as the population requirement for this nutrient and for this growing interval. This population response may be biological, technical, economic and/or environmental in nature (Jean dit Bailleul *et al.*, 2000), but different response criteria may also suggest different nutrient requirement estimations (Baker, 1986). For example, Hauschild *et al.* (2010) found that by simulating the growth of a population of growing-finishing pigs optimal lysine (Lys) to net energy (NE) ratio (Lys/NE ratio) for average daily gain (ADG) was 9%, 6% and 3% higher than the optimal Lys/NE ratio for feed conversion ratio (FCR), respectively, in the three feeding phases simulated between 25 kg and 105 kg of live body weight (BW). In fact, feed intake and daily gain (DG) evolved differently in response to changes in Lys/NE, thus explaining why FCR and ADG do not necessarily reach the same Lys/NE optimal value. The results of Hauschild *et al.* (2010) indicate that the amount of Lys required for optimal FCR of a given population can be lower than the amount of Lys required for maximal ADG, in agreement with other studies (O'Connell *et al.*, 2005; Main *et al.*, 2008). Besides the diversity of the responses of the pigs raised in groups, the statistical model used to establish this population optimal response with the empirical method should be considered. The linear-plateau model is frequently the preferred model for representing the responses of animals to graded levels of limiting nutrients (Baker, 1986; Hauschild *et al.*, 2010). Although this model may provide adequate statistical fit, it tends to underestimate optimal nutrient requirement levels since it does not take into account the physiological differences that exist between the individuals in a population (Remmenga *et al.*, 1997). In this respect, the model may not be suitable because it does not consider the curvilinear nature of the response of a population to graded levels of a limiting nutrient (Pomar *et al.*, 2003; Wellock *et al.*, 2004). A curvilinear-plateau model has been recommended for describing the curvilinear nature of the responses of heterogeneous populations (Baker *et al.*, 2002; Pomar *et al.*, 2003; Simongiovanni *et al.*, 2011). In this type of model, the optimum nutrient level is attributed to the intersection between the curvilinear function and the plateau. From that point onward, increases in the ingestion of the limiting nutrient are assumed not to have any effect on population responses. Furthermore, maximal ADG or minimal FCR may not necessarily result in maximum economic return. This is due to the fact that population responses to increasing levels of limiting nutrients (i.e. Lys) progressively decline as the limiting nutrient approaches the plateau level. Because Lys- or protein-rich diets are more expensive than low-Lys or low-protein diets, marginal economic returns can be expected to decrease faster than Lys marginal efficiency

(Hauschild *et al.*, 2010). Determinations of nutrient requirements or optimal nutrient levels are therefore difficult to obtain, due to the curvilinear nature of population responses and to the progressive decrease in the marginal efficiency of the limiting nutrients observed in animals (Bikker *et al.*, 1994; O'Connell *et al.*, 2005) or in simulation studies (Pomar *et al.*, 2003; Wellock *et al.*, 2004; Brossard *et al.*, 2009; Hauschild *et al.*, 2010). Variability among the animals of a given population significantly contributes to the decrease in nutrient efficiency over varying nutrient levels (Curnow, 1973), independently of animal variation arising from genetic (Knap, 2000; Knap and Jorgensen, 2000; Pomar *et al.*, 2003), environmental or animal management sources (Wellock *et al.*, 2004). Furthermore, Pomar *et al.* (2003) demonstrated that increasing the time over which animal responses are measured increases the curvilinearity of the responses, which also contributes to the curvilinear nature of marginal nutrient efficiencies. Nonetheless, the empirical approach can be used to determine the optimal amounts of nutrients that need to be provided to populations to optimize production efficiencies from animal, economic or environmental perspectives. Any attempt to extrapolate these findings to other production situations calls for caution (Baker, 1986; Pomar *et al.*, 2003; Hauschild *et al.*, 2010).

In the factorial method, however, daily requirements are estimated as the sum of the requirements for maintenance and production (Fuller and Chamberlain, 1982). These requirements are estimated for each nutrient or its precursor and take into account the efficiency with which each nutrient is used for each metabolic function (van Milgen and Noblet, 2003). For a given growing period, requirements are assumed to be the amount of the given limiting nutrient that will allow the animal to perform its needed functions in a normal manner and, thus, without limiting growth. For example, as performed by Cloutier *et al.* (2013), maintenance Lys requirements can be estimated adding the basal endogenous losses (0.313 g Lys/kg DM × daily feed intake), losses related to desquamation in the digestive tract (0.0045 g Lys/kg$^{0.75}$ day × BW$^{0.75}$) and losses related to basal renewal of body proteins (0.0239 g Lys/kg$^{0.75}$ day × BW$^{0.75}$) (van Milgen *et al.*, 2008). The requirements of Lys for growth can be estimated assuming 16% protein in daily gain (de Lange *et al.*, 2003), 7% Lys in protein gain (Mahan and Shields, 1998) and 72% Lys retention efficiency (Mohn *et al.*, 2000). Lys requirements estimated with the factorial method as implemented in this example are driven by BW (Lys basal endogenous, desquamation, protein renewal losses), BW gain (Lys retention) and, to a lesser extent, by feed intake (basal endogenous losses). Because pigs within a population differ in terms of BW and growth potential, each pig has its own requirement and this requirement evolves over time according to each pig's own pattern of feed intake and growth. When the factorial method is used to estimate the nutrient requirements of a population of animals, it is common practice to use the average pig to represent the population. However, care has to be taken with this assumption since using the average pig to feed the population implies that half of the population will be overfed while the other half will be underfed (Brossard *et al.*, 2009; Hauschild *et al.*, 2010), thus leading to undesired population performance. Furthermore, unlike the empirical method, the factorial method estimates nutritional requirements using information from one individual at one specific point in time. Thus, changes that occur during the growing interval under study are not evaluated. However, when the objective is to maximize animal performance, maximum requirements normally appear at the beginning of each feeding phase (Brossard *et al.*, 2009). Variation between animals in estimated requirements for maintenance and growth and in metabolic nutrient efficiencies cannot easily be considered given the limited knowledge available in relation to the factors that can modulate these requirements and efficiencies.

Ultimately, both methods of estimating nutrient requirements are based on experimental results from trials studying the relationship between nutrient intakes and animal responses. In the empirical method, this relationship is used to estimate the optimal response to varying nutrient levels of a population of animals showing some degree of heterogeneity. In contrast, the factorial method estimates, for a unique animal at one specific growing state, the requirement for expressing the full growth potential. Thus, when the factorial method is used to estimate the requirements of a given population, the chosen individual should be the best representative of the population (Pomar *et al.*, 2003; Hauschild *et al.*, 2010). The empirical method estimates optimal nutrient allowances from a population perspective, whereas the factorial method addresses the needs of one reference animal during a very short period, normally 1 day. The relationship between the empirical and factorial methods is difficult to establish and is affected by many factors related to the animal, the growth state and population heterogeneity. For instance, Hauschild *et al.* (2010) found that maximum ADG was reached in 25–50 kg BW pigs with a Lys:NE ratio 12% higher than the requirement of the average pig estimated by the factorial method (Fig. 12.1). This estimation corresponded to an animal whose requirement for this nutrient was in the 82nd percentile of the population. For the FCR, however, the empirical estimates corresponded to those for a pig in the 58th percentile of the population (Fig. 12.2). These results cannot, however, be generalized, as the difference between the factorial method and the empirical method can be expected to increase with the level of heterogeneity of the population (Pomar *et al.*, 2003).

One of the problems in evaluating the empirical and the factorial requirements for optimizing population responses lies in the difficulty of integrating the main factors implicated in animal responses. Variation among animals, which is an important factor modulating population responses, is rarely taken into account. The importance of considering variability among animals in evaluations of biological responses and in nutritional programmes has been demonstrated in recent years (Pomar *et al.*, 2003; Main *et al.*, 2008; Brossard *et al.*, 2009; Vautier *et al.*, 2013). Between-animal variation shapes population responses and, therefore, the overall efficiency of nutrient utilization (Pomar *et al.*, 2003) and optimal nutrient levels (Leclercq and Beaumont, 2000; Pomar *et al.*, 2003; Brossard *et al.*, 2009).

Mechanistic mathematical models that implement the factorial approach are proposed in an attempt to represent the complexity of

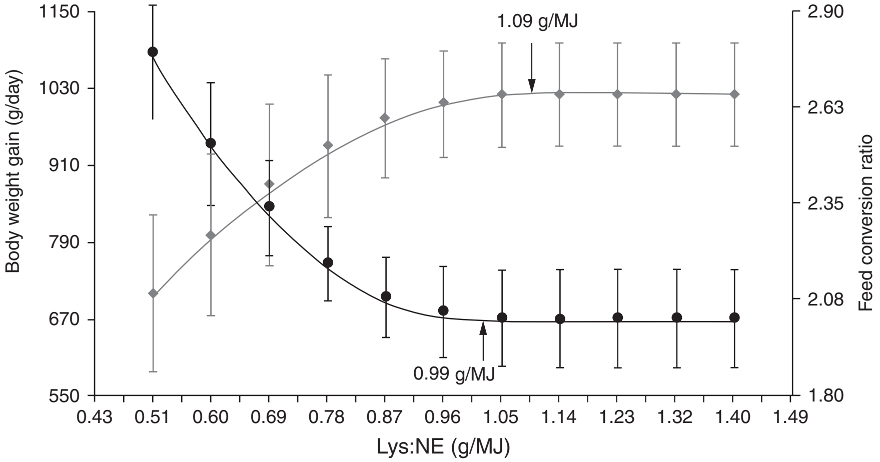


Fig. 12.1. The effect of different lysine:net energy (Lys:NE) ratios (g/MJ) on ADG and FCR and maximum response of pigs fed between 26 to 53 kg (◆ADG, • FCR), standard error of the mean and curve estimated by the quadratic equation (—ADG, —FCR). (From Hauschild *et al.*, 2010.)

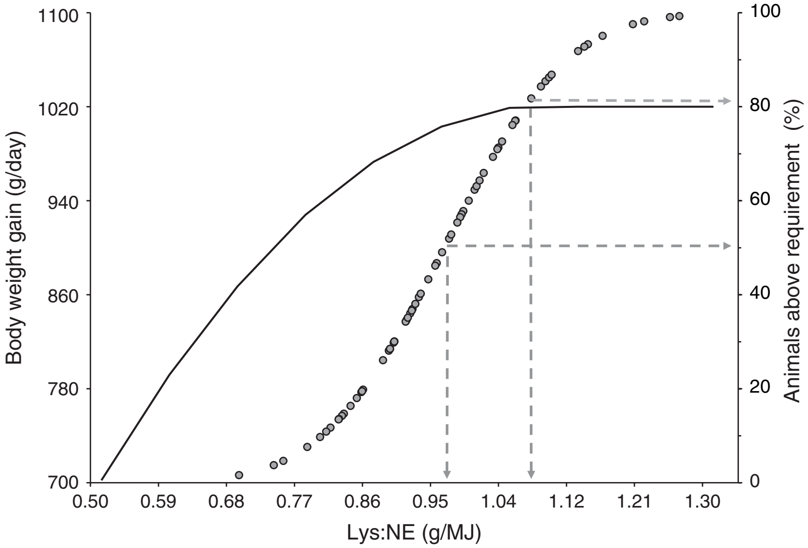


Fig. 12.2. Cumulative distribution of requirements estimated by the factorial method (○) and effect of different lysine:net energy (Lys:NE) ratios on weight gain estimated by the empirical method (—) for a live weight interval from 24 to 54 kg. (From Hauschild *et al.*, 2010.)

animal responses and the numerous factors modulating them. These models have been developed to simulate the growth of single pig (Whittemore and Fawcett, 1976; Black *et al.*, 1986; Moughan *et al.*, 1987; Pomar *et al.*, 1991; Birkett and de Lange, 2001; van Milgen *et al.*, 2008; NRC, 2012) or a group of pigs (Ferguson *et al.*, 1997; Knap, 1999; Pomar *et al.*, 2003; Wellock *et al.*, 2004; Ferguson, 2008; Brossard *et al.*, 2009; Vautier *et al.*, 2013). These models must, however, be properly calibrated *a priori*, using data collected from bygone reference populations to allow accurate estimates of the nutrient amounts that will optimize animal performance while minimizing nutrient excesses and excretion. In contrast with conventional systems, which give fixed tabulated 'values-needs', these models can take into account the interactions between the nutrients and the animal. They are, however, challenged by the difficulty in identifying the right reference population for calibration, the inadequacy of most of these models to represent population heterogeneity and the fact that animals from actual populations may follow different feed intake and growth patterns from the ones observed in the reference population. Therefore, model users have to be very careful to identify any differences that may exist between the reference and the target populations as well as any changes in the evolution of this target population during growth. Furthermore, these methods optimize population responses when pigs are fed with a unique feed during given periods.

Real-time Estimation of Individual Pig Nutrient Requirements

The procedure presented in this section has been described in detail elsewhere (Hauschild *et al.*, 2012) and was implemented in the form of a mathematical model estimating daily amino acid requirements and their optimal dietary concentrations for each individual growing-finishing animal in the herd according to its actual BW and actual growth and feed intake patterns. This model follows the 'grey box model' approach (Roush, 2006), which results from the combination of a 'black box' (empirical) and a 'knowledge-based' (mechanistic) component (Fig. 12.3).

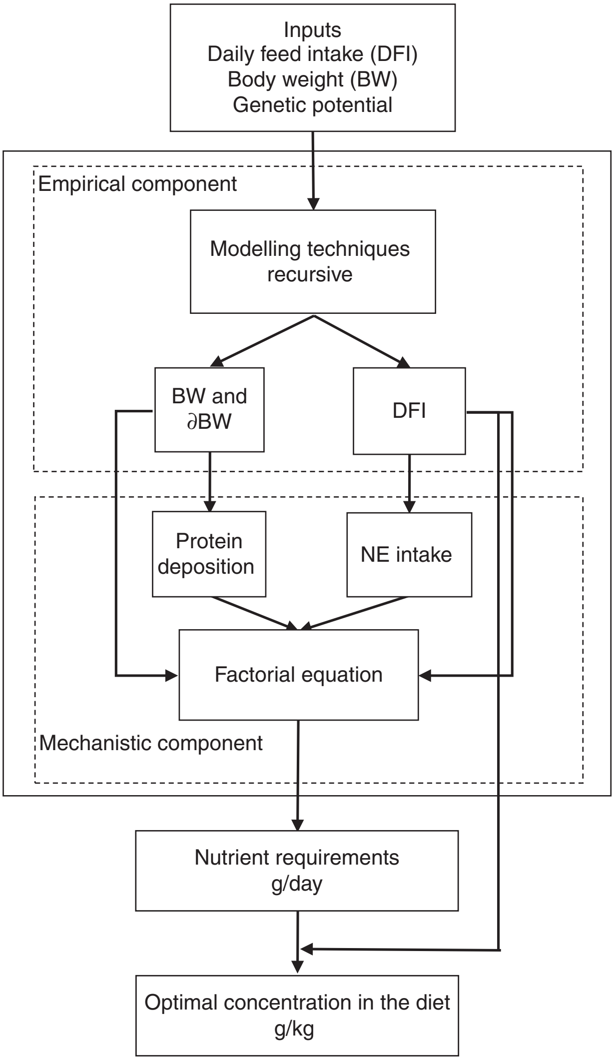


Fig. 12.3. General outline of the model with the empirical and mechanistic model components used to estimate daily nutrient requirements for each individual from one pig population according to their actual growth and feed intake patterns. (From Hauschild *et al.*, 2012.)

The empirical component of the model is used to estimate the starting day (*t* + 1) daily feed intake (DFI), BW and DG from the information measured in each individual animal up to the current day (*t*). The objective of this approach is to follow in real time the dynamic DFI and BW trajectories of each pig from the herd. Short-term variation over time and temporary drops in performance are not taken into account in this model. For this, forecasting methods using exponential smoothing techniques, which weigh recent and past observations in different ways, are appropriate because they reduce the fluctuations from irregular observations in the observed time series (Claycombe and Sullivan, 1977). The double exponential smoothing forecasting time series method was chosen in this model because DFI and BW of pig populations show evident long-run trends and because this method can work with limited number of observations. The double exponential forecasting equation, which produces an *i*-period-ahead forecast at time *t* was evaluated (Hauschild *et al.*, 2012) for pigs using individual DFI and WT data collected from nine performance tests (2406 pigs) at the CDPQ Experimental Station in Deschambault (Quebec, Canada) and more recently calibrated (Rivest *et al.*, 2012).

The mechanistic component of the model was used to estimate starting day nutrient requirements and optimal dietary amino acid concentrations for each pig in the herd based on starting day expected DFI (or NE intake), BW and DG information previously estimated by the empirical model component. Daily protein deposition (PD) is assumed to be a given proportion of DG (PD/DG); this proportion evolving over time according to a function calculated from trials that were held at Lennoxville's research farm (Rivest *et al.*, 2013, unpublished results). In this mechanistic model component, BW, DFI and DG are the driving variables used in a factorial procedure estimating the amino acid requirements (g/day) of each individual animal using the relationships described by Cloutier *et al.* (2013) and previously presented in this chapter. The optimal concentration of these amino acids (g/NE) that should be provided in its daily individually tailored diet is then calculated by dividing the sum of the maintenance and growth requirements by the expected NE intake. At this point in time, other nutrient requirements, including minerals or vitamins, are not yet explicitly estimated in the described model.

Thus, the empirical model component uses each pig's up-to-date data to estimate the starting day expected DFI, BW and DG values, while these forecasted values are then used by the mechanistic model component to estimate the standardized ileal digestible lysine (SID Lys) and other amino acid requirements, as well as the optimal concentration of these nutrients in the feed for the starting day. An initial evaluation of the model (Hauschild *et al.*, 2012) was completed with data from a study that investigated the effect of feeding pigs with a three-phase or daily-multiphase system. The mechanistic model component estimated the optimal SID Lys/NE ratio with reasonable between-animal (average coefficient of variation (CV) = 7%) and over-time (average CV = 14%) variation. Thus, the amino acid requirements estimated by the model are animal- and time-dependent and follow, in real time, the individual DFI and BW growth patterns. It was concluded that the proposed model can follow the DFI and BW trajectories of each individual pig in real time with good accuracy (Hauschild *et al.*, 2012). Based on these trajectories and using classical factorial equations, the model estimates dynamically the amino acid requirements of each individual animal. The factorial method was calibrated in two animal trials (Zhang *et al.*, 2011, 2012; Cloutier *et al.*, 2013) and the overall approach of estimating real-time amino acid requirements was challenged in two validation trials (Andretta *et al.*, 2014). This model has recently been updated (Rivest *et al.*, 2012; Rivest *et al.*, 2013, unpublished data) and will soon be evaluated in commercial conditions.

First calibration trial

The mechanistic component of the mathematical model estimating in real time the individual Lys requirement was calibrated with growing (from 25 to 55 kg of BW) and finishing (from 70 to 100 kg of BW) pigs. For this calibration trial, four experimental diets were mixed daily in different proportions to provide each pig with a diet containing 60, 70, 80, 90, 100 or 110% of the estimated Lys requirements while maintaining adequate levels of all other nutrients. The four diets were formulated on the basis of NE and apparent ileal digestible (AID) amino acids. The two sets of diets, A_1/A_2 and B_1/B_2, only differed in the level of added crystalline Lys and were all formulated to have a minimum of 10 MJ of NE per kilogramme of feed. Feed A_1 was formulated to satisfy the requirements of the most demanding pigs at the beginning of the first growing period and B_1 those of the less demanding pigs at the end of the last growing period (NRC, 1998). Feeds A_2 and B_2 contained, respectively, the same amounts of nutrients as A_1 and B_1

with the exception of the AID Lys, which was reduced in concentration by 60%. Dietary phosphorus (P) and calcium (Ca) requirements were estimated according to Jondreville and Dourmad (2005). Microbial phytase (500 FTU/kg, *Aspergilus Niger*, Natuphos) was added to all feeds in which the Ca:P ratio was maintained constant. Feeds were steam-pelleted at 4 mm. The four feeds were blended daily for each pig to constitute the experimental diets.

Sixty pigs were assigned to treatments at 25 kg of BW (group 25–55) and 60 others at 70 kg of BW (group 70–100). Pigs were housed in groups of 60, but fed individually using automatic and intelligent precision feeders (AIPF) specially developed for this project (Pomar *et al.*, 2009a, 2011) and able to provide to each pig at each visit the estimated mix of the four experimental diets. These AIPFs consisted of a single space feeder in which precision Archimedes' screw conveyors delivered and blended simultaneously volumetric amounts of up to four diets contained in independent feed containers. To this end, the AIPF identified each pig when their head was introduced into the feeder and the feeds were blended and delivered upon the animal's request according to the estimated optimal Lys concentration and assigned experimental treatment. A serving is composed of the amount of feed delivered upon each effective serving request. A time lag was imposed to ensure that pigs ate each serving before requesting a new one. Serving size was progressively increased during the experiment and ranged between 15 and 25 g. A meal includes all the servings delivered during each feeder visit. Pigs tend to leave the feeder hopper empty or leave very small amounts of feed after each visit, thus ensuring that each pig received the assigned amount of blended feed. Feed density was measured weekly and this information used to convert feed volumes to feed weights. Pigs had free access to the AIPFs and water throughout the experiment. Feeding phases lasted for 28 days for a total experimental length of 84 days. Pigs were weighed weekly in both trials and their body composition measured at the beginning of each feeding phase and at the end of the trials by dual X-ray densitometry (DXA, GE Lunar Prodigy Advance, GE Healthcare).

In the 25–55 kg of BW pig group, the level of Lys did not affect average DFI (ADFI), but in the 70–100 group, ADFI showed a quadratic response (Lin: $P = 0.04$, Quad: $P = 0.04$) with maximal values observed in pigs fed 10% below requirements. The ADG and average PD (APD) increased linearly ($P < 0.01$) with the level of dietary Lys. In the first group, however, ADG and APD increased linearly ($P < 0.01$) although maximal ADG (1.00 kg/day) and APD (174 g/day) were observed in animals fed according to their requirements (100%). Similar linear effects (Lin: $P < 0.01$) were observed for the second group with maximal ADG (1.19 kg/day) and APD (185 g/day) reached with diets providing 110% of estimated Lys requirements. The factorial method used in this study to estimate the dynamic Lys requirements of individual pigs seemed appropriate for pigs fed between 25 to 55 kg of BW, but it appeared to underestimate the requirements of heavier pigs. The detailed results of this trial have been described elsewhere (Zhang *et al.*, 2011, 2012).

Second calibration trial

The objective of the second trial was to validate the mechanistic component of the mathematical model estimating in real time the individual Lys requirements after adjustment based on the previous results. For this purpose, 75 castrated pigs corresponding to a terminal genetic line and 72 castrated pigs corresponding to a maternal genetic line were used for this study. This trial consisted of two 28-day experimental phases, one beginning at 25.8 ± 2.5 kg live weight and the other at 73.3 ± 5.2 kg live weight. The treatments were randomly assigned to the pigs according to a 2 × 4 factorial design with the two genetic lines and the four Lys levels (70%, 85%, 100% and 115% of requirements) as the factors. Feeds were prepared, the animals were cared for and measurements were taken as indicated for the previous trial. From 25 to 50 kg of BW, the amino acid estimation method slightly underestimated the pigs' Lys requirements, given that maximal APD and ADG were achieved at 115% of Lys requirements. In terms of feed efficiency, optimum performance seemed to be achieved at a lower Lys level. From 70 to 100 kg, the method adequately estimated the pigs' requirements, given that optimum performance was achieved at 100% of Lys requirements. The two genetic lines did not differ significantly in terms of ADG, APD, protein or fat lipid masses and, therefore, the ability of the proposed method of estimating requirements to automatically take into account the composition of the gain could not be evaluated. The detailed results of this trial have been published elsewhere (Cloutier *et al.*, 2013).

The Impact of Feeding Individual Pigs Using Precision Feeding Techniques

The impact of moving from a conventional three-phase feeding programme to the precision feeding system on animal performance, nutrient utilization and feed cost in growing-finishing operations was evaluated in two recent studies (Andretta *et al.*, 2014) completed at the Dairy and Swine Research and Development Centre of Agriculture and Agri-Food Canada at Sherbrooke, Quebec. For this purpose, five automatic feeders similar to those described in the previous experiments were used to feed the pigs during the two 84-day experimental periods herein described.

Two diets (named A and B) were formulated without additives. The diets differed from each other in the concentration of nutrients, diet A being a high nutrient concentration diet formulated to satisfy the requirements of the most demanding pig at the beginning of the growing period, and diet B being a low nutrient concentration diet formulated to satisfy the requirements of the least demanding pig at the end of the growing period. These two diets were formulated independently as complete feeds,[1] although significant feed cost reductions (>1.2%) can be obtained by formulating these feeds simultaneously, letting them be complementary rather than complete feeds, with the objective of minimizing the cost of the consumed feed (CAN$/pig) rather than the cost per kilogramme of the formulated feed ($/kg) (Joannopoulos, 2012; Joannopoulos *et al.*, 2013).

In the first trial evaluating the impact of feeding pigs individually with daily tailored diets (named AIPF I), 60 barrows with an average initial BW of 41.2 ± 3.9 kg were randomly assigned to the four following treatments:

- Tailored three-phase feeding programme (3P) providing within each phase a fixed blend of diets A and B calculated at the beginning of each feeding phase to satisfy the Lys requirement of the 80th percentile pig of this treatment group as suggested by Hauschild *et al.* (2010). The level of Lys given during the entire feeding phase was estimated during the first 3 days of each phase.
- Commercial three-phase feeding programme (COM) in which pigs were fed with complete diets provided by a commercial feed manufacturer.
- Daily-phase group feeding (MPG) in which all pigs of this treatment group received the same blend calculated at the beginning of each day to satisfy the Lys requirement of the 80th percentile pig of this group.
- Individually tailored daily-phase feeding (MPI) in which pigs were fed with a blend of diets A and B satisfying the Lys requirements as described for precision feeding systems earlier in this document.

In a second trial (named AIPF II), 70 pigs (35 females and 35 barrows) with an average initial BW of 30.4 ± 2.2 kg were assigned to five dietary treatments as follows:

- Three-phase feeding programme (3P) similar to the equivalent treatment of AIPF I trial; and
- Four individually tailored daily-phase feeding programmes in which pigs were served with blends of A and B diets providing 110% (MPI110), 100% (MPI100), 90% (MPI90) or 80% (MPI80) of the estimated Lys requirements. The MPI100 treatment of this AIPF II trial is then equivalent to the MPI treatment of the previous (AIPF I) trial.

All the pigs in each trial were kept in the same pen but fed individually as described in previous experiments. Feeding phases lasted for 28 days for a total experimental length of 84 days. Pigs were weighed weekly in both trials and their DXA body composition measured at the beginning of each feeding phase and at the end of the trials. Feed costs were calculated using recent feed ingredient prices of Quebec, Canada.

Feeding pigs individually with daily tailored diets (MPI) in the first validation trial (AIPF I, Table 12.1) did not affect ADG, FCR, APD or final BW in relation to the two other tailored treatment groups (3P and MPG). However, pigs fed with the COM diets consumed less feed ($P < 0.05$) and had lower FCR ($P < 0.05$) than the three other treatment groups, which may be related to the variation in nutrient and ingredient compositions of the diets. Interactions ($P < 0.05$) between period and treatment effects were found for ADFI, ADG and FCR. These interactions resulted from the performance differences observed between COM and the other experimental groups.

The sex by treatment interaction was not significant for any of the variables studied in the second validation trial (AIPF II, Table 12.2) and therefore, only the across-sex pooled values are presented in this chapter. In this trial, ADFI and FCR were not affected by treatments. Feeding pigs based on a daily basis programme considering 110% or 100% of the estimated individual nutrient requirements also did not influence ADG, APD and final BW in relation to animals in the 3P feeding programme. Pigs fed MPI90 showed intermediate results between MPI100 and MPI80. The model used to estimate individual Lys requirements seems to be properly calibrated since feeding pigs at 80% Lys requirements decreased ($P < 0.05$) ADG and APD in relation to MPI100 and 3P pigs.

Accounting for the variation among animals in nutritional requirements may be an important tool to control the heterogeneity of performance data. In the second validation trial, animals fed MPI100 diets showed a lower degree of dispersion compared to the 3P treatment in ADFI (CV of 14.5% in the MP100 group and 17.7% in the 3P group), ADG (7.1% and 9.1%), APD (6.0% and 8.4%) and final BW results (5.1% and 8.1%). Although the homogeneity within the populations is not frequently reported, this positive effect of precision feeding on animal homogeneity may be an important advantage in industrial scenarios.

In the first validation trial, average SID Lys concentrations in 3P diets were 1.05%, 0.73% and 0.64% during feeding phases 1 to 3, respectively (Fig. 12.4). The SID Lys concentration given during the first week of each feeding phase may slightly differ

Table 12.1. Performance of pigs fed according to a three-phase feeding programme (3P) obtained by blending fixed proportions of diets A and B, a commercial three-phase feeding programme (COM) or two daily-phase feeding programmes in which the blending proportions of diets A and B were estimated daily to match the lysine requirements of the group (MPG) or of each individual pig (MPI) (trial AIPF I)[1].

	Treatments					
	3P	COM	MPG	MPI	SEM	*P* value[2]
ADFI,[3] kg/day	3.05^{a}	2.73^{b}	3.07^{a}	3.05^{a}	0.043	0.0025
ADG, kg/day	1.11	1.07	1.11	1.10	0.011	0.5805
FCR, kg/kg	2.76^{a}	2.58^{b}	2.81^{a}	2.78^{a}	0.035	0.0095
APD, g/day	161	155	155	154	0.210	0.6492
Final BW, kg	134	131	135	136	1.170	0.2422

[1] Least square means obtained from a repeated measures analysis; ADFI: average daily feed intake; ADG: average daily gain; FCR: feed conversion ratio; APD: average daily protein deposition; BW: body weight.

[2] Effects of treatment, period and interaction were considered in the analysis. Period was significant ($P < 0.01$) for all variables. Interaction period × treatment was significant for ADFI ($P < 0.01$), ADG ($P < 0.01$) and FCR ($P < 0.05$).

[3] Means within lines followed by different letters are significantly different ($P < 0.05$).

^{a} and ^{b} indicate significant statistical differences among means within rows.

Table 12.2. Performance of pigs fed according to either a three-phase (3P) or a daily-phase feeding programme, the latter providing 110% (MPI110), 100% (MPI100), 90% (MPI90) or 80% (MPI80) of the estimated lysine requirements of individual pigs (trial AIPF II)[1].

	Treatments						
Item	3P	MPI110	MPI100	MPI90	MPI80	SEM	*P* value[2]
ADFI	2.44	2.43	2.53	2.57	2.33	0.035	0.5166
ADG,[3] kg/day	1.05^{a}	1.05^{a}	1.03^{a}	1.00^{ab}	0.93^{b}	0.013	0.0029
FCR, kg/kg	2.34	2.33	2.50	2.63	2.53	0.037	0.0501
APD, g/day	167^{a}	167^{a}	166^{a}	158^{ab}	148^{b}	0.304	0.0003
Final BW, kg	119^{a}	119^{a}	116^{ab}	115^{ab}	108^{b}	1.201	0.0184

[1] LS means obtained from a repeated measures analysis; ADFI: average daily feed intake; ADG: average daily gain; FCR: feed conversion ratio; APD: average daily protein deposition; BW: body weight.

[2] Effects of treatment, period, sex and interactions were considered in the analysis. Period was significant ($P < 0.01$) for all variables. Sex was significant for ADFI ($P < 0.01$), APD ($P < 0.05$) and BW ($P < 0.01$). Interaction period × treatment was significant for BW ($P < 0.01$). Interaction period × sex was significant for ADFI and BW ($P < 0.01$). Interactions treatment × sex and treatment × sex × period were not significant for all variables.

[3] Means within lines followed by different letters are significantly different ($P < 0.05$).

^{a} and ^{b} indicate significant statistical differences among means within rows.

from the rest of the phase because Lys concentration was estimated during the first 3 days of the feeding phase. Nonetheless, moving from 3P group-feeding to individual precision feeding (MPI) allowed the reduction of the average SID Lys concentration in diets by 31% in the first phase, by 29% in the second phase and by 20% in the third phase. Similar results were obtained in AIPF II (results not shown). The MPG pigs consumed on average 10% less crude protein ($P < 0.05$) and 17% less SID Lys ($P < 0.05$, Table 12.3) than the 3P pigs. Likewise, the use of the MPI feeding programme allowed the reduction of the intake of crude protein by 16% ($P < 0.05$) and SID Lys by 27% ($P < 0.05$) in relation to the 3P feeding programme. Overall, the amount of SID Lys consumed per unit of retained protein was reduced by 24% in MPI when compared to 3P pigs, which is in agreement with values estimated earlier by simulation (Pomar *et al.*, 2010).

Average nitrogen retention was not affected by feeding treatments applied in the first validation trial, indicating that in all cases pigs were fed to or near requirements. Similar results were obtained for treatments 3P, MPI110, MPI100 and MPI90 of the second validation trial (results not shown). However, in relation to 3P pigs, the estimated excretion of nitrogen was reduced ($P < 0.05$) by 12% in MPG and by 22% in MPI pigs. This reduction is lower than the 39% estimated by Pomar *et al.* (2010) because pigs were fed in these animal trials according to Lys requirements and the Lys/crude protein ratio was lower in diet B than in diet A.

In relation to the 3P conventional system, feeding pigs with daily individual tailored diets allowed the reduction of ($P < 0.05$) total feed cost by \$6.9/pig (–8%) in the first validation trial and by \$7.6/pig (–10%) in the second one. Likewise, in AIPF I, feed cost per kilogramme of BW gain was \$0.92, \$0.90 and \$0.85 in pigs fed according to 3P, MPG or MPI feeding programmes, respectively. Precision feeding allows the reduction of the excess of the most economically detrimental nutrients/ingredients. The estimated intake of soybean meal (results not shown), one of the most expensive ingredients in the current study, was reduced by 25% in the MPG group and by 43% in the MPI group in relation to 3P treatment. In addition, feeding pigs with just two premixes may also be a promising option for industries, because it means only two rations to be prepared, transported and stored. In this context, greater economic benefits could be expected if a global scenario (including other costs than just ingredients) were to be considered in the economic evaluation.

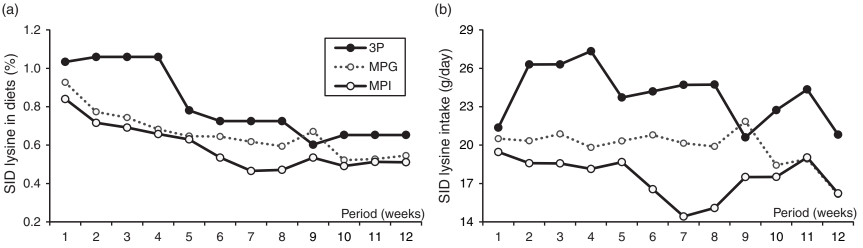


Fig. 12.4. Average weekly SID Lys concentration in diets (a) and average weekly SID Lys intake (b) in pigs fed according to three-phase (3P), group daily-phase (MPG) and individual daily-phase (MPI) feeding systems in trial AIPF I (see text for treatment details).

Table 12.3 Nutrient intake and nitrogen balance of pigs fed according to a three-phase feeding programme (3P) obtained by blending fixed proportions of diets A and B, a commercial three-phase feeding programme (COM), or two daily-phase feeding programmes in which the blending proportions of diets A and B were estimated daily to match the lysine requirements of the group (MPG) or of each individual pig (AIPF I)[1].

	Treatments					
Item	3P	COM	MPG	MPI	SEM	P values[2]
Crude protein intake, g/day	480^{a}	433^{b}	433^{b}	405^{b}	5.2023	<0.0001
SID Lys intake, g/day	23.8^{a}	23.9^{a}	19.7^{b}	17.4^{c}	0.4160	<0.0001
Protein intake/ADG,[3] g/kg	433^{a}	409^{b}	395^{b}	368^{c}	5.3600	<0.0001
SID Lys intake/ADG, g/kg	21.4^{b}	22.6^{a}	17.9^{c}	15.8^{d}	0.4349	<0.0001
Nitrogen retention, kg/pig	2.17	2.08	2.08	2.06	0.0147	0.6385
Nitrogen excretion, kg/pig	4.04^{a}	3.52^{b}	3.54^{b}	3.17^{b}	0.0729	0.0002

[1] LS means obtained from a repeated measures analysis.

[2] Effects of treatment, period and interaction were considered in the statistical analysis. Period was significant ($P < 0.01$) for all variables. The interaction period × treatment was significant ($P < 0.05$) for crude protein intake, SID Lys intake, protein intake/ADG and nitrogen excretion.

[3] Means within lines followed by different letters are significantly different ($P < 0.05$).

^{a,b} and ^{c} indicate significant statistical differences among means within rows.

Conclusions and Perspectives

Feeding growing pigs individually with daily tailored diets, whose formulation is based on each animal's real-time patterns of feed intake and growth, is a key element of the sustainable precision pig farming system approach proposed in this chapter and described elsewhere (Pomar and Pomar, 2012). To feed individual pigs with daily tailored diets, nutrient requirements have to be estimated in real time using the available information from the farm. In the context of farms equipped with precision feeding systems, as those used in the described experiments, such information will be daily feed intake and body weight. The real-time estimation of individual pig nutrient requirements based on each pig's patterns of feed intake and growth represents a fundamental paradigm shift in pig nutrition since nutrient requirements are no longer a population attribute estimated from past data as used in actual models (e.g. van Milgen *et al.*, 2008; NRC, 2012) but a dynamic process that evolves for each animal independently following its own feed intake and growth trajectories. These trajectories result from each animal's intrinsic (i.e. appetite, genetic growth potential, physiological state, etc.) and extrinsic (i.e. ambient temperature, humidity, space allowance, group size, space feeder allowance, etc.) driving forces. In the proposed feeding approach, these forces are not explicitly represented in the model for the real-time estimation of individual nutrient requirements as they are taken into account by the empirical model component. Body protein deposition as a proportion of ADG has, however, been recently included in the model (Rivest *et al.*, unpublished data) to increase model accuracy, and other factors such as health status may require further attention.

Precision livestock farming is proposed to the swine industry as an essential tool to enhance sustainability and competitiveness as described by Pomar and Pomar (2012). For this purpose, innovative feeding systems controlled by effective decision support systems are being developed to:

- *Feed pigs within a herd according to their daily individual nutrient requirements* to: (i) reduce feeding costs by reducing expensive (protein, phosphorus and others) excess nutrients in pig diets; (ii) reduce feed manufacturing, storage, management and shipping costs by using the same premixes for all farms; and (iii) reduce nitrogen, phosphorus and other polluting manure constituents and thus the amount of land required for manure application.
- *Manage feeds and animals by advanced computerized technologies* to: (i) allow real-time off-farm monitoring of feeds and animals for optimal slaughter and production strategies; (ii) reduce labour requirements and costs by automatic monitoring and management of feeds and animals; and (iii) allow early identification of disease and precise application of individual treatments, thus improving herd performance and reducing veterinarian costs.
- *Allow easy application of optimal production strategies in each farm* to: (i) automatically manage individual feed supply (e.g. *ad libitum* or restricted feeding) and composition (e.g. providing higher levels of phosphorus to future reproduction gilts, limiting or enhancing fatness to market pigs, etc.) to manipulate growth rate and composition of each pig to address specific production or target markets; (ii) facilitate the evaluation of new feeds and feed sub-products; and (iii) facilitate the determination of nutrient requirements.

Note

[1] Compound feeds or diets are said to be complete in this chapter when they are formulated to be served as unique feed and they provide the animals with all the daily required nutrients; complementary feeds or premixes need to be blended with other feeds or premixes to become complete feeds.

References

Andretta, I., Pomar, C., Rivest, J., Pomar, J., Lovatto, P.A. and Radunz-Neto, J. (2014) Effet de l'alimentation de précision sur les performances, l'excrétion de nutriments et le coût d'alimentation du porc charcutier. *Journées de la Recherche Porcine* 46, 107–112.

Baker, D.H. (1986) Problems and pitfalls in animal experiments designed to establish dietary requirements for essential nutrients. *Journal Nutrition* 116, 2339–2349.

Baker, D.H., Batal, A.B., Parr, T.M., Augspurger, N.R. and Parsons, C.M. (2002) Ideal ratio (relative to lysine) of tryptophan, threonine, isoleucine, and valine for chicks during the second and third weeks posthatch. *Poultry Science* 81, 485–494.

Berckmans, D. (2004) Automatic on-line monitoring of animals by precision livestock farming. *Conference on Animal Production in Europe: The Way Forward in a Changing World*, ISPAIA, Ploufragan, France, pp. 27–31.

Bikker, P., Verstegen, M.W., Campbell, R.G. and Kemp, B. (1994) Digestible lysine requirement of gilts with high genetic potential for lean gain, in relation to the level of energy intake. *Journal of Animal Science* 72, 1744–1753.

Birkett, S. and de Lange, C.F.M. (2001) A computational framework for a nutrient flow representation of energy utilization by growing monogastric animals. *British Journal of Nutrition* 86, 661–674.

Black, J.L., Campbell, R.G., Williams, I.H., James, K.J. and Davies, G.T. (1986) Simulation of energy and amino acid utilisation in the pig. *Research and Development in Agriculture* 3, 121–145.

Bourdon, D., Dourmad, J.Y. and Henry, Y. (1995) Réduction des rejets azotés chez les porcs en croissance par la mise en oeuvre de l'alimentation multiphase, associée a l'abaissement du taux azoté. *Journées de la Recherche Porcine* 27, 269–278.

Brossard, L., Dourmad, J.-Y., Rivest, J. and van Milgen, J. (2009) Modelling the variation in performance of a population of growing pig as affected by lysine supply and feeding strategy. *Animal* 3, 1114–1123.

Claycombe, W. and Sullivan, W. (1977) *Fundamentals of Forecasting*. Reston Publishing, Reston, Virginia, USA.

Cloutier, L., Letourneau Montminy, M.-P., Bernier, J.F., Pomar., J. and Pomar, C. (2013) Effet d'un protocole de déplétion-réplétion en lysine chez le porc en croissance. *Journées de la Recherche Porcine* 45, 149–154.

Curnow, R.N. (1973) A smooth population response curve based on an abrupt threshold and plateau model for individuals. *Biometrics* 29, 1–10.

de Lange, C.F.M., Morel, P.C.H. and Birkett, S.H. (2003) Modeling chemical and physical body composition of the growing pig. *Journal Animal Science* 81, E159–E165.

Ferguson, N.S. (2008) Application of an integrated management system to improve performance and profitability in finishing pigs. *Banff Pork Seminar 2008 Proceedings*, Banff, Alberta, Canada.

Ferguson, N.S., Gous, R.M. and Emmans, G.C. (1997) Predicting the effects of animal variation on growth and food intake in growing pigs using simulation modelling. *Animal Science* 64, 513–522.

Fuller, M.F. (2004) *The Encyclopedia of Farm Animal Production*. CAB International, Wallingford, UK.

Fuller, M.F. and Chamberlain, A.G. (1982) Protein requirements of pigs. In: Haresign, W. (ed.) *Recent Advances in Animal Nutrition*. Butterworths, London, pp. 175–186.

Groot Koerkamp, P.W.G., Bos, A.P. and van Henten, E. (2007) Precision livestock farming: creating order beyond control. In: Cox, S. (ed.) *Proceedings of the Third European Congress on Precision Livestock Farming*. Wageningen Academic Publishers, Wageningen, The Netherlands, pp. 17–26.

Hauschild, L., Pomar, C. and Lovatto, P.A. (2010) Systematic comparison of the empirical and factorial methods used to estimate the nutrient requirements of growing pigs. *Animal* 4, 714–723.

Hauschild, L., Lovatto, P.A., Pomar, J. and Pomar, C. (2012) Development of sustainable precision farming systems for swine: estimating real-time individual amino acid requirements in growing-finishing pigs. *Journal of Animal Science* 90, 2255–2263.

Jean dit Bailleul, P., Bernier, J.F., van Milgen, J., Sauvant, D. and Pomar, C. (2000) The utilization of prediction models to optimize farm animal production systems: the case of a growing pig model. In: McNamara, J.P., France, J. and Beever, D. (eds) *Modelling Nutrient Utilization in Farm Animals*. CAB International, Wallingford, UK, pp. 379–392.

Joannopoulos, E. (2012) Nouvelles approches de modélisation et d'optimisation de diète animale. MSc Thesis, Université de Sherbrooke, Sherbrooke, Québec, Canada.

Joannopoulos, E., Pomar, C., Dubeau, F. and Dussault, J.-P. (2013) Impacts économiques et environnementaux de différents programmes de formulation et d'alimentation chez le porc charcutier. *Journées de la Recherche Porcine* 45, 161–162.

Jondreville, C. and Dourmad, J.Y. (2005) Le phosphore dans la nutrition des porcs. *INRA Production Animal* 18, 183–192.

Knap, P.W. (1999) Simulation of growth in pigs: evaluation of a model to relate thermoregulation to body protein and lipid content and deposition. *Animal Science* 68, 655–679.

Knap, P.W. (2000) Stochastic simulation of growth in pigs: relations between body composition and maintenance requirements as mediated through protein turn-over and thermoregulation. *Animal Science* 71, 11–30.

Knap, P.W. and Jorgensen, H. (2000) Animal-intrinsic variation in the partitioning of body protein and lipid in growing pigs. *Animal Science* 70, 29–37.

Leclercq, B. and Beaumont, C. (2000) Etude par simulation de la réponse des troupeaux de volailles aux apports d'acides aminés et de protéines. *INRA Production Animal* 13, 47–59.

Letourneau Montminy, M.-P., Boucher, C., Pomar, C., Dubeau, F. and Dussault, J.-P. (2005) Impact de la méthode de formulation et du nombre de phases d'alimentation sur le coût d'alimentation et les rejets d'azote et de phosphore chez le porc charcutier. *Journées de la Recherche Porcine* 37, 25–32.

Mahan, D.C. and Shields, R.G. (1998) Essential and nonessential amino acid composition of pigs from birth to 145 kilograms of body weight, and comparison to other studies. *Journal of Animal Science* 76, 513–521.

Main, R.G., Dritz, S.S., Tokach, M.D., Goodband, R.D. and Nelssen, J.L. (2008) Determining an optimum lysine:calorie ratio for barrows and gilts in a commercial finishing facility. *Journal of Animal Science* 86, 2190–2207.

Mohn, S., Gillis, A.M., Moughan, P.J. and de Lange, C.F. (2000) Influence of dietary lysine and energy intakes on body protein deposition and lysine utilization in the growing pig. *Journal of Animal Science* 78, 1510–1519.

Moughan, P.J., Smith, W.C. and Pearson, G. (1987) Description and validation of a model simulating growth in the pig (20–90 kg liveweight). *New Zealand Journal of Agricultural Research* 30, 481–490.

Niemi, J.K. (2006) A dynamic programming model for optimising feeding and slaughter decisions regarding fattening pigs. *Agricultural and Food Science* 15, 6–121, Suppl. 121.

Noblet, J. and Quiniou, N. (1999) Principaux facteurs de variation du besoin en acides aminés du porc en croissance. *Techni-Porc* 22, 9–16.

Noblet, J. and van Milgen, J. (2004) Energy value of pig feeds: effect of pig body weight and energy evaluation system. *Journal of Animal Science* 82, E229–E238.

NRC (1998) *Nutrient Requirements of Swine*. 10th edn. National Academy Press, Washington, DC.

NRC (2012) *Nutrient Requirements of Swine*. 11th edn. National Academy Press, Washington, DC.

O'Connell, M.K., Lynch, P.B. and O'Doherty, J.V. (2005) Determination of the optimum dietary lysine concentration for growing pigs housed in pairs and in groups. *Animal Science* 81, 249–255.

Patience, J.F. (1996) Precision in swine feeding programs: an integrated approach. *Animal Feed Science and Technology* 59, 137–145.

Patience, J.F., Thacker, P.A. and de Lange, C.F.M. (1995) *Swine Nutrition Guide*. 2nd edn. University of Saskatchewan, Prairie Swine Center, Saskatoon, Saskatchewan, Canada.

Pomar, C. and Pomar, J. (2012) Sustainable precision livestock farming: a vision for the future of the Canadian swine industry. *Banff Pork Seminar 2012 Proceedings*, Banff, Alberta/Canada, pp. 207–213.

Pomar, C., Harris, D.L. and Minvielle, F. (1991) Computer-simulation model of swine production systems. 1. Modeling the growth of young pigs. *Journal of Animal Science* 69, 1468–1488.

Pomar, C., Kyriazakis, I., Emmans, G.C. and Knap, P.W. (2003) Modeling stochasticity: dealing with populations rather than individual pigs. *Journal of Animal Science* 81 (E. Suppl. 2), E178–E186.

Pomar, C., Hauschild, L., Zhang, G.H., Pomar, J. and Lovatto, P.A. (2009a) Applying precision feeding techniques in growing-finishing pig operations. *Revista Brasileira de Zootecnia* 38 226–237 (Suppl. special).

Pomar, C., Hauschild, L., Zhang, G.H., Pomar, J. and Lovatto, P.A. (2009b) Applying precision feeding techniques in growing-finishing pig operations. L'utilisation d'une alimentation de precision chez les porcs à l'engrais. *45th Eastern Nutrition Conference of Canada*, Animal Nutrition Association of Canada, Québec, 103–116.

Pomar, C., Hauschild, L., Zhang, G.H., Pomar, J. and Lovatto, P.A. (2010) Precision feeding can significantly reduce feeding cost and nutrient excretion in growing animals. In: Sauvant, D., van Milgen, J., Faverdin, P. and Friggens, N. (eds) *Modelling Nutrition Digestion and Utilization in Farm Animals*. Wageningen Academic Publishers, Wageningen, The Netherlands, pp. 327–334.

Pomar, J., López, V. and Pomar, C. (2011) Agent-based simulation framework for virtual prototyping of advanced livestock precision feeding systems. *Computers and Electronics in Agriculture* 78, 88–97.

Quiniou, N., Vautier, B., Salaün, Y., Van Milgen, J. and Brossard, L. (2013) Modélisation de l'effet des stratégie alimentaire et du contecte de prix des matières premières sur les performances moyennes, leur variabilité et les rejets azotés à l'échelle d'une population de porcs. *Journées de la Recherche Porcine* 45, 155–160.

Remmenga, M.D., Milliken, G.A., Kratzer, D., Schwenke, J.R. and Rolka, H.R. (1997) Estimating the maximum effective dose in a quantitative dose-response experiment. *Journal of Animal Science* 75, 2174–2183.

Rivest, J., Pomar, C., Pomar, J. and Hauschild, L. (2012) Estimating optimal smoothing parameters for the daily feed intake and weight forecasts required to implement sustainable precision farming systems for swine. *Canadian Journal of Animal Science* 91, 720 (Abstr.).

Roush, W.B. (2006) Mechanistic modelling in pig and poultry production. In: Fisher, C., Gous, R. and Morris, T. (eds) *Advancements in Empirical Models for Predictions and Prescription*. CAB International, Wallingford, UK, pp. 97–116

Simongiovanni, A., Corrent, E., Le Floc'h, N. and van Milgen, J. (2011) Estimation of the tryptophan requirement in piglets by meta-analysis. *Animal* FirstView, 1–9.

Stein, H.H., Seve, B., Fuller, M.F., Moughan, P.J. and de Lange, C.F.M. (2007) Invited review: amino acid bioavailability and digestibility in pig feed ingredients: terminology and application. *Journal of Animal Science* 85, 172–180.

van Milgen, J. and Noblet, J. (2003) Partitioning of energy intake to heat, protein, and fat in growing pigs. *Journal of Animal Science* 81 (E. Suppl. 2), E86–E93.

van Milgen, J. Valancogne, A., Dubois, S., Dourmad, J.-Y., Seve, B. and Noblet, J. (2008) InraPorc: a model and decision support tool for the nutrition of growing pigs. *Animal Feed Science Technology* 143, 387–405.

van Milgen, J. Noblet, J., Dourmad, J.-Y., Labussière, E., Garcia-Launay, F. and Brossard, L. (2012) Precision pork production: predicting the impact of nutritional strategies on carcass quality. *Meat Science* 92, 182–187.

Vautier, B., Quiniou, N., van Milgen, J. and Brossard, L. (2013) Accounting for variability among individual pigs in deterministic growth models. *Animal* 7, 1265–1273.

Wathes, C.M., Kristensen, H.H., Aerts, J.M. and Berckmans, D. (2008) Is precision livestock farming an engineer's daydream or nightmare, an animal's friend or foe, and a farmer's panacea or pitfall? *Computers and Electronics in Agriculture* 64, 2–10.

Wellock, I.J., Emmans, G.C. and Kyriazakis, I. (2004) Modeling the effects of stressors on the performance of populations of pigs. *Journal of Animal Science* 82, 2442–2450.

Whittemore, C.T. and Fawcett, R.H. (1976) Theoretical aspects of a flexible model to stimulate protein and lipid growth in pigs. *Animal Science* 22, 87–96.

Zhang, G. H., Pomar, C. and GongShe, Y. (2011) Estimation of lysine requirement for growing-finishing pigs using a precision feeding technique. *China Agriculture Science* 44, 3840–3849.

Zhang, G.H., Pomar, C., Pomar, J. and Del Castillo, J.R.E. (2012) L'alimentation de précision chez le porc charcutier: estimation des niveaux dynamiques de lysine digestible nécessaires à la maximisation du gain de poids *Journées de la Recherche Porcine* 44, 171–176.

13 A Model to Optimize Broiler Productivity

R.M. Gous*
University of KwaZulu-Natal, Pietermaritzburg, South Africa

Abstract

Optimizing the feeding of commercial broilers is made difficult because of the many interacting factors influencing their growth and food intake. Not all broilers are the same, nor are they housed in the same environments, and the costs of feeding and the revenue derived from the sale of the product differs markedly from one locality to another. When making decisions about how to maximize an economic index, such as margin/m^2/year or breast meat yield in a commercial broiler operation, all of these interacting factors should be considered simultaneously. This is now possible, using optimization techniques, but only where food intake can be accurately predicted.

The basis of such an optimization process is that specifications for feeds and feeding schedules are passed to a feed formulation program, which produces the least-cost feeds and passes these on to a broiler growth model that, in turn, evaluates the suggested feeding programme. By following certain rules the optimizer continues to alter the specifications of the feeds and/or feeding programme until no improvement can be made in the objective function. Without an accurate prediction of the amount of food that a given broiler will consume in the given environment, such an optimization process is bound to fail. The broiler growth model described here predicts food intake accurately under most circumstances that would be experienced in a commercial broiler operation, making it possible now to optimize the feeding programme of commercial broilers under a wide range of biological, environmental and economic circumstances, using many different objective functions.

In this chapter a method of predicting food intake, and hence the rate of growth of the body and its components in broilers is described, and the basis of the optimization process that determines the most profitable feeding programme for broilers is outlined. Some examples are given of the effect of changing ingredient prices, revenue and the objective function on the amino acid composition of the resultant optimum feeds and on the optimum feeding programme.

Introduction

Commercial broiler production is all about making decisions, and then implementing those decisions, the objective in most cases being to move towards an optimum such as maximizing profit for the enterprise. The process of decision making is one that everyone practises every day: identify the problem; evaluate alternative courses of action; choose the most appropriate on some or other basis; implement the decision; evaluate the

---

*E-mail: gous@ukzn.ac.za

Nutritional Modelling for Pigs and Poultry (eds N.K. Sakomura *et al.*)

consequences; and repeat the cycle. The concept of optimization is succinctly described by Ruby (2003):

> Producers exist to convert inputs into desired goods and services in an efficient manner. Given that output prices and factor prices are determined in competitive markets, efficiency means exploiting existing production technology to the greatest extent possible. Profits earned by the entrepreneur represent the reward for taking risks (facing an uncertain demand for the output) and achieving efficiency in production (relative to competing producers). A producer optimum represents a solution to a problem facing all business firms – maximizing the profits from the production and sales of goods and services subject to the constraint of market prices, technology and market size.

In order to achieve this goal effectively, we need to be able to predict the consequences of the alternative courses of action.

There is a common belief that experience and/or experiments are an accurate means of predicting these consequences, but this is not the case. It is necessary to have an accurate theory in order to make the right decisions. Experience is a relatively poor predictor of performance in broiler production, simply because the broiler genotypes with which we work change each year. In Table 13.1, the time that it has taken a broiler to reach 1.8 kg in live weight, and the amount of food that has been needed per kilogramme of gain, are given for each decade over the past five decades. There can be little doubt that experience of rearing broilers even 10 years ago is not the best way of knowing how to maximize profitability in the industry today.

Table 13.1. Changes over the past six decades in the length of time taken by broilers to reach 1.8 kg and the amount of food required per unit gain.

Period	Days to 1.8 kg	Food per unit gain g/g
1950	84	3.25
1960	70	2.50
1970	59	2.20
1980	51	2.10
1990	42	1.93
2000	36	1.55
2010	32	1.50

The performance characteristics given in Table 13.1 are easily measured, and clearly show the remarkable rate of improvement in broiler performance in the past 60 years. But genetic changes have also taken place as a result of selection by the primary breeding companies for improved food conversion efficiency, reduction in body lipid content and increase in breast meat yield. These selection criteria have changed the broiler in subtle ways that are difficult to measure, and the effects are almost impossible to separate from the general improvement in performance, yet they have a profound effect on the way in which the broiler should be fed to maximize performance and efficiency. Most broiler producers would largely be unaware that such changes have taken place, especially if they have continued to make use of technology that suited the performance of broilers one to three decades ago. More importantly, commercial breeders invariably aim for different selection targets, with the result that the response to nutrition or the environment may differ between genotypes, as the example by Kemp *et al.* (2005) illustrates in Fig. 13.1. When two strains of commercial broiler were subjected to changes in the ideal dietary protein content, one strain responded to a decrease in protein by consuming more feed, while the other strain did the opposite. Clearly the optimum feeds and feeding programme for the two strains would not be the same.

The results of past experiments with broiler chickens have been invaluable in providing information about their responses to nutrients and to the environment, but the major problem with the use of experiments in attempting to predict performance is that there are so many variables that influence this performance. Each time an experiment is conducted different conditions prevail in the research facility. Because we are interested in the interaction between the bird, the environment and the feed and feeding programme used, extremely complex experiments would be needed to test all combinations of these factors. And then, because of the changes that take place in the genotypes

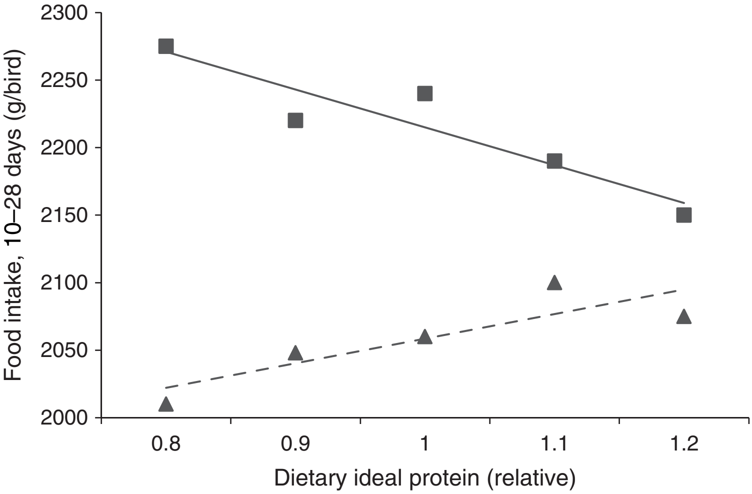


Fig. 13.1. Changes in food intake in response to dietary ideal protein content, relative to the Aviagen (2009) recommendations, for Ross 308 broilers in two commercial broiler strains. (From Kemp *et al.*, 2005.)

themselves, these experiments would have to be repeated at regular intervals in order to measure the changes in these interactions. This should not be an excuse to conduct yet more experiments: the purpose of experiments should be to measure the numbers that will make a theory work, to test a theory or to allow us to choose between two theories; that is, experiments should be conducted only once a theory or a hypothesis has been proposed.

When it comes to determining the optimum amino acid contents in feeds used by broilers, the general tendency of regarding these 'requirements' as being fixed makes it difficult to progress in this area. Fisher *et al.* (1973) showed that there was an advantage in seeing the requirements of animals as variable, dependent on the marginal cost of the amino acid and the marginal returns of the product. The major reason for the apparent reluctance to move from an outdated and inaccurate system to a more dynamic one is that there are so many factors that have to be integrated before the optimum economic feeding schedule can be determined. This is especially true of feeding programmes for growing animals. Factors to be considered include the potential protein growth rate of the genotype, differences between individuals at a time and within individuals over time, the effect of different nutrient concentrations and energy-to-protein ratios on food intake, carcass composition and protein gains, the effects of differences between genotypes in the amount of excess energy that may be stored as body lipid, and the maximum rate at which this can take place, and the constraints placed on birds by the environment and by the feed which prevent them from consuming the necessary amount of a feed to grow at their potential. The above factors deal with the interaction of the bird with its environment, but equally important when determining the optimum feeds and feeding programme for a flock of broilers is the manner in which the birds will be sold, whether at the farm gate, processed or further processed. This is perhaps the most neglected of all criteria influencing the profitability of a broiler enterprise, with far too much emphasis conventionally being placed on the feed conversion ratio and other non-economic criteria.

It is only through the development of a plausible theory, and the advent of computers, that it has become possible to integrate all these factors into a workable form. It is now possible to predict voluntary food intake, and this has opened up a wealth of opportunities that were not available previously to nutritionists, geneticists and producers wishing to make the broiler production enterprise more efficient and profitable. In fact, there is no defensible way of predicting the response of growing animals to nutrients, or of optimizing the feeding of broilers, other than by the use of simulation models that can accurately predict food intake.

'Nutrient Requirements' vs Optimization

Fisher (2008) reasoned that the predominant model used in poultry nutrition, the idea of a 'nutrient requirement', which is seen as a characteristic of the broiler and is the nutrient level required to support 'maximum' or 'optimum' production levels, is outdated and needs to be replaced with one in which nutritional decisions are made entirely in terms of the objectives of the business. With this approach, which applies systems thinking and modelling to the problem of feed formulation, nutrient levels are chosen that will maximize margin or perhaps combine with some other business objective. The 'needs' of the broiler in this case are not considered when making decisions about what nutrient levels to use. This approach builds on the principle espoused by the Reading Model (Fisher *et al*., 1973) in which the optimum economic intake of amino acids for laying hens becomes the basis on which their feeds are formulated. Feeding animals to achieve some commercial objective(s) rather than feeding them to meet a 'requirement' makes good business sense, but requires a paradigm shift in the attitude of nutritionists to feed formulation: the nutrition of the broilers must be integrated into the management of the business. This shift in thinking raises at least two interesting and important issues.

Because economic circumstances change from time to time, the nutritional strategy applied to maximize margins will also need to change. As Fisher (2008) points out, these strategies may or may not be compatible with the other objectives of the business (e.g. satisfying market demands) but at least management should know what options exist so that the best overall strategy can be selected. Also, and equally importantly, a choice must be made about which stage in the production process margin is to be assessed for nutritional decisions. For example, if nutrition is optimized for margin at the farm gate, with live bird weight (and perhaps downgrading) affecting revenue, then nutritional responses in growth, feed conversion ratio and mortality will need to be considered. If, however, margin is measured after the production of processed portions or meat, then nutritional responses in these characteristics, as well as those operating at the farm gate, will affect the outcome. These are real differences which lead to different nutritional decisions (Fisher, 2008). All decisions, therefore, whether these apply to the choice of the genotype to be used, the instantaneous environmental conditions that should be applied throughout the growing period (Timmons and Gates, 2003) or the nutrient composition of feeds to be offered, should be made as far as possible in terms of the objectives of the business.

Using the results of a balanced protein response trial, Fisher (2008) calculated the revenue derived from selling broilers at the farm gate, processed, or further processed, making use of the measured food intakes, growth rates and yield of parts of male and female broilers of two different strains fed a range of balanced dietary protein levels. He then compared the profit derived from these sales taking account of the cost of ingredients in the UK in 2006 and demonstrated that using a fixed (recommended) protein level under all circumstances resulted in considerable loss of potential profitability. The loss of margin when using a fixed level of protein as opposed to that which yielded the highest margin is shown for two revenue categories in Table 13.2. Broiler producers

Table 13.2. Loss of margin (£/100 birds) when using the recommended dietary balanced protein level rather than the level yielding the maximum potential margin. (From Fisher, 2008.)

	Loss of margin (£/100 birds) at sale of:	
Strain/sex	Live bird at farm	Processed bird
Ross 308 M	Nil	60.5
Ross 708 M	Nil	50.4
Ross 308 F	9.45	Nil
Ross 708 F	13.6	32.7

who stick rigidly to the ‘requirements’ irrespective of changes in ingredient prices or the way in which their broilers are marketed, forego considerable opportunities that are otherwise available to them.

Many indices are used to measure profitability on a farm and with which to compare farms, such as net farm income, rate of return on farm assets, operating profit margin ratio and asset turnover ratio (Olsen, 2004). Of particular importance in a broiler operation in which capital (fixed) costs are high is the number of livestock units that can be passed through the facility in a unit of time. So, whereas many objective functions could be used when deciding on the objectives of a business, for example, minimizing feed conversion ratio or fat content, maximizing breast meat yield or margin over feed cost, the factors to be considered should include both fixed and variable costs, the revenue generated, the length of time that the broiler houses are occupied, which includes the clean-out or down-time, and the number of livestock units occupying a unit of space. For this reason, maximizing margin/m^2/year would seem to be a sensible objective function in the case of growing broilers, and from a nutritional point of view this objective could be achieved with the use of an optimum feeding programme. Determining the optimum nutrient density, the optimum concentrations of amino acids relative to energy in each feed and the optimum length of time (or amount) that each feed should be fed is therefore both a nutritional and an economic decision.

The information required for optimization consists of feed costs at different levels of amino acid provision, a description of all the relevant animal responses, both fixed and variable costs affecting the production system and details of revenue. The complexity of the information required would depend on the level of organization at which the optimization is to be made. If profit of the broiler grower is to be maximized at the farm gate, then responses in liveability, growth and feed conversion ratio will probably suffice. However, and more realistically, a wider view will be required, and the effect of broiler nutrition on slaughterhouse variables (eviscerated yield, rejects, etc.) and further processing (carcass composition) will need to be defined. Mack *et al.* (2000) emphasized the importance of broiler companies considering all aspects of the production cycle when making nutritional decisions.

Feed costs for any nutritional specification are readily calculated by linear programming. This will take account of feed ingredient availability, analysis and costs. Processing and transport costs may be added. Broiler production costs are complex but will usually be specified by each company. So the only persistent problem in optimization lies in the definition of animal response, the accuracy of prediction hinging on the prediction of voluntary food intake, which leads to the prediction of the rates of growth of the body components and hence revenue. Only with the use of an accurate simulation model could such an optimization be contemplated.

An Overview of a Theory of Growth and Voluntary Food Intake

Describing the genotype

In order to predict food intake it is necessary to have some view on what a bird or an animal is attempting to achieve when faced with a given food. Emmans (1981) suggested that broilers attempt to grow as fast as possible, and in such a way as to start the reproductive process as early as possible and to produce as many chicks as possible. Based on this premise, it is necessary to know the potential growth rate of a broiler before a theory of food intake can be applied. But predicting the performance of animals is a general problem in animal production, the solution depending, in part, on being able to describe the animals adequately (Emmans and Fisher, 1986). In the past there has been neither consensus nor any general discussion in the literature on methods of defining genotypes that would allow similarities and differences between animals to be compared. However, with the advent of simulation models for describing the growth and food intake of animals, an adequate description of the genotype has become essential.

The approach suggested by Emmans (1989) to describe and evaluate different genotypes begins with a definition of potential protein growth using a Gompertz growth curve, and the live weight of the animal is built up from this, using the allometric relationships that exist between protein, water, ash and lipid; that is a bottom-up approach. He has shown that a few simple assumptions can lead to a description of an animal that is sufficient for predicting its performance in non-limiting conditions and for calculating what these conditions are. It seems sensible to be able to predict performance in non-limiting conditions before the more difficult question is tackled, namely, that of defining growth in limiting conditions.

Values for the genetic parameters that define an animal can be measured by rearing animals in environmental conditions that are as near to ideal as possible. Under these conditions, growth curves are obtained that represent the genetic potential for a particular genotype. The growth curves obtained in this way allow comparisons to be made between breeds and strains. Examples of such investigations are in Hancock *et al.* (1995) and Gous *et al.* (1999).

Predicting nutrient requirements

For a model of growth to be successful it must be able to calculate the nutritional and environmental requirements of the bird that are needed for potential growth, and it must be able to predict the consequences of deviations from these optimum conditions. A growing animal needs to be supplied with nutrients in order to meet the requirements for maintenance of the body and for the growth of all other components of the body, including feathers. The resources needed to meet these requirements can be determined from the growth rate and composition of the various components of the body. The resources available for supplying these requirements, which are present in various feedstuffs, need to be described in the same terms as are those used to describe the nutrient requirements. Hence, where the requirements for protein and fat growth are defined in terms of the digestible amino acid and effective energy contents (Emmans, 1994) of the tissues being formed, these same units must be used to define the nutrient content of the feed on offer.

Predicting voluntary food intake

The implication from the above is that an animal requires certain resources in order to maintain its current state and to grow according to its growth plan. Because the bird is motivated to grow at this potential rate, the acquisition of food as a means of obtaining the required resources becomes a priority. Appetite can be seen to be dependent on the nutrient requirement of the animal and the content of those nutrients in the food (Emmans and Fisher, 1986).

An animal would need to eat a given amount of a given food, termed the desired food intake by Emmans and Fisher (1986), if its potential growth rate is to be achieved. The actual food intake would be expected to deviate from the desired when the food is unbalanced in some way or if the animal were placed in an unfavourable environment where it is unable to lose the additional heat that would be produced if more food were consumed. Where a feed marginally deficient in an amino acid is fed, the bird will overconsume energy in an attempt to obtain sufficient of the limiting resource, and this energy will be deposited as lipid. It has been shown that broilers exhibit higher feed conversion efficiencies and lower lipid contents when higher concentrations of amino acids than are conventionally used in the broiler industry are included in the feed (Gous *et al.*, 1990).

A Novel Approach to Optimization

Given that food intake can be accurately predicted by the method described above, this enables the accurate prediction of growth and carcass composition of a given genotype in a given environment on a given feed and feeding programme, which leads on to the possibility of being able to optimize the way in which the birds should be fed to maximize or minimize a given objective function. An optimization tool developed by EFG Software (1995) combines three types of computer program, namely, a feed formulation program using linear programming, a broiler growth model and an optimization algorithm. The flow of information between these components approximates a hill-climbing algorithm, which is defined below.

Hill-climbing algorithms are commonly used in optimization. These start with a given solution and then proceed deterministically, by following the direction of the gradient, to the optimum solution. Such an algorithm is likely to fail where there are local optima, since it will stop at the first, and not necessarily the highest, peak. Heuristic methods (Feigenbauem and Feldman, 1963) offer a wide range of techniques to solve this problem. Many of the heuristic techniques have been inspired by evolutionary or biological processes, examples being genetic algorithms and differential evolution (Gilli and Winker, 2008). Allowing for an impairment of the objective function, maintaining a whole population of solutions at one time, the deliberate use of randomness for creating new candidate solutions and local searching are common principles used in heuristics. In spite of the enormous increase in computing power these techniques are still time consuming, and do not offer a solution as rapidly as would a least-cost feed formulation problem, for example. However, the advantage of using statistical and modelling techniques to optimize performance rather than relying on the results of a series of commercial trials compensates fully for the delay.

A robust but simplified method that works well is to explore the entire response surface using a grid that could initially be rough, and that is used simply to identify the area in which the highest peak resides; thereafter a hill-climbing algorithm is used to home in on the optimum point. Such a method is used in the EFG optimization procedure. The optimizer defines nutritional constraints for practical broiler feeds. These are passed to the feed formulation program where the least-cost feed that meets these constraints is determined. The characteristics of this formulated feed are then passed, as input, to the broiler growth model. The performance expected from this feed when given to a defined flock of broilers in a given environment is predicted by the model, and this predicted performance is then passed to the optimizer to complete the cycle. The next cycle starts with the optimizer modifying the feed specifications, moving, according to some in-built rules, to an optimum point. The objective function to be optimized can be defined in terms of any output from the broiler growth model, but realistically would be an economic index of some sort, such as margin over feed cost or margin per m^2/year.

The system is extremely versatile, allowing for a wide range of management practices, such as separate sex rearing, multiple harvesting from one flock and sales of any mixture of whole-bird, processed or further processed products from which the revenue is derived. Typical economic variables are included, although these are readily customized to fit with individual enterprises. The key to this approach lies in the ability of the broiler growth model to reflect accurately the performance expected under commercial conditions.

The simulation model, which predicts food intake and hence growth rate and carcass composition, is embedded in the Windows-based feed formulation program, WinFeed. Practical feed specifications are set up in the usual way and these provide the starting point for the optimization. A feeding programme is set up from these formulated feeds in which the amount, the form of the feed (mash, crumbles, pellets), the proportion of fines, and the cost of manufacture and transport are defined. The optimization process takes account of all the other settings in both the feed formulation program (feed prices, feed and nutrient constraints, etc.) and broiler model (genotype, environment, fixed and variable costs, sources and rates of revenue).

Optimizations Applied in EFG Broiler and Pig Growth Models

At present the program optimizes three aspects of a commercial broiler feeding programme: for a given feeding schedule it optimizes the amino acid contents and the nutrient density of each feed, and the optimum feeding schedule is determined, given feeds of a fixed composition. These options are described below.

Optimizing amino acid contents in each feed

The optimum relationships between the essential amino acids and energy change during the growing period, and the optimizer determines the relationship within each specified feeding period that maximizes (usually) or minimizes the objective function. The objective is to determine the optimum amino acid to energy ratio in each of the feeds in the feeding programme, such that the overall performance (or objective) is maximized. This differs from the technique previously described by Fisher and Wilson (1974) in which the feed for each given feeding period is optimized, because the performance on one feed impacts on the performance on subsequent feeds (Kyriazakis *et al.*, 1991; Eits *et al.*, 2003; Gous *et al.*, 2012). This is an essential prerequisite in optimizing the feeding of broilers, the optimum in each phase changing as the feeding programme changes.

To optimize amino acid contents the process works only with lysine. The contents of the other essential amino acids are controlled by reference to an (user-defined) 'ideal' protein ratio in each phase of the programme. An example of such ideal protein ratios is given in Ajinomoto-Eurolysine (2013). The dietary amino acid and energy contents may be optimized simultaneously, or the user may fix either of these while optimizing the other, thereby increasing flexibility.

Optimizing nutrient density

Given an optimum ratio between the essential amino acids and energy within each phase of the growing period, the program will optimize the nutrient density in each of these feeds in the feeding programme by maximizing the objective function over the entire growth period. As Fisher and Wilson (1974) have shown, the optimum nutrient density depends on such factors as sex, the ratio between input and output costs, and mixing and transport costs. These factors, and others, may be considered by the user in determining the optimum nutrient density of each of the feeds in the programme.

Optimizing the feeding schedule

Many broiler producers do not have the opportunity of having feeds mixed according to their specifications, but are constrained to make use of proprietary feeds. An almost infinite variety of options is open to such producers in designing their feeding schedule, which can be based on amounts fed in each period or on fixed feeding periods for each feed. The optimum feeding schedule is dependent on the composition of the feeds, their respective prices, the revenue to be derived from the sale of the broilers, and many other biological and economic considerations.

Response modifiers

A number of relationships between inputs to and outputs from the model cannot be simulated mechanistically. Pellet quality, for example, which influences the maintenance requirement for energy (Jensen *et al.*, 1962) may be modified by the content of fat in the feed; lysine digestibility may be modified by the crude fibre content (Giles *et al.*, 1984); and the number of downgrades due to hock burns, foot pad dermatitis, etc. may be related to dietary protein content (Nagaraj *et al.*, 2007). These response modifiers may be introduced empirically by the user, who must specify the relationship between the modifier (e.g. feed fat content) and the responder (e.g. feed fines). In this way, the model accounts for user-defined modifications when determining the optimum feeds.

Some Optimization Exercises

Because circumstances differ to such an extent from producer to producer and from country to country, examples relevant to one set of circumstances are unlikely to be of interest to others, so these examples of the optimization process should not be regarded as being universally applicable. However, some illustrations of the use of the program may be useful.

The first exercise has been mentioned above. Fisher (2008) demonstrated that the optimum balanced protein levels in the feed differed depending on the way in which the broilers were sold (Table 13.2). Using the same dataset but different feed ingredient prices (those applicable in 2006 and in 2008) he also demonstrated that these optimum protein levels differed when the cost of protein relative to energy changed, the optimum often being higher than the recommended level (Table 13.3).

The exercise by Fisher (2008) was based on actual performance, and the use of different ingredient costs and revenues for the various scenarios. Three additional exercises are discussed below that are based on simulated data using the EFG broiler growth model and optimizer (EFG Software, 1995), their purpose being to illustrate the effects of changes to different objective functions or variables on the optimum feed composition and feeding schedule. Birds were reared to a fixed weight of 2.3 kg or to 35 days and revenue was generated on a processed basis only. Feed ingredient availability and price were set at some arbitrary but currently realistic conditions. Broiler house turn-round (7 days), fixed production costs in Rand, R273/m^2 per annum) and variable costs (R9.20/bird per cycle) are illustrative. Mortality was set at 5% to 35 days. Base revenue was generated at R25/kg dressed weight.

Table 13.3. Level of balanced protein (%) relative to Aviagen recommendations yielding the maximum profit when birds were sold either at the farm gate or processed, using feed ingredient prices applicable in either 2006 or 2008. (From Fisher, 2008.)

	Farm gate prices		Processed prices	
Strain	2006	2008	2006	2008
Ross 708 M	100	115	130	130
Ross 708 F	90	115	115	115
Ross 308 M	100	115	115	130
Ross 308 F	90	115	100	115

Optimizing amino acid contents in each feed using different objective functions

In this exercise a three-stage feeding programme was used, using 800 g starter/bird, 1200 g grower and offering a finisher until the mean live weight of the mixed flock of broilers reached 2.3 kg. All feeds had an energy content of 13 MJ ME/kg. Four objective functions were chosen (scenarios A–D); namely, maximizing margin over feed cost (A), maximizing breast meat yield (B), minimizing feed conversion ratio (FCR) (C) and minimizing nitrogen (N) excretion (kg N/flock of 30,000 birds) (D). Table 13.4 shows a summary of the optimum digestible lysine contents in each of the three feeds offered, as well as the predicted value of each of the objectives at the optimum for each scenario.

The effect of choosing different objective functions is to change the protein (shown here as digestible lysine) contents in each of the feeds on offer, with the result that the profitability of the enterprise changes. The objective of any broiler enterprise should be to maximize profit, but in this example costs and revenue were included in only one of the objective functions (scenario A), hence margin over food cost was lower by comparison in the three other cases. In many operations the aim appears to be to minimize FCR, but when this is achieved (scenario C) the profit margin may be seriously eroded, as shown in Table 13.4. Clearly the differences in profitability depend on prevailing circumstances, being larger or smaller than indicated depending on the ratio between ingredient costs and returns. In some countries the cost of removing N waste may be so great that the lower performance and margin of broilers on scenario D, where N excretion is minimized, may be the most acceptable and beneficial for the enterprise.

Optimizing nutrient density

In this example, three broiler feeds were again offered using the same feeding programme as above, but with the ratios between the amino acids and apparent metabolizable energy (AME) fixed in these feeds. Nutrient density was optimized for males and females reared separately, using two revenues (base and base + 25%), and maximizing margin over feed cost. The results are in Table 13.5.

The optimum nutrient densities in the initial feeds were higher for females than for males, but the opposite was true in the final feeding period. The optimum therefore increased with each subsequent feed in the feeding schedule in the case of males, but decreased in the females. By increasing revenue the optimum nutrient density increased in the starter feed but this had no effect on FCR or breast meat yield.

The results from this optimization exercise are specific to the conditions described, including the ingredient prices and revenues, so they should simply be viewed for illustrative purposes and should not be used for commercial purposes.

Optimizing the feeding schedule

In this case three feeds were again offered, with fixed (13 MJ/kg) AME contents and with digestible lysine contents in the starter, grower and finisher being 13.7, 12.4 and 11.0 g/kg, respectively. The objective function was to maximize margin over feed cost for males and females separately at three revenues, R10, R20 and R30/kg. The results are in Table 13.6.

The optimum amounts of feed in each period for the two sexes differed, sensibly,

Table 13.4. Effect of using different objective functions on the optimum lysine levels in the three feeds offered and on the predicted value of each objective at the optimum for each scenario. The four objective functions chosen (scenarios A–D) were: maximizing margin over feed cost (A), maximizing breast meat yield (B), minimizing feed conversion ratio (FCR) (C) and minimizing N excretion (kg N/flock of 30,000 birds) (D).

Scenario		Dig. lysine (g/kg) at optimum			Margin over feed cost for each scenario			
		Starter	Grower	Finisher	A	B	C	D
A	Maximize margin over feed cost (c/bird)	14.3	10.3	9.8	**3131**	417	1.591	1672
B	Maximize breast meat	14.9	10.1	9.8	3127	**419**	1.593	1672
C	Minimize FCR	13.7	11.4	10.5	3086	413	**1.536**	1706
D	Minimize N excretion	14.6	10.1	7.6	2989	393	1.714	**1598**

Table 13.5. Optimum nutrient densities (expressed as MJ AME/kg feed), days to 2.3 kg, margin over food cost, feed conversion ratio (FCR) and breast meat yield at 2.3 kg live weight of male and female broilers at two revenues (base, and base + 25 %); the objective function maximized was margin over feed cost.

Sex	Revenue Rand/kg	AME (MJ/kg) at optimum ND			Days to 2.3 kg	Margin over food cost	FCR	Breast g
		starter	grower	finisher				
M	Base	11.39	11.58	11.60	34	3202	1.768	408
M	+25%	11.44	11.59	11.58	34	4302	1.768	408
F	Base	12.77	11.59	10.79	38	3200	1.827	424
F	+25%	12.82	11.55	10.73	38	4486	1.830	424

AME = apparent metabolizable energy.

Table 13.6. Optimum amounts of three feeds of fixed composition, for male and female broilers reared separately.

	Males			Females		
	R10/kg	R20/kg	R30/kg	R10/kg	R20/kg	R30/kg
Starter	945	945	421	632	632	632
Grower	1684	1580	474	2684	2684	2684
Finisher	1244	1329	3110	0	0	0

Revenue varied from R10 to R30/kg dressed weight (currency is South African Rand, R). The objective function maximized was margin over food cost.

reflecting the lower amino acid requirements of the females compared with the males. As the revenue per kilogramme increased, the optimum amount of starter and grower for females remained the same throughout, but for males these decreased, which is counterintuitive: most producers would be inclined to feed less expensive feeds when revenue decreases, thereby assuming that losses would be minimized. However, these results suggest that when revenue and hence margins are low, broilers should be given the opportunity to grow closer to their potential than when profits are high. This is corroborated by the evidence in Table 13.7 in which the EFG broiler optimizer was used to determine the optimum lysine contents in the three feeds for the three revenues used above, but for fixed amounts of starter (800 g), grower (1200 g) and finisher. This was for a mixed flock of broilers. The lysine content in the grower and finisher was considerably increased at the lowest revenue/kg, once again suggesting that under such unprofitable circumstances the best option is to grow the birds close to their potential thereby minimizing the loss in profitability.

The decision as to the optimum time to switch from one feed to the next is dependent on many variables, including the sex of the broiler and the relationship between ingredient costs and revenue obtained. Where a broiler producer purchases proprietary feeds from a feed mill and has no say in the composition of such feeds, it is possible to alter the feeding programme as circumstances change thereby maximizing profit at all times.

Table 13.7. Optimum lysine content (g/kg) in fixed amounts of starter (800 g), grower (1200 g) and finisher (remainder) to 35 days of age in a mixed flock of broilers at three revenues (R10, R20 and R30/kg dressed weight).

	Revenue (R/kg)		
	10	20	30
Starter	13.77	13.77	13.77
Grower	11.53	10.09	10.01
Finisher	10.33	10.00	9.97

Currency used is South African Rand, R.

Conclusions

Until the advent of an accurate predictor of food intake, and hence growth and carcass composition of broilers, it was virtually impossible for poultry nutritionists to move away from the comfort zone of using fixed amino acid requirements when designing feeds for commercial broilers. Once such a facility became available the logical step was to combine this with a feed formulation program and an optimization routine, which would enable the nutritionist to change the feed composition and feeding programme so as to maximize profitability for the enterprise. With account being taken of all inputs, the cost of production may be accurately calculated, and the revenue generated may also be accurately predicted given the diverse options available in the model for selling the product and the accurate assessment of what is to be sold. A wide range of objective functions is available, given that the aims of different broiler producers may not be the same: hence, maximizing weight at an age, breast meat yield at a weight or margin/m^2/year, or minimizing feed conversion ratio or N excretion are different objectives that are available to the producer.

Broiler managers and nutritionists now have at their disposal a tool for making informed decisions on the feeds and feeding programmes that will maximize profitability under most circumstances. Given the wide fluctuations in product value, ingredient prices and other input costs, such a nutrition tool would be an asset to any poultry nutritionist.

References

Ajinomoto-Eurolysine (2013) *Ideal Protein Content: Balance is Essential*. Available at: http://ajinomoto-eurolysine.com/ideal-protein.html (accessed 12 June 2014).

Aviagen (2009) *Ross 308 Broiler Nutrition Specifications*. Available at: http://en.aviagen.com/ross-308/ (accessed July 2012).

EFG Software (1995) Available at: www.efgsoftware.net (accessed April 2013).

Eits, R.M., Kwakkel, R.P., Verstegen, M.W.A. and Emmans, G.C. (2003) Responses of broiler chickens to dietary protein: effects of early life protein nutrition on later responses. *British Poultry Science* 44, 398–409.

Emmans, G.C. (1981) A model of the growth and feed intake of *ad libitum* fed animals, particularly poultry. In: Hillyer, G.M., Whittemore, C.T. and Gunn, R.G. (eds) *Computers in Animal Production*. Animal Production, Occasional Publication No. 5, London. pp. 103–110.

Emmans, G.C. (1989) The growth of turkeys. In: Nixey, C. and Grey, T.C. (eds) *Recent Advances in Turkey Science*. Butterworths, London, pp. 135–166.

Emmans, G.C. (1994) Effective energy: a concept of energy utilization applied across species. *British Journal of Nutrition* 71, 801–821.

Emmans, G.C. and Fisher, C. (1986) Problems in nutritional theory. In: Fisher, C. and Boorman, K.N (eds) *Nutrient Requirements of Poultry and Nutritional Research*. Butterworths, London, pp. 9–39.

Feigenbauem, A. and Feldman, J. (eds) (1963) *Computers and Thought*. McGraw Hill, New York.

Fisher, C. (2008) Improving nutrition through modelling. *27th Annual WPSA Scientific Day*, Pretoria, South Africa.

Fisher, C. and Wilson, B.J. (1974) Response to dietary energy concentration by growing chickens. In: Morris, T.R. and Freeman, B.M. (eds) *Energy Requirements of Poultry*. British Poultry Science Ltd, Edinburgh, 151–184.

Fisher, C., Morris, T.R. and Jennings, R.C. (1973) A model for the description and prediction of the response of laying hens to amino acid intake. *British Poultry Science* 14, 469–484.

Giles, L.R., Dettmann, E.B. and Batterham, E.S. (1984) Daily gain response to dietary lysine of growing pigs as influenced by sex, live weight and cereal. *Animal Production in Australia* 15, 361–364.

Gilli, M. and Winker, P. (2008) Heuristic optimisation in economics and econometrics. Available at: www.voxeu.org/article/heuristic-optimisation-economics-and-econometrics (accessed 12 June 2014).

Gous, R.M., Emmans, G.C., Broadbent, L.A. and Fisher, C. (1990) Nutritional effects on the growth and fatness of broilers. *British Poultry Science* 31, 495–505.

Gous, R.M., Moran, E.T. Jr, Stilborn, H.R., Bradford, G.D. and Emmans, G.C. (1999) Evaluation of the parameters needed to describe the overall growth, the chemical growth, and the growth of feathers and breast muscles of broilers. *Poultry Science* 78, 812–821.

Gous, R.M., Emmans, G.C. and Fisher, C. (2012) The performance of broilers on a feed depends on the feed protein content given previously. *South African Journal of Animal Science* 42, 63–73.

Jensen, L.S., Merrill, L.H., Reddy, C.V. and McGinnis, J. (1962) Observations on eating patterns and rate of food passage of birds fed pelleted and unpelleted diets. *Poultry Science* 41, 1414–1419.

Hancock, C.E., Bradford, G.D., Emmans, G.C. and Gous, R.M. (1995) The evaluation of the growth parameters of six breeds of commercial broiler chickens. *British Poultry Science* 36, 247–264.

Kemp, C., Fisher, C. and Kenny, M. (2005) Genotype – nutrition interactions in broilers; response to balanced protein in two commercial strains. *15th European Symposium on Poultry Nutrition*, 25–29 September, Balatonfüred, Hungary.

Kyriazakis, I., Stamataris, C., Emmans, G.C. and Whittemore, C.T. (1991) The effects of food protein content on the performance of pigs previously given foods with low or moderate protein contents. *Animal Production* 52, 165–173.

Mack, S., Hohler, D., and Pack, M. (2000) Evaluation of dose-response data and implications for commercial formulation of broiler diets. *Proceedings of the Australian Poultry Science Symposium*, 82–87.

Nagaraj, N., Wilson, C.A.P, Hess, J.B. and Bilgili, S.F. (2007) Effect of high-protein and all-vegetable diets on the incidence and severity of pododermatitis in broiler chickens. *Journal of Applied Poultry Research* 16, 304–312.

Olsen, K. (2004) *Farm Management: Principles and Strategies*. Wiley, Hoboken, New Jersey, USA.

Ruby, D.A. (2003) A producer optimum Available at: www.digitaleconomist.org/po_4010.html (accessed 12 June 2014).

Timmons, M.B. and Gates, R.S. (2003) Economic optimization of broiler production. *Transactions of the American Society of Agricultural and Biological Engineers* 29, 1373–1378.

14 AvinespModel: Predicting Poultry Growth, Energy and Amino Acid Requirements

L. Hauschild,* N.K. Sakomura and E.P. Silva
Universidade Estadual Paulista, Jaboticabal, São Paulo, Brazil

Abstract

In Brazil, modelling is still rarely used as there are no local models that can be applied as tools to optimize poultry or pig production. Aiming at filling this gap and stimulating interest in modelling in Brazil, the Nutrition and Modelling research group of Universidade Estadual Paulista (UNESP)-Jaboticabal developed the AvinespModel. The objective of this chapter is to present the theoretical background of the AvinespModel, to describe its structure, to demonstrate how it was evaluated, and to discuss its implications and future perspectives. The model estimates *ad libitum* feed intake, live weight, body composition and nutritional requirements of broilers and layer replacement pullets. It also estimates the response of an average chicken to a given feed and environment. Diet composition and chicken genotype are considered model inputs. Actual protein and lipid body mass are used as body state variables. The effective energy (EE) system, as proposed by Emmans (1994), is applied. Euler's integration method was applied to solve equations with one-day integration steps (*dt*). Rates are expressed on a daily basis, energy in megajoules and mass in grammes. In the model, feed intake and nutritional requirements of an animal are estimated as a function of its growth rate and body composition. The Gompertz (1825) equation is used in this model to describe protein deposition in the body and feathers based on biologically meaningful parameters. In order to estimate the desired lipid deposition, its ratio to protein deposition potential is established in the model. All the parameters required to describe specific genetic strains were obtained from studies conducted at the Poultry Science Laboratory of the Faculty of Agriculture and Veterinary Sciences (FCAV) at UNESP-Jaboticabal. The principle used to estimate feed intake in the model assumes that the bird attempts to eat sufficient to meet its growth potential (desired feed intake), considering its digestive capacity limitations and the environment. Estimates obtained with Avinesp for growth and responses to nutrient intake, health challenge and environmental temperature were consistent with the findings in the literature. Avinesp simulates the effects of different nutritional, feeding, health and environmental scenarios. Therefore, the proposed model, in addition to estimating nutritional requirements, may also be used as a tool to aid decision making by farmers and companies.

Introduction

The competitiveness of the global poultry industry generates a constant demand for technologies both to optimize production and improve sustainability. Nutrition strategies have been applied to enhance the efficiency of nutrient utilization, aiming at

---

*E-mail: lhauschild@fcav.unesp.br

© CAB International 2015. *Nutritional Modelling for Pigs and Poultry* (eds N.K. Sakomura *et al.*)

reducing costs, maximizing productivity and complying with environmental legislation. In this scenario, fitting feed nutrient supply to the nutritional requirements of animals may considerably improve feed efficiency.

Under practical conditions, nutritional requirements are estimated using an empirical or factorial method. The empirical method uses the requirements for maximizing or minimizing one or several performance parameters. In the factorial method, requirements are estimated as the sum of maintenance and production requirements. On the other hand, mathematical models are often based on the factorial method to estimate nutritional requirements. These are technological tools that allow not only growth and nutritional requirements to be estimated, but also for the different feeding scenarios applied in different production systems to be simulated. Consequently, production, environmental and social aspects may be taken into consideration when trying to establish nutritional and feeding strategies for poultry.

Broiler growth models based on these aspects have been developed in several countries, such as the EFG broiler growth model (EFG Software, 1995), the Pesti Brill Model (Pesti *et al.*, 1986) and OMINIPRO (Fancher, 1999). These models have been applied both in experimental and commercial settings. In Brazil, modelling is still rarely used as there are no local models that can be applied as tools to optimize poultry or pig production. Aiming at filling this gap and stimulating interest in modelling in Brazil, the Nutrition and Modelling research group of UNESP-Jaboticabal developed the Avinesp-Model. This model estimates growth and energy and amino acid requirements of meat-type and egg-type chickens, as well as simulating bird response under different nutritional, feeding and environmental settings.

The objective of this chapter is to present the theoretical background of the AvinespModel, to describe its structure, to demonstrate how it was evaluated and to discuss its implications and future perspectives.

Theoretical Assumptions of the Model

Feed intake is essential for animals as it allows the animal to perform its biological functions (Emmans, 1997). Under this concept, it is assumed that the animal will try to eat the amount of food it needs to fulfil its requirement for the first-limiting nutrient in the feed on offer (Emmans, 1997). In a thermal-neutral environment it is assumed that an immature animal needs energy only for maintenance, which includes some physical activity, as well as for protein and lipid retention. Knowing the energy and amino acid requirements of an animal for maintenance and protein and lipid deposition enables its nutrient requirement to be calculated.

Maintenance and protein and lipid deposition requirements of an animal not subjected to nutritional restriction may be expressed as a function of its protein weight (Emmans, 1997) as these components and animal growth potential are closely related (Gous *et al.*, 1999). Therefore, it seems reasonable to propose that feed intake and nutritional requirements of an animal can be estimated as a function of its growth rate and body composition.

Different genetic strains may present differences in mature body weight expressed in terms of protein, mature body composition (fat:protein ratio) and maturation rate of body chemical components (water, protein, fat and ashes). These variables determine feed intake as well as energy and amino acid requirements for the expression of the genetic potential of each genetic strain (Emmans, 1997, 1999).

The body changes from birth to mature age: first, bones, viscera, feathers and muscles are developed, and finally, the reproductive organs. The ratio among these components also changes as the animal ages. The mathematical description of these phenomena helps to predict these changes with age (Emmans, 1999). Therefore, the first step to estimate nutritional requirements is to describe a genotype's growth, which is usually estimated using the Gompertz function.

Model Description

The model proposed here is based on a theory that developed over time (Emmans, 1974, 1981, 1987, 1994, 1999). The general structure of the model follows the proposal of Ferguson *et al.* (1997), although here it is used for chickens, not for pigs (Fig. 14.1).

The model estimates *ad libitum* feed intake, live weight, body composition and nutritional requirements of broilers and layer replacement pullets. It also estimates the response of an average chicken to a given feed and environment. Diet composition and chicken genotype are considered model inputs. Actual protein and lipid body mass are used as body state variables. The effective energy (EE) system, as proposed by Emmans (1994), is applied. Euler's integration method was applied to solve equations with 1-day integration steps (*dt*). Rates are expressed on a daily basis, energy in megajoules and mass in grammes.

Body Protein Deposition Potential

The Gompertz (1825) equation is used in this model to describe protein deposition based on three biologically meaningful parameters: maturation rate (B), protein mass at a moment in time (Pt) and protein mass at maturity (Pm). The derivative of the Gompertz equation describes the potential protein growth rate (pPD), according to Ferguson *et al.* (1994). Equation parameters are obtained by fitting a non-linear model to growth data (Hancock *et al.*, 1995):

$$pPD = B \times Pt \times \ln(Pm/Pt) \text{ (g/day)}$$

This equation indicates that the growth rate of an animal depends on its current state. Potential protein deposition will only be achieved if sufficient energy and amino acids are supplied.

Body protein deposition potential will be achieved only if the chicken consumes adequate amounts of all essential nutrients;

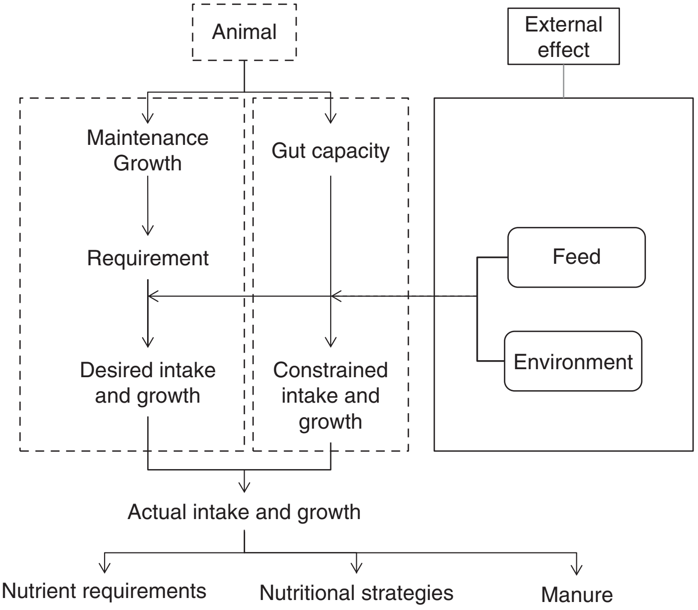


Fig. 14.1. General description of the AvinespModel to estimate growth and nutritional requirements.

otherwise, body protein deposition (*PD*) will be lower than *pPD*.

Feather Protein Deposition Potential

Feathers make up a large proportion of the chicken's body, and its amino acid requirements differ from those of the rest of the body. The potential for feather protein deposition (*pPDf*) is defined by genotype and can also be described by a Gompertz function:

$$pPDf = Bf \times Pft \times \ln(Pmf/Pft) \text{ (g/day)}$$

Where *Pft* is the feather protein content at a determined point in time (g), *Pmf* is feather protein content at maturity (g) and *Bf* is feather protein maturity rate.

Body Lipid Deposition Potential

Lipid deposition in poultry is influenced by dietary composition. Therefore, in order to estimate the desired lipid deposition, its ratio to protein deposition potential should be established (Emmans, 1981). This allows the desired lipid composition of a specific genotype to be estimated.

The best way of describing the desired lipid deposition or lipid body composition relative to body protein is based on lipid: protein ratio at maturity (*LPm*), and during growth, using an allometric coefficient of lipid content relative to protein (Emmans and Kyriazakis, 1999). The desired lipid composition (*dLt*) in the model at a determined point in time is estimated as:

$$dLt = LPm \times Pm \times (Pt/Pm)^{b1} \text{ (g/day)}$$

Where:

$$b1 = 1.46 \times LPm^{0.23}$$

Thus, desired daily lipid deposition (*dLD*) can be estimated as:

$$dLD = pPD \times LPm \times b1 \times (Pt/Pm)^{b1-1} \text{ (g/day)}$$

When *dLt* is estimated, compensatory gain may be identified, as lipid deposition is influenced by nutritional and environmental factors and current body status. The compensatory response will be determined by adding *dLD* to the difference between current lipid mass and *dLt*:

$$LD = dLD + (dLt - Lt) \text{ (g/day)}$$

The concept of maintaining a desired lipid composition will allow the bird to use its body reserves at any time to supply its energy requirements when the feed contains excesses of all essential nutrients other than energy.

Water and Ash Deposition

Under non-limiting conditions, the relationship between ash and water does not vary much between sexes or among genotypes (Gous *et al.*, 1999). Therefore, the deposition of ash (*AD*) and water (*WD*) is described in the model by an allometric ratio to protein.

$$AD = \text{Exp}(aA + bA \times \text{Log}(P) \text{ (g/day)}$$

$$WD = \text{Exp}(aW + bW \times \text{Log}(P) \text{ (g/day)}$$

All the parameters required to describe specific genetic strains were obtained from studies conducted at the Poultry Science Laboratory of FCAV at UNESP-Jaboticabal and are presented in Table 14.1.

Estimate of Current Status

Empty body weight gain (*EBWG*, that is, carcass with feathers and no gut fill) on a given day is calculated as the sum of five components.

$$EBWG = PD + LD + WD + AD + PDf \text{ (g/day)}$$

This gain is added to empty body weight on the previous day to determine current body weight.

EBWG is divided by the values that represent the ratio of the gastrointestinal tract (*GIT*) to whole body weight (5%, according to Lopez *et al.*, 2007) in order to estimate average daily gain (*ADG*).

$$EBWG = ADG \times 1/GIT \text{ (g/day)}$$

Table 14.1. Growth parameters in UNESP studies.

	Cobb		Ross		Hy-Line Brown	Hy-Line White	Hisex Brown	Hisex White
	Male	Female	Male	Female				
B	0.047	0.050	0.037	0.044	0.025	0.028	0.026	0.026
Pm	1042	666	1309	866	364	284	329	248
LRPm	0.80	1.17	1.00	1.00	1.00	0.80	1.10	1.00
Bf	0.040	0.042	0.035	0.036	0.027	0.028	0.029	0.030
Pmf	303	233	483	395	155	144	143	124
a (water/protein)	1.74	1.74	1.74	1.74	1.82	1.82	1.82	1.82
b (water/protein)	0.92	0.92	0.92	0.92	0.82	0.82	0.82	0.82

Therefore, live weight (BWt) at any age is estimated by the equation:

$$BWt = BW_{(t-1)} + ADG \text{ (g/day)}$$

Similarly to BWt, each body component is determined as the sum of the current status (protein (Pt), lipid (Lt), water (Wt), ash (At) and feather protein (FPt)) with their respective depositions.

Estimating Voluntary Feed Intake

The principle used to estimate feed intake in the model assumes that the bird attempts to eat sufficient to meet its growth potential, considering its digestive capacity limitations and the environment. This concept was first proposed by Emmans (1981).

Desired Feed Intake

This concept assumes that the bird attempts to ingest the amount of feed that will meet its energy and amino acid requirements. Therefore, the desired feed intake is the amount of feed required to supply the requirement of the most limiting nutrient, be it energy or amino acids.

Energy as the most limiting component

In order to determine energy requirements for maintenance (M) and growth (PD and LD) the EE requirement (EER) for chickens (Emmans, 1994) is calculated as:

$$EER = M + 50 \times DP + 56 \times DL \text{ (KJ/day)}$$

EE requirement for maintenance

Maintenance heat production can be estimated as a function of current protein mass and protein content at maturity (Emmans and Fisher, 1986). Based on this proposal and considering the daily maintenance energy requirement estimated by Emmans and Fisher (1986) of 1.63 MJ per maintenance unit, the following equation is used:

$$M = (1.63 \times Pt \times Pm^{-0.27})/1000 \text{ (kJ/day)}$$

The maintenance coefficient may present different values for different genotypes. This assumption has been confirmed for pigs by van Milgen and Noblet (1999), but it has not been tested in poultry. A meta-analysis was performed by the Group of Study and Research in Modelling and Nutrition in Monogastric (Gnutrim) – FCAV, UNESP-Jaboticabal, to test this hypothesis (Sakomura *et al.*, 2011). In that meta-analysis, a database was built using data from four PhD theses and contains information on 1024 chickens of two types (broilers and layers) and six genetic strains. Information on EE intake, live weight and body composition (protein and fat) was collected during the experiments every 7 days.

In place of 1.63 in the above equation this maintenance coefficient was estimated from the data collected. In order to evaluate the effect of chicken strain (broiler and layer) on EE requirements for maintenance the EE for maintenance was first calculated ($EEmaintenance = EEintake - 50 \times DP - 56 \times DL$) and these were then regressed against the unit of maintenance ($Pm^{-0.27} \times Pt$) for the two chicken strains. Regressions were significant ($P < 0.05$) for EE (Fig. 14.2). However, EE requirements for maintenance were not different ($P > 0.05$) between chicken types, resulting in a single equation, applicable both to broilers and layers. The estimated EE requirement for maintenance (1.67 MJ/$Pm^{-0.27} \times Pt$) is similar to that proposed by Emmans (1994).

EE requirement for growth

In the case of poultry, body and feather protein deposition is combined to produce *DP*.

In a feed, effective energy content (*EEC*) of the feed is calculated as:

$$EEC = ME_n - 3.8 \times FOM - 4.67 \times dCP + 12z \times dCL \text{ (kJ/day)}$$

Where ME_n = metabolizable energy for nitrogen retention ($ME_n = ME - 8.22 \times dCP$); *FOM* = non-digested feed organic matter; *dCP* = feed digestible protein content (g/kg); *z* = proportion of dietary fat retained as body fat (poultry, $z = 0.3$); and *dCL* = feed digestible lipid content (g/kg).

The desired feed intake that will supply energy requirements in a thermoneutral environment (dFI_e) is estimated as:

$$dFI_e = EER/EEC \text{ (g/day)}$$

Amino acid as the most limiting component

When an amino acid is limiting in a feed the *dFI* will be based on the requirement for that amino acid and its concentration in the feed.

Amino acid requirements are based on the sum of the requirement for maintenance and for protein deposition, divided by their respective utilization efficiencies. Most studies relate daily amino acid requirements for maintenance with fasted body weight (mg/kg) or with metabolic weight (mg/kg$^{0.75}$). In this context, it is difficult to compare maintenance among genotypes with different mature sizes, among birds of a same genotype at different maturity stages or even among birds with the same body weight and different body fat content (Emmans and Oldham, 1988; Burham and Gous, 1992; Gous, 2007).

In order to consider these aspects the model adopts the proposal of Emmans and Fisher (1986). A general equation is applied to determine body protein maintenance requirements:

$$MP = 0.008 \times (Pt \times Pm^{-0.27}) \text{ (mg/day)}$$

Where *MP* is maintenance protein requirement (g/day); 0.008 is a constant (kilogrammes of ideal protein/maintenance unit; $Pm^{0.73} \times u$), defined on the assumption that poultry require 8 g of protein with adequate

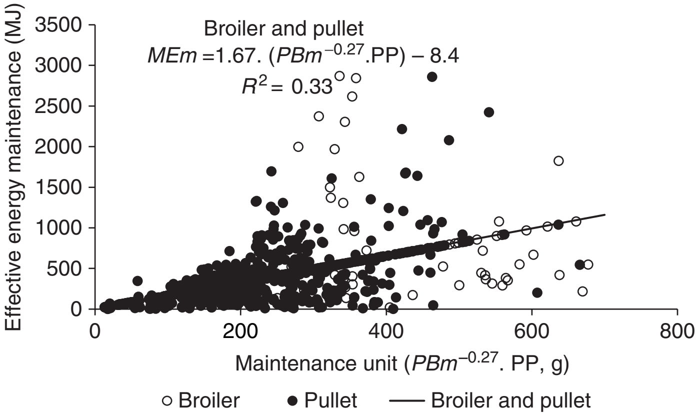


Fig. 14.2. Regression of energy for maintenance as a function of unit for maintenance (*EEmaintenance* = $PBm^{-0.27} \times PP$) for broiler and layer strains.

composition (ideal protein) to supply its maintenance requirements, and *Pm* is protein weight at maturity (kg).

In this equation, maintenance requirements are related to body protein content, which is more appropriate to express requirements, because lipid content may be different even among birds with similar body weights.

In order to determine maintenance requirements for each amino acid using this approach, the equation considers body protein amino acid profile (*AAb*), as shown in Table 14.2.

$$AAm = [(Pm^{-0.27}) + (0.08 \times Pt \times AAb)] \text{ (mg/day)}$$

Where *AAm* is the requirement of a specific amino acid (AA) for maintenance.

Another important aspect of the model is that maintenance and body growth components were divided into specific ratios to feather-free body and to feathers, because feather growth characteristics are different from the rest of the body and are influenced by genotype, sex and age, among other factors (Emmans and Fisher, 1986). Protein requirements for feather maintenance are considered to be proportional to feather losses (Martin *et al.*, 1994). According to Emmans (1989) these losses are equivalent to 0.01g/g of feathers daily. Thus, amino acid requirements for feather maintenance (*AAmf*) were calculated as:

$$AAmf = 0.01 \times FPt \times AAf \text{ (mg/day)}$$

Where *AAf* is amino acid content of feather protein (Table 14.2).

Table 14.2. Amino acid composition of the body and feather for chickens.[a] (From Stilborn *et al.*, 1997, 2010.)

Amino acid	Body	Feather
Arginine	6.51	6.65
Cystine	1.00	7.46
Histidine	2.41	0.71
Isoleucine	3.94	4.60
Leucine	7.19	7.87
Lysine	6.87	1.97
Methionine	2.16	0.69
Phenylalanine	3.79	4.66
Tyrosine	2.74	2.59
Threonine	4.07	4.80
Tryptophan	0.69	0.74
Valine	4.67	6.14
Alanine	6.26	4.09
Glycine	7.86	7.04

[a] Means for male and female.

In order to determine amino acid requirements for growth the factorial equation takes into account the amino acid profiles of both body and feather protein and an efficiency of amino acid utilization for body and feather protein deposition of 0.8. Considering all the above-mentioned aspects, a general equation was built to estimate amino acid requirements:

$$AA = AAm + AAmf + (AAb \times PD/k) + (AAf \times PDf/k) \text{ (mg/day)}$$

Where *AA* is digestible amino acid requirement and *k* is the efficiency of the utilization of that amino acid for feather-free body deposition and feather deposition. The model estimates the requirements for the following amino acids: lysine, methionine, methionine + cystine, threonine, tryptophan, isoleucine, leucine, valine, phenylalanine, histidine and arginine.

In order to determine the amount of feed required for potential growth the digestible amino acid content (*AAd*) must be known. Therefore, the desired intake to supply amino acid requirements is calculated as:

$$dFI_{AA} = AAd/AA \text{ (g/day)}$$

Physical Capacity of the Digestive Tract

Nutrient intake by poultry may be limited by dietary fibre content due to the physical limitations of their digestive tract, particularly during early growth stages. To account for the effect of dietary fibre on feed intake, a meta-analysis was performed by taking into account four studies (Nascimento *et al.*, 1998; Bellaver *et al.*, 2004; Montazer-Sadegh *et al.*, 2008; Sara *et al.*, 2009). In those studies, broilers were fed diets with different total dietary fibre contents (*TDF*). Feed intake reduction (*rFI*) of birds fed diets with *TDF* increasing levels was expressed as a percentage relative to a control diet (conventional diet containing corn and soybean meal). Data on *rFI* were regressed against *TDF* content (Fig. 14.3).

The equation estimates feed intake reduction as a function of *TDF* percentage in the diet:

$$rFI = [100 + (17.6 + 0.52 \times (36 - TDF))]/100\ (\%)$$

Total dietary fibre content (*TDF*) of the feedstuffs in the model may be obtained using the equation of Bellaver *et al.* (2004):

$$TDF = 2212.56 - 0.0492 \times EM - 1.103 \times ADF - 7.053 \times EE - 9.196 \times MM(\%)$$

Where *ADF* is acid-detergent fibre, *EE* is ether extract and *MM* is ashes.

In order to correct feed intake according to physical capacity, based on the effect of dietary fibre, the following equation is applied:

$$cFI = rFI \times mFI\ \text{(g/day)}$$

Where *cFI* is feed intake corrected for physical capacity and *mFI* is maximum feed intake. In order to calculate *mFI*, daily feed intake was related to protein weight (*x*). The equation for each genetic strain is presented below:

Cobb male: $mFI = -0.0006279x^2 + 0.71542x + 1.7489$ (g/day)

Cobb female: $mFI = -0.001146346x^2 + 0.8735x + 7.7553$ (g/day)

Ross male: $mFI = -0.000482069x^2 + 0.66129x + 8.708551$ (g/day)

Ross female: $mFI = -0.0007711x^2 + 0.74407x + 9.24998$ (g/day)

Hy-Line white: $mFI = -0.0002677x^2 + 0.34919x + 6.2229$ (g/day)

Hy-Line brown: $mFI = -0.000666269x^2 + 0.44387x + 5.6498$ (g/day)

Hisex white: $mFI = -0.0005078x^2 + 0.40907x + 5.07180$ (g/day)

Hisex brown: $mFI = -0.0003668x^2 + 0.38615x + 4.89426$ (g/day)

One aspect that must be considered in the model is the hypothesis confirmed by Gous *et al.* (2012) that chickens of any age attempt to maintain the body lipid to protein ratio determined by their genetic potential by long-term regulation mechanisms. Therefore, feed intake will always depend on the bird's current state. According to this theory, which was first proposed by Emmans (1981), when an animal has more body lipid than its genetically determined lipid:protein ratio, the extra amount of lipid will be used as an energy source whenever possible. In a recent study, Gous *et al.* (2012) observed that for a given feed, body lipid reserves in broilers increased at first due to the need to consume

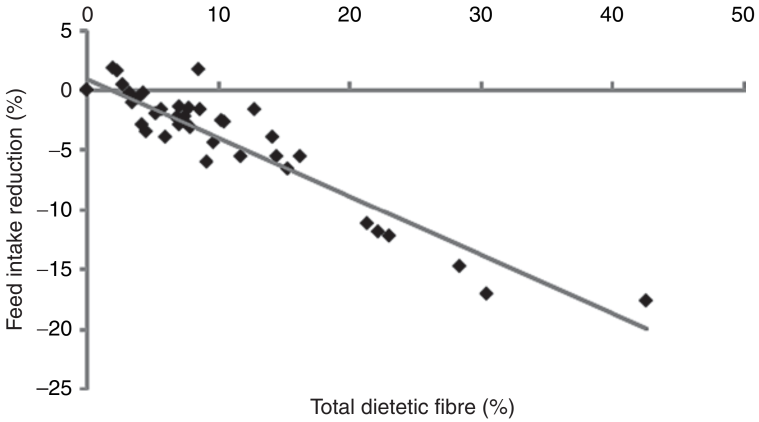


Fig. 14.3. Effect of total dietary fibre on broiler feed intake.

sufficient to meet their amino acid requirement, leading to an overconsumption of energy. As the requirement for protein as a proportion of the feed decreases, birds make use of body lipid as an energy source thereby utilizing the feed very efficiently. When these body lipid reserves are depleted, energy intake increases again. Nevertheless, it must be noted that external effects, such as environmental temperature, may also limit feed intake. These findings are consistent with the hypothesis that there is a desired body lipid content that the bird attempts to maintain.

Actual Feed Intake

The desired feed intake (*dFI*) of a bird in a thermal-neutral environment would be the greater of dFI_e and dFI_{AA}, while the actual daily feed intake (*aFI*) would be the lower of *dFI* and *cFI*. For a perfectly balanced diet, dFI_e would equal dFI_{AA}.

External Effects on Bird Response

Health challenges

Immune challenges affect body homeostasis, and consequently, maintenance nutritional requirements (Latshaw, 1991). In addition, changes in daily feed intake and daily average weight gain (Marcq *et al.*, 2011; Quinteiro-Filho *et al.*, 2012) and feed efficiency (Marcq *et al.*, 2011) depend on the type of health challenge imposed. There are still many gaps when considering the quantitative determination of the effects of immune challenges on maintenance, growth rate and efficiency. Therefore, a meta-analysis on the performance responses of chickens subjected to immune challenge by different enteric bacteria was performed. The database included 60 papers published between 1997 and 2012 (mode: 2006) with a total of 86,300 birds. The meta-analysis showed that birds challenged with *Clostridium* spp., *Escherichia coli* and *Salmonella* spp. reduced their feed intake by 15%, 7% and 9%, and growth rate by 40%, 10% and 29%, respectively (Table 14.3).

In an attempt to explain the mechanisms responsible for these reductions, daily average weight gain (*ADG*) was regressed against average daily feed intake (*ADFI*). Feed intake and weight gain data of the challenged birds were transformed into percentages relative to the control treatment (not challenged) in order to reduce variation between studies. In the regression equation the intercept (*a*) shows that *ADG* reduction is not related to *ADFI*

Table 14.3. Effect of different health challenges on feed intake and growth of broilers.

	Clostridium spp.		*Escherichia coli*		*Salmonella* spp.	
Description	*n*[a]	Mean ± SD	*n*	Mean ± SD	*n*	Mean ± SD
Birds/treatment	198	775 ± 872	309	445 ± 463	213	1576 ± 2903
Initial age[b]	212	11 ± 9	320	10 ± 8	242	11 ± 11
Initial BW	85	311 ± 353	200	249 ± 227	144	230 ± 352
Duration experiment (days)	148	17 ± 0	320	11 ± 8	187	14 ± 11
Response						
Feed intake reduction[c] (%)	–15.83 R^2 = 86.6		–7.09 R^2 = 95.8		–9.29 R^2 = 99.8	
Growth rate reduction[c] (%)	–40.09 R^2 = 79.8		–10.55 R^2 = 77.1		–29.19 R^2 = 98.8	

[a] Number of treatments used to calculate the mean.

[b] At the beginning of the experimental challenge.

[c] Results are the slope differences between challenged and control birds (not challenged), expressed as a percentage of the slope obtained with control birds.

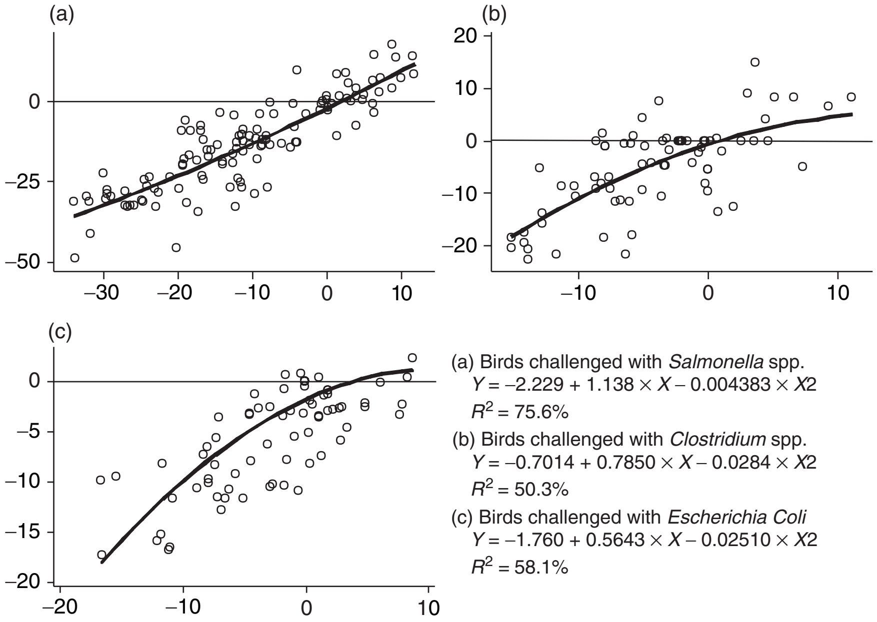
reduction, which may be interpreted as an indication of maintenance. The slope (b) represents the extent of the change in *ADG* associated with the reduction in *ADFI* between challenged and control broilers, and is an indication of feed efficiency. The precision of the regression equations of ΔADG as a function of $\Delta ADFI$ was acceptable ($R^2 > 0.60$) for all challenges, although a significant part of the variation remained unexplained (Fig. 14.4). The intercepts of all challenges (*Salmonella* spp., *Clostridium* spp. and *E. coli*) differed from zero and were negative (–2.2, –0.70 and –1.76, respectively) indicating that all challenges increased maintenance requirements. Moreover, the curvilinear response showed that the higher the reduction in $\Delta ADFI$, the worse the feed efficiency for all health challenges. The detailed results of this meta-analysis was published (Remus *et al*., 2014) elsewhere. Therefore, we may conclude that the evaluated health challenges had an important effect on maintenance requirements.

Growth rate reduction

The model uses a health profile that can be modified, depending on the health status of the bird, by adjusting growth rate (B). Based on the meta-analysis an average value (20%) was adopted, representing maximal growth rate reduction (B) in the presence of health challenge. The health coefficient of the profile is used to reduce B and, therefore, *PD*, *LD* and feed intake, accordingly. The severity of the reductions in *PD*, *LD*, live weight and feed intake depends on the health status of the bird.

Increase in maintenance requirements

There is no consistent information on the maintenance requirements of poultry reared in poor health conditions. Our meta-analysis showed a weak effect of disease on maintenance, and therefore, we decided to



(a) Birds challenged with *Salmonella* spp.
$Y = -2.229 + 1.138 \times X - 0.004383 \times X2$
$R^2 = 75.6\%$
(b) Birds challenged with *Clostridium* spp.
$Y = -0.7014 + 0.7850 \times X - 0.0284 \times X2$
$R^2 = 50.3\%$
(c) Birds challenged with *Escherichia Coli*
$Y = -1.760 + 0.5643 \times X - 0.02510 \times X2$
$R^2 = 58.1\%$

Fig. 14.4. Relationship between growth (ΔADG) and feed intake ($\Delta ADFI$) changes in birds challenged with *Salmonella* spp., *Clostridium* spp. or *Escherichia coli*. Responses are expressed as results of the challenged birds relative to the control group. Lines represent quadratic model adjustments. Estimated parameters differed from zero ($P > 0.05$).

use no more than a 20% increase in maintenance requirements.

Health status adjustment is calculated as:

Maintenance_Adjust: 1/Health status

Where Maintenance_Adj ≤1.20 and ≥1.0. This adjustment is applied only for energy maintenance requirements.

Effect of Environmental Temperature on Heat Production

Environmental temperature influences heat production (HP), and consequently affects growth rate and feed intake. Estimating total heat production (THP) of a bird, considering both dietary and environmental factors, assists in determining its feed intake. When THP is between maximum (THL_{max}) and minimum (THL_{min}) heat loss, feed intake is not affected. However, THP outside that range affects feed intake, which is used as a regulatory mechanism for body heat homeostasis. In addition to environmental temperature, body heat production may be influenced by the relative humidity and air velocity.

Total heat loss (THL) is the sum of sensible (SHL) and evaporative (EHL) heat losses. Therefore, in order to estimate THL_{max} and THL_{min}, both the minimum and maximum SHL and EHL, respectively, need to be determined.

The concept of Emmans (1989) was adopted to estimate THL_{max} and THL_{min}. In order to calculate THL, HP can be partitioned into SHL and EHL:

$$THL_{max} = SHL + EHL_{max} \text{ (kJ/day)}$$

$$THL_{min} = SHL + EHL_{min} \text{ (kJ/day)}$$

SHL is obtained by the equation:

$$SHL = SHL_{slope} \times (41 \times T) \times (EBWFF^{0.67}) \text{ (kJ/day)}$$

Where $EBWFF$ is feather-free empty body weight. The SHL_{slope} equation was obtained from Emmans (1989), and allows the effect of feathering on sensible heat loss to be considered.

$$SHL_{slope} = 64 - 0.5 \times (FP/BW^{0.67}) \text{ (kJ/day)}$$

Where FP is feather protein weight.

Estimating EHL_{min} and EHL_{max}

Evaporative heat loss is minimal (EHL_{min}) and constant for a particular body weight at low temperatures and may represent up to 20% of the thermoneutral heat production ($TerHP$).

$$EHL_{min} = 0.20 \times TerHP \text{ (kJ/day)}$$

$TerHP$ is estimated by the following equation:

$$TerHP = (aFI \times ME) - [(50 \times PD) + (56 \times LD)] \text{(kJ/day)}$$

Maximum EHL is usually constant and several times greater than EHL_{min}. In the study of Simmons *et al.* (1997) an equation was derived to calculate the external effects of temperature and ventilation on body heat production. That study was carried out to determine latent HP in 35- and 42-day-old broilers subjected to different air velocities and temperatures under conditions similar to those found in commercial settings. The authors estimated 12 polynomial equations to predict latent HP as a function of air speed and temperature. Those equations were re-parameterized in a single equation to predict latent HP (kJ/day) as a function of air velocity, temperature (T, °C) and body weight.

$$EHL_{max} = BW \times [9.4434 \times (Vel - 0.0215) \times T] \text{ (kJ/day)}$$

Where Vel = air velocity (m/s).

In order to determine thermal environment effects on growth rate and feed intake, THP is compared with THL_{max} and THL_{min}. THP is calculated as the difference between energy intake and energy retention for protein and fat deposition:

$$THP = (aFI \times ME) - [(23.8 \times PD) + (39.6 \times LD)] \text{ (kJ/day)}$$

Comparing maximum or minimum THL with THP indicates whether the birds are too hot, too cold or comfortable, and enables adequate voluntary feed intake and growth rates to be calculated.

Response to environmental conditions

When heat produced by the bird is greater than the maximum it can lose ($THP > THL_{max}$) to the environment the bird is hot and, therefore, will attempt to reduce THP to THL_{max}. In this case, feed intake declines to maintain the heat production balance:

$$aFI = dFI_e - (THP - THL_{max})/ME \text{ (g/day)}$$

The impact of aFI reduction on PD and LD depends on whether amino acid intake is still sufficient to meet pPD (PD_{AA}) requirements, given that PD is determined by:

$$PD_{AA} = [(AAintake - AAm) \times k]/AAb \text{ (g/day)}$$

Lipid deposition (LD) is estimated as the difference between energy intake and energy retained for PD and lost as heat.

$$LD = [(aFI \times ME) - THP - (23.8 \times PD)]/39.6 \text{ (g/day)}$$

When the amount of heat loss is greater than heat production ($THP < THL_{min}$) the bird is cold. In this case extra heat will be necessary to maintain body temperature and ensure $THP = THL_{min}$. The energy difference between THL_{min} and THP causes maintenance requirements to increase and feed intake will therefore increase by:

$$ExtraFI = (THL_{min} - THP)/ME \text{ (g/day)}$$

If ($ExtraFI + aFI$) > cFI (bulk constraint) then feed intake will decline to cFI, and PD and LD will be adjusted accordingly, as previously discussed under constrained feed intake.

Model Evaluation

Under adequate nutritional supply

Estimating growth and body composition

The ability of the model to estimate body weight and cumulative feed intake (*CFI*) was evaluated by comparing measured and predicted data. The model was calibrated to predict the observed *BW* and *CFI* of each genetic strain. All strains were fed according to the feeding phases applied in the original experiment. All feeds contained 11.5 MJ EE/kg and were assumed to contain all other nutrients in excess, including Lys. For the evaluation, observed and predicted data for each strain were compiled according to chicken strain (broiler and pullet). The quality of fit was tested by the procedure of Theil (1966) in which the mean squared prediction error (MSPE) is calculated as the sum of squares of differences between simulated and observed measurements divided by the number of experimental observations. MSPE was decomposed into error in central tendency, error due to regression (ER) and error due to disturbances, and expressed as MSPE%, as suggested by Benchaar *et al.* (1998).

Simulated and observed values were similar across all feeding periods both for body weight and cumulative feed intake of broilers and pullets (Figs 14.5, 14.6, 14.7 and 14.8). Model accuracy, as estimated by MSPE, was 0.01 (broilers) and 0.72 kg (pullets) for BW and 0.68 (broilers) and 1.99 kg (pullets) for CFI. Deviations between observed and predicted performance values were small, which is consistent with the fact that model parameters were estimated for each strain and chicken type. However, the slope between the predicted and observed BW (broilers) and CFI (pullets) was 1.04, which is higher than 1 ($P < 0.001$), indicating that the model slightly underestimated these parameters during the first feeding phase, and slightly overestimated them in older birds. In fact, more than 20% of the observed error between predicted and observed BW and CFI is given by the difference between the slopes (ER error).

Because unique parameters (maintenance coefficient, energy cost for protein and lipid deposition, etc.) were applied both for meat-type and layer-type chickens, except for those used for bird description, the model was able to obtain growth and intake estimates very close to observed values.

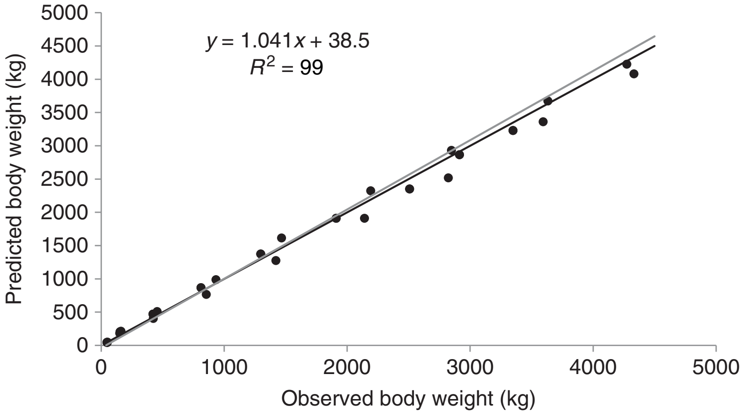


Fig. 14.5. Predicted vs observed body weight of broilers fed a balanced diet for 56 days using AvinespModel. Root mean square prediction error (%) = 0.01; error in central tendency (ECT) = 5.68; error due to regression (ER) = 21.06; error due to disturbances (ED) = 73.25. Regression line (—); line of equality (**—**). Equality line intercept = 0 and slope = 1.

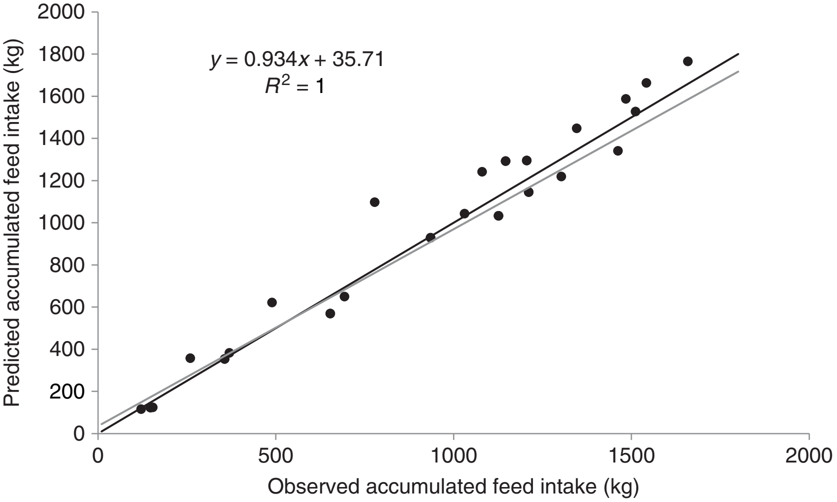


Fig. 14.6. Predicted vs observed accumulated feed intake of broilers fed a balanced diet for 56 days using AvinespModel. Root mean square prediction error (%) = 0.68; error in central tendency (ECT) = 6.21; error due to regression (ER) = 10.11; error due to disturbances (ED) = 83. Regression line (—); line of equality (**—**). Equality line has intercept = 0 and slope = 1.

Evaluation of the model under restricted nutritional conditions

This simulation was carried out to evaluate the model when levels of single amino acids were changed in the diet. The study of Dozier *et al.* (2010), evaluating the response of 28- to 42-day-old broilers to different lysine intakes, was used for comparison. In the present study, the amino acid:protein ratio was kept constant. Cobb male broiler parameters ($B = 0.047$, $Pm = 1041$ g, $LPRm = 0.80$) were adopted for bird description. The results of the comparison in Figs 14.9 and 14.10 show that the responses estimated by the model are similar to those observed

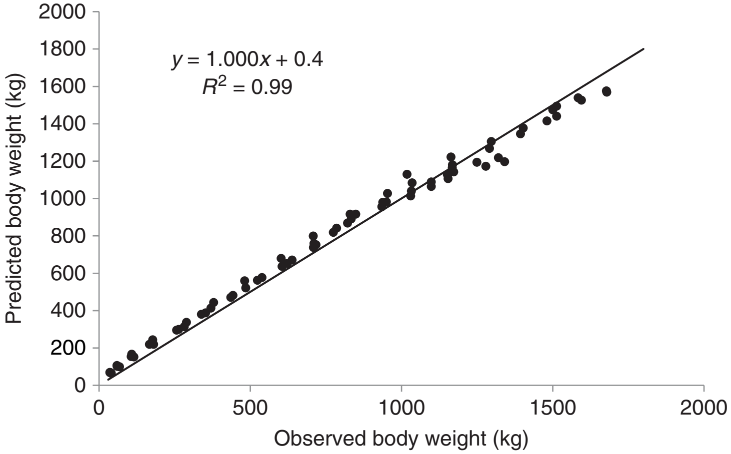


Fig. 14.7. Predicted vs observed body weight of pullets fed a balanced diet for 126 days using AvinespModel. Root mean square prediction error (%) = 0.72; error in central tendency (ECT) = 8; error due to regression (ER) = 35.06; error due to disturbances (ED) = 56.14. Regression line (—); line of equality (—). Equality line has intercept = 0 and slope = 1.

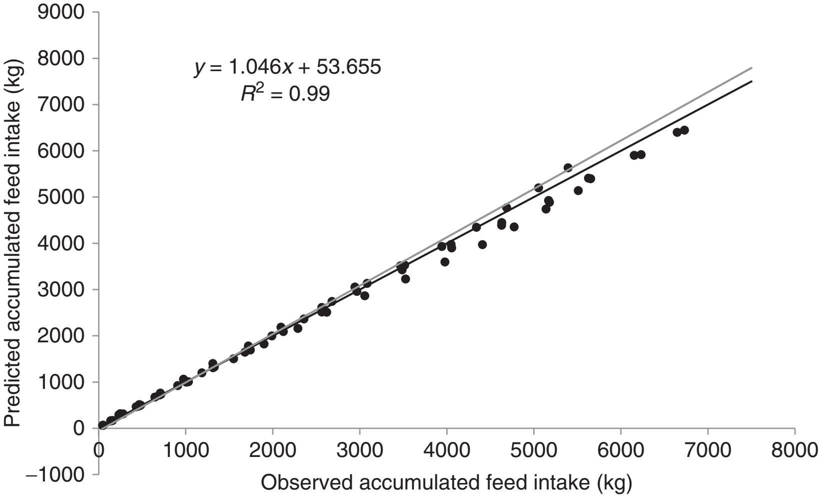


Fig. 14.8. Predicted vs observed accumulated feed intake of pullets fed a balanced diet for 126 days using AvinespModel. Root mean square prediction error (%) = 1.99; error in central tendency (ECT) = 13.01; error due to regression (ER) = 28; error due to disturbances (ED) = 57. Regression line (—); line of equality (—). Equality line has intercept = 0 and slope = 1.

when broilers were fed different dietary lysine levels. The estimated values, in addition to simulating a response similar to the observed, are within the range of one standard deviation. This allows for a greater degree of confidence in the model, and supports the underlying theory of growth and feed intake regulation, especially when protein and/or an amino acid are the first-limiting nutrients, as is often the case in the growing poultry.

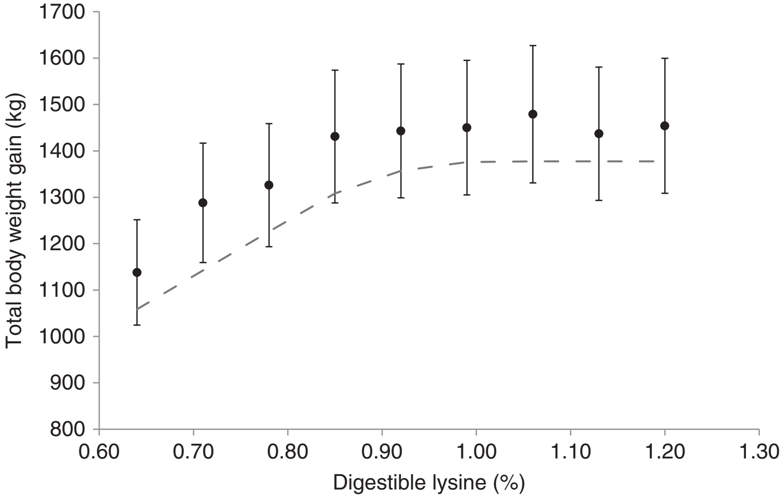


Fig. 14.9. Effect of different digestible lysine levels on total body weight gain estimated for 28- to 42-day-old broilers. Data presented are those observed (●) by Dozier *et al.* (2010) and predicted by model (- - -). Bars represent one standard deviation.

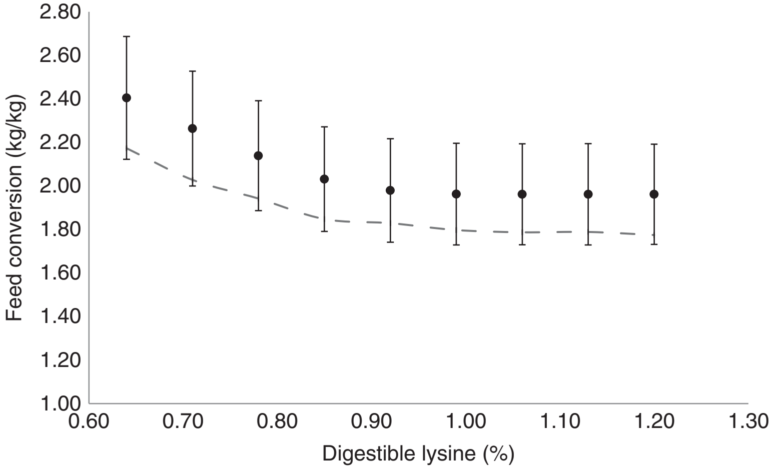


Fig. 14.10. Effect of different digestible lysine levels on feed conversion response estimated for 28- to 42-day-old broilers. Data presented are those observed (●) by (Dozier *et al.*, 2010) and predicted by model (- - -). Bars represent one standard deviation.

Evaluation of the model under health challenge conditions

In order to evaluate the model in the presence of health challenges, information on live weight, feed intake and weight gain of 323 male Cobb flocks reared on farms in a specific geographical region of Brazil was collected. Out of these, 146 flocks were housed after a shorter downtime than that recommended to achieve proper disinfection of the facilities (<12 days). The other 177 flocks were housed after a downtime longer than 12 days. Broilers housed after downtimes shorter than 12 days may be subject to health challenges emanating from the previous flock. Therefore, in order to evaluate the model in the presence of health challenge, the flock database was divided into two groups (1 = downtime shorter than 12 days and 2 = downtime longer than 12 days). There were differences among flocks relative to breeder age, rearing season and market age, and therefore performance variables were adjusted as a function of these factors. Final BW and BWG of broilers reared in a healthy environment (>12 days, High Health) were 4–5% higher than those submitted to health challenge ($P > 0.05$) (<12 days, Poor Health) (data not presented). However, feed intake was not different between the High Health and Poor Health groups ($P > 0.05$). The same feed intake and different weight gain between the two systems indicates changes in maintenance requirements.

In order to simulate the different health conditions in the model, the health status Poor Health in the model was considered as 0.95. Cobb male broiler parameters (B = 0.047, Pm = 1041 g, $LPRm$ = 0.80) were adopted as the bird description. Live weight, weight gain and feed intake results simulated by the model and compared with the observed results are presented in Fig. 14.11. The results show that the model is able to simulate the response of broilers reared under health challenge conditions. Despite being empirical, the applied approach allows the model to account for the health challenge aspect when estimating growth and intake.

Response to environmental temperature

In order to evaluate the effects of environmental temperature on the model, data from Alleman and Leclercq (1997) were used. That study evaluated the performance of broilers between 23 and 43 days kept at two different environmental temperatures, 21°C or 32°C. Ross male broiler parameters were used for the bird description (B = 0.036, Pm = 1313 g, $LPRm$ = 1.0). For the simulation, diet composition was the same as that used in that study (CP: 19%; Lys: 1.00%). Observed and predicted results are summarized in Fig. 14.12a and b. The predicted values were within one standard deviation of the observed data. The observed weight gain and feed intake were reduced by 37% and 25%, respectively, when birds were kept at 32°C compared with 21°C. The predicted feed intake reduction at 32°C was similar to that observed (25%); however, predicted weight gain reduction was 25% and not 37%, as observed. That difference could be related to the genetic potential difference of the birds from the study compared to that used to calibrate the model. Nevertheless, the important point is that the model is able to represent the effect of temperature on bird performance. Broilers housed in hot environments reduce their feed intake as a regulatory mechanism to limit body temperature increase. It is assumed that a large part of the growth reduction of broilers housed at high temperatures compared with those at thermoneutral temperatures is the result of energy and amino acid intake differences (Alleman and Leclercq, 1997).

Model Perspectives

The model presented here is based on a widely accepted growth and feed intake theory that is used in some existing pig and poultry models. This theory adopts the EE system, which considers variation in feedstuff composition and nutritional requirements. The information on chicken growth and their response to energy and amino acid intake obtained from studies carried out at UNESP, together with that theory, enabled a model to be constructed that would estimate growth and nutritional requirements for different chicken types (broilers and layer pullets), genotypes and sexes.

The EE system is not widely applied in Latin America, but the information available in feedstuff nutritional composition tables allows their EE content to be estimated.

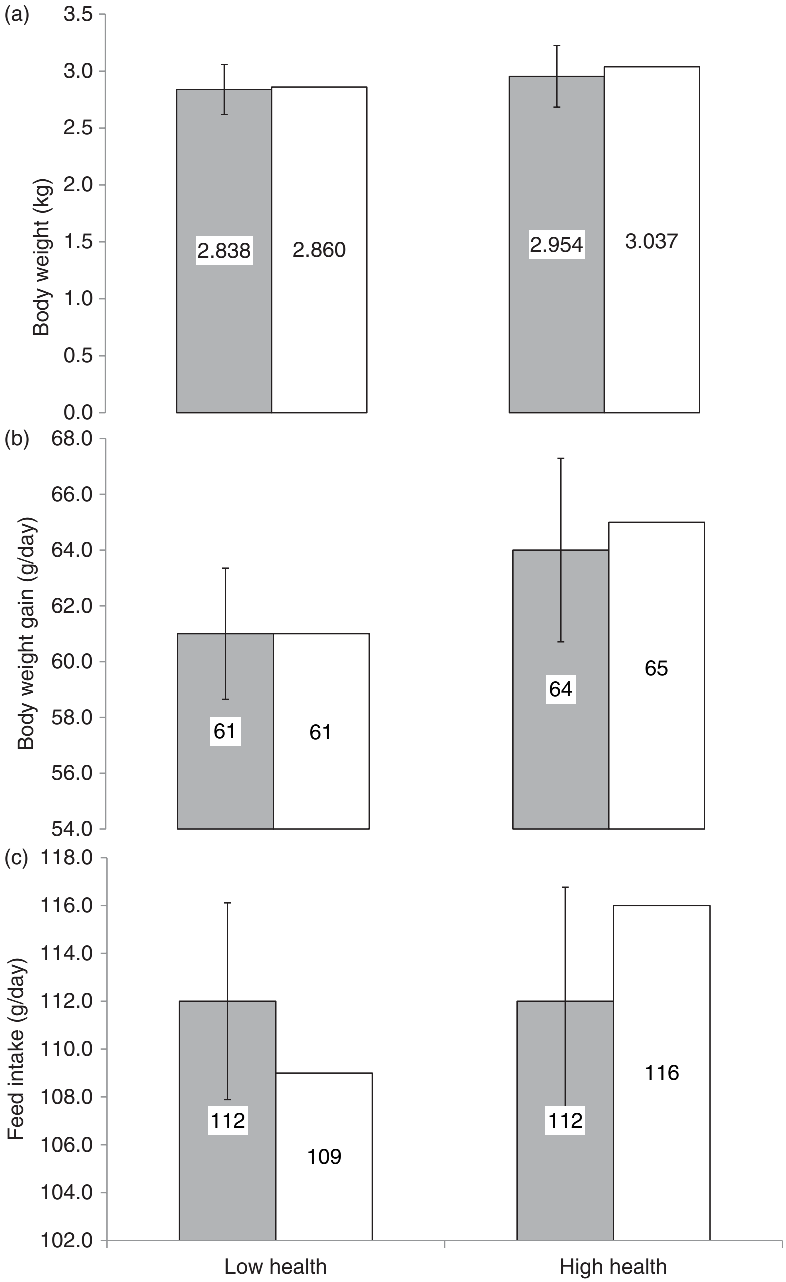


Fig. 14.11. Comparison of Actual (▩) and Predicted (☐) body weight (a), growth rate (b) and feed intake (c) of 1- to 46-day-old broilers reared in High or Low Health status farms. Bars represent one standard deviation.

Unlike some available broiler models with similar purposes, Avinesp also allows the estimation of growth and the nutritional requirements of layer replacement pullets. Estimates obtained with Avinesp for growth and responses to nutrient intake, health challenge and environmental temperature were consistent with the findings

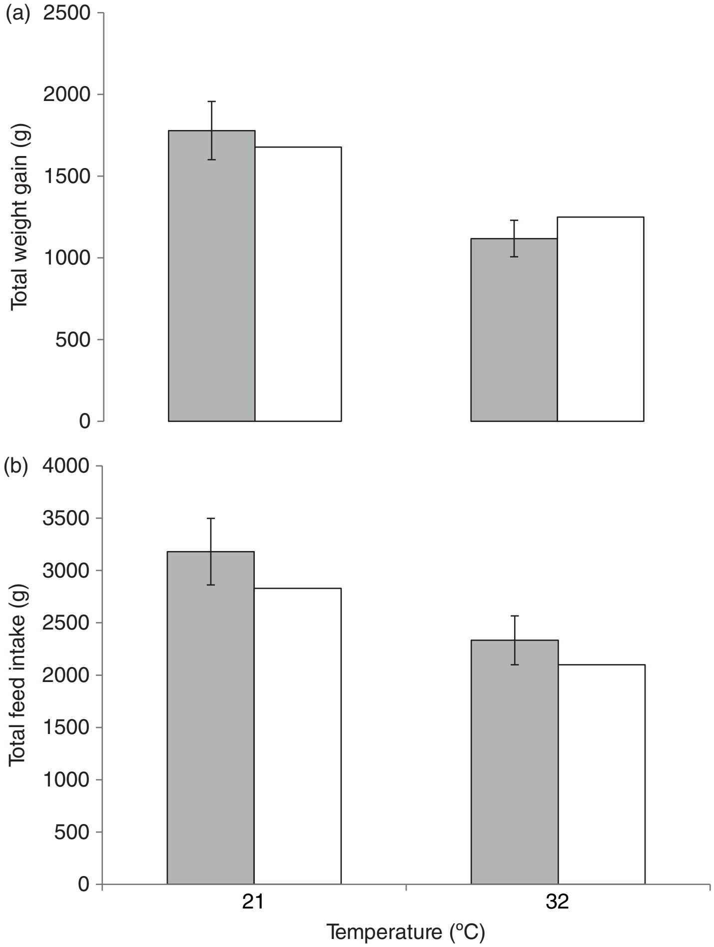


Fig. 14.12. Comparison of observed (▨) vs predicted responses (☐) in weight gain (a) and feed intake (b) to ambient temperature, in birds grown from 23 to 43 days. Data from Alleman and Leclercq (1997). Bars represent one standard deviation.

in the literature. Avinesp simulates the effects of different nutritional, feeding, health and environmental scenarios. Therefore, the proposed model, in addition to estimating nutritional requirements, may also be used as a tool to aid decision making by farmers and companies.

Acknowledgements

The authors thank Fundação de Amparo and Pesquisa do Estado de São Paulo for funding the research projects, and for the grants that allowed us to obtain the results mentioned in this chapter.

References

Alleman, F. and Leclercq, B. (1997) Effect of dietary protein and environmental temperature on growth performance and water consumption of male broiler chickens. *British Poultry Science* 38, 607–610.

Bellaver, C., Zanotto, D.L., Guidoni, A.L. and Brum, P.A.R. (2004) Metabolizable energy and amino acids relationships with the soluble fractions of protein and fiber of vegetable feed ingredients. *Revista Brasileira de Zootecnia* 33, 2274–2282.

Benchaar, C., Rivest, J., Pomar, C. and Chiquette, J. (1998) Prediction of methane production from dairy cows using existing mechanistic models and regression equations. *Journal of Animal Science* 76, 617–627.

Burham, D. and Gous, R.M. (1992) Isoleucine requirements of the chicken: requirement for maintenance. *British Poultry Science* 33, 59–69.

Dozier, W.A., Corzo, A., Kidd, M.T., Tillman, P.B., McMurtry, J.P. and Branton, S.L. (2010) Digestible lysine requirements of male broilers from 28 to 42 days of age. *Poultry Science* 89, 2173–2182.

EFG Software (1995) EFG software. Available at: www.efgsoftware.net (accessed 13 June 2014)

Emmans, G.C. (1974) The effect of temperature on performance of laying hens. In: Morris, T.R. and Freeman, B.M. (eds) *Energy Requirements of Poultry*. British Poultry Science, Edinburgh, UK, pp. 79–90.

Emmans, G.C. (1981) A model of the growth and feed intake of *ad libitum* fed animals, particularly poultry. In: Hillyer, G.M., Whittemore, C.T. and Gunn, R.G. (eds) *Computers in Animal Production*. Animal Production Occasional, London, pp. 103–110.

Emmans, G.C. (1987) Growth body composition and feed intake. *World Poultry Science* 3, 208–227.

Emmans, G.C. (1989) The growth of turkeys. In: Nixey, C. and Grey, T.C. (eds) *Recent Advances in Turkey Science*. Butterworths, London, pp. 135–166.

Emmans, G.C. (1994) Effective energy: a concept of energy utilization applied across species. *The British Journal of Nutrition* 71, 801–821.

Emmans, G.C. (1997) A method to predict the food intake of domestic animals from birth to maturity as a function of time. *Journal of Theoretical Biology* 186, 189–200.

Emmans, G.C. (1999) Energy flows. In: Kyriazakis, I. (ed.) *A Quantitative Biology of the Pig*. CAB International, Wallingford, UK, pp. 363–377.

Emmans, G.C. and Fisher, C. (1986) Problems in nutritional theory. In: Boorman, K.N. and Fisher, C. (eds) *Nutrient Requirements of Poultry and Nutritional Research*. Butterworths, London, pp. 9–39.

Emmans, G.C. and Kyriazakis, I. (1999) Growth and body composition. In: Kyriazakis, I. (ed.) *A Quantitative Biology of the Pig*. CAB International, Wallingford, pp. 181–197.

Emmans, G.C. and Oldham, J.D. (1988) Modelling of growth and nutrition in different species. In: Korver, S. and Van Arendonk, J.A.M. (eds) *Modelling of Livestock Production Systems*. Kluwer Academic Publishers, Amsterdam, pp. 13–21.

Fancher, B.I. (1999) Use of broiler growth modeling technology in live production strategic planning. *Proceedings of the Maryland Nutrition Conference*. College Park, Maryland, USA, pp. 41–50.

Ferguson, N.S., Gous, R.M. and Emmans, G.C. (1994) Preferred components for the construction of a new simulation model of growth, feed intake and nutrient requirements of growing pigs. *South African Journal of Animal Science* 24, 10–17.

Ferguson, N.S., Gous, R.M. and Emmans, G.C. (1997) Predicting the effects of animal variation on growth and food intake in growing pigs using simulation modelling. *Animal Science* 64, 513–522.

Gompertz, B. (1825) On nature of the function expressive of the law of human mortality, and on a new mode of determining the value of life contingencies. *Philosophical Transactions of the Royal Society* 115, 513–585.

Gous, R.M. (2007) Methodologies for modelling energy and amino acid response in poultry. *Revista Brasileira de Zootecnia* 36, 236–275.

Gous, R.M., Moran, E.T. Jr, Stilborn, H.R., Bradford, G.D. and Emmans, G.C. (1999) Evaluation of the parameters needed to describe the overall growth, the chemical growth, and the growth of feathers and breast muscles of broilers. *Poultry Science* 78, 812–821.

Gous, R.M., Emmans, G.C. and Fisher, C. (2012) The performance of broilers on a feed depends on the feed protein content given previously. *South African Journal of Animal Science* 42, 63–73.

Hancock, C.E., Bradford, G.D., Emmans, G.C. and Gous, R.M. (1995) The evaluation of the growth parameters of six strains of commercial broiler chickens. *British Poultry Science* 36, 247–264.

Latshaw, J.D. (1991) Nutrition – mechanisms of immunosuppression. *Veterinary Immunology and Immunopathology* 30, 111–120.

Lopez, G., de Lange, K. and Leeson, S. (2007) Partitioning of retained energy in broilers and birds with intermediate growth rate. *Poultry Science* 86, 2162–2171.

Marcq, C., Cox, E., Szalo, I.M., Théwis, A. and Beckers, Y. (2011) *Salmonella typhimurium* oral challenge model in mature broilers: bacteriological, immunological, and growth performance aspects. *Poultry Science* 90, 59–67.

Martin, P.A., Bradford, G.D. and Gous, R.M. (1994) A formal method of determining the dietary amino acid requirements of laying-type pullets during their growing period. *British Poultry Science* 35, 709–724.

Montazer-Sadegh, R., Ebrahim-Nezhad, Y. and Maheri-Sis, N. (2008) Replacement of different levels of rapeseed meal with soybean meal on broilers performance. *Asian Journal of Animal and Veterinary Advances* 3, 278–285.

Nascimento, A.H., Gomes, P.C., Rostagno, H.S., Albino, L.F.T., Gomes, M.F.M. and Runho, R.C. (1998) Uso do Farelo de Canola em Rações para Frangos de Corte. *Revista Brasileira de Zootecnia* 27, 1168–1176.

Pesti, G.M., Arraes, R.A. and Miller, B.R. (1986) Use of the quadratic growth response to dietary protein and energy concentrations in least-cost feed formulation. *Poultry Science* 65(6), 1040–1051.

Quinteiro-Filho, W.M., Gomes, A.V.S., Pinheiro, M.L., Ribeiro, A., Ferraz-de-Paula, V., Astolfi-Ferreira, C.S., Ferreira, A.J.P. *et al.* (2012) Heat stress impairs performance and induces intestinal inflammation in broiler chickens infected with *Salmonella enteritidis*. *Avian Pathology* 41, 421–427.

Remus, A., Hauschild, L., Andretta, I., Kipper, M., Lehnen, C.R. and Sakomura, N.K. (2014) A meta-analysis of the feed intake and growth performance of broiler chickens challenged by bacteria. *Poultry Science* 93, 1149–1158.

Sakomura, N.K., Hauschild, L., Silva, E.P. and Araújo, J.A. (2011) Factorial model to estimate nutrient requirements for poultry. In: Rostagno, H.S. (ed.) *III International Symposium on Nutritional Requirements of Poultry and Swine*. UFV, Viçosa, pp. 45–76.

Sara, J.R., Gous, R.M. and Bureau, D.P. (2009) Describing growth and predicting feed intake in the marine prawn *Fenneropenaeus indicus*: Part I: Theoretical and practical aspects of measuring and predicting genetic parameters. *Aquaculture* 287, 402–413.

Simmons, J.D., Lott, B.D. and May, J.D. (1997) Heat loss from broiler chickens subjected to various air speeds and ambient temperatures. *Applied Engineering in Agriculture* 13, 665–669.

Stilborn, H.L., Moran, E.T. Jr, Gous, R.M. and Harrison, M.D. (1997) Effect of age on feather amino acid content in two broiler strain crosses and sexes. *Journal of Applied Poultry Research* 6, 205–209.

Stilborn, H.L., Moran, E.T. Jr, Gous, R.M. and Harrison, M.D. (2010) Influence of age on carcass (feather-free) amino acid content for two broiler strain-crosses and sexes. *Journal of Applied Poultry Research* 19(1), 13–23.

Theil, H. (1966) *Applied Economic Forecasting*. North-Holland Publishing Company, Amsterdam.

van Milgen, J. and Noblet, J. (1999) Energy partitioning in growing pigs: the use of a multivariate model as an alternative for the factorial analysis. *Journal of Animal Science* 77, 2154–2162.

Reports of the Project 'Models to Estimate Amino Acid Requirements of Poultry'

The remaining chapters in this book present the results of research conducted by postgraduate students of the Faculdade de Ciências Agrárias e Veterinárias – Universidade Estadual Paulista, Jaboticabal, São Paulo, Brazil. The project 'Models to estimate amino acid requirements of poultry' conducted at this university (supported by Fundação de Amparo a Pesquisa do Estado de São Paulo, Brazil) over a period of 5 years resulted in five Masters and six PhD theses, with five undergraduate and two post-doctoral students also assisting with the project. The research was directed towards the development of a simulation model, the AVINESP Model, designed to simulate growth and to estimate energy and amino acids requirements of broilers and laying pullets. The following eight papers were presented by five of the postgraduate students supervised by Professor Nilva Kazue Sakomura, during the International Symposium in Modeling in Pig and Poultry Production held in Jaboticabal, São Paulo, Brazil, from 18 to 20 June, 2013.

15 Maintenance Requirements for Amino Acids in Poultry

M.A. Bonato,[1] N.K. Sakomura,[1]* J.C.P. Dorigam[1] and R.M. Gous[2]
[1] *Universidade Estadual Paulista, Jaboticabal, São Paulo, Brazil;*
[2] *University of KwaZulu-Natal, Pietermaritzburg, South Africa*

Abstract

Maintenance may be defined as the state in which the animal can maintain all its vital functions without any loss or gain in body tissue and without producing any product. Defining the amino acid requirements for maintenance by poultry is an area of nutrition that has still not been satisfactorily resolved. A number of difficulties arise, among which are the difficulty in defining the methodology required to measure these requirements, and in agreeing upon a general scaling rule that relates the maintenance requirement to the animal's characteristics and state. Based on these assumptions one methodology was used to estimate the methionine + cystine (Met+Cys), threonine (Thr), lysine (Lys) and valine (Val) maintenance requirements for poultry with several metabolic trials using Cobb® and Bovans White® roosters. Measured amounts of a nitrogen-free diet and first-limiting amino acid were fed by intubation each day for 3 days. A nitrogen-free diet containing energy, vitamins and minerals was made available *ad libitum* during the balance period, to ensure that the birds remained in positive energy balance. The excreta were collected in trays for 3 days. The nitrogen content of the excreta was determined with dried homogenized samples, as well as diet samples, in order to determine the nitrogen balance (*NB*). Linear regressions describing the effect of each limiting amino acid intake on nitrogen retention were: $NB = -279\ (\pm 48.0) + 3.20\ (\pm 0.20)$ Met+Cys ($r^2 = 0.82$); $NB = -191\ (\pm 59.7) + 2.53\ (\pm 0.20)$ Thr ($r^2 = 0.60$); $NB = -304\ (\pm 38.5) + 3.56\ (\pm 0.20)$ Lys ($r^2 = 0.94$); $NB = -501\ (\pm 53.4) + 2.29\ (\pm 0.16)$ Val ($r^2 = 0.89$); where the amino acid intake is in mg/$BP_m^{0.73}$ day. The Met + Cys, Thr, Lys and Val required to maintain the body at zero nitrogen retention were estimated to be 87.2, 44.7, 85.2 and 219 mg/$BP_m^{0.73}$ day, respectively.

Introduction

The estimation of the maintenance requirements of animals poses particular problems because maintenance is a concept, and is therefore difficult to define and measure. A complete description of the concept of maintenance was made by Armsby and Moulton (1925), who explained that maintenance involves the idea of the conservation status of an animal that is not performing any work or producing any product. In addition, nutrient intake and excretion must be perfectly balanced in order not to have losses or gains.

Many studies have been carried out since the 1960s attempting to estimate the maintenance requirement of each amino acid for different chicken classes (broilers,

---

*E-mail: sakomura@fcav.unesp.br

Nutritional Modelling for Pigs and Poultry (eds N.K. Sakomura *et al.*)

laying hens, broiler breeders, roosters), and a wide range of methods has been used. All methodologies that estimate requirements may be criticized because biological phenomena are, in general, difficult to measure precisely or to explain mathematically. In addition to different methodologies, there are also several factors that affect requirements, such as the scale of measurement. In addition to Armsby and Moulton (1925), many other authors have attempted to define the concept of maintenance. According to Leveille and Fisher (1958, 1960) and Leveille *et al.* (1960), maintenance is a status in which laying hens are able to maintain egg production and to stay alive, and minimal amounts of nutrients are needed to maintain the balance between intake and excretion. The generally accepted definition of amino acid maintenance requirement of chickens is the situation where nitrogen intake is exactly equal to the sum of its losses, thereby keeping body nitrogen (N) content constant (Owens and Pettigrew, 1989; Sakomura and Coon, 2003; Sakomura and Rostagno, 2007).

During maintenance, metabolism results in body protein loss, which must be replaced by the diet (Bonato *et al.*, 2011). Moughan (2003) lists these processes in chickens: amino acid losses via skin and feathers; amino acid-derived nitrogen losses in the urine indicating body protein turnover inefficiency; endogenous amino acid losses from the gut (mainly mucus, bile, sloughed cells); irreversible amino acid loss due to the synthesis of essential non-amino acid nitrogenous metabolites (e.g. creatinine); irreversible chemical changes of amino acids (e.g. lysine to hydroxyl lysine); and the loss of free amino acids in the urine. In order to maintain nitrogen balance, amino acids must be supplied at the same rate as they are lost through metabolism, secretion or excretion from the body (Sakomura and Rostagno, 2007) and in the precise ratio in the feed.

Several approaches have been applied for the determination of maintenance requirements. For instance, the Reading Model is a factorial approach that estimates maintenance by extrapolation (Fisher *et al.*, 1973; Bowmaker and Gous, 1991). The Gottingen approach also uses the factorial method based on nitrogen balance (Samadi and Liebert, 2006a,b, 2007a,b, 2008; Liebert, 2008). Nitrogen balance trials measuring the point where retention is equal to zero, that is, losses are equal to intake, were reported by Gous *et al.* (1984), Burnham and Gous (1992), Nonis and Gous (2008), Bonato *et al.* (2011) and Siqueira *et al.* (2011). The comparative slaughter technique has been used to measure nitrogen retention (Edwards *et al.*, 1997, 1999; Kim *et al.*, 1997a,b,c). Each of these approaches may be criticized because maintenance is a biological phenomenon and, therefore, difficult to measure and to explain mathematically.

Different diet formulations have been used for the determination of the maintenance requirements of chickens. Leveille and Fisher (1959, 1960) used a whole egg diet and an amino acid-free mixture, which contained 13 amino acids at the same levels as those found in whole egg protein. The curvilinear response they obtained for isoleucine (the test amino acid) suggests that other amino acids may have been limiting. The method using supplementation of crystalline amino acids does not reflect practical situations, when amino acids are included in plant and animal protein, because they are fully digestible and, therefore, true amino acid requirements may be underestimated (Siqueira, 2009). Another method applied is diet dilution, proposed by Fisher and Morris (1970), where amino acid ratios are kept constant at the different evaluated levels.

When determining maintenance requirements feeding methods must also be considered, with both *ad libitum* and force feeding being commonly applied. However, some problems may arise. For instance, Leveille and Fisher (1959, 1960) observed that chickens rejected a pelleted feed deficient in threonine. This may be explained by the fact that diets used to estimate maintenance requirement must contain extremely low levels of the test amino acid, casting doubts on the validity of the results of these trials. Sibbald (1976) described a force-feeding method in which feed is introduced directly into the crop of the bird, which enables feed intake to be precisely determined. Gous *et al.* (1984) proposed the method of force feeding of the test diet, together with *ad libitum* supply of a nitrogen-free diet, in order to ensure that the other nutrients are not limiting. This method, according to Burnham and Gous (1992), offers the advantage of precisely measuring intake, preventing the feed refusal and waste sometimes observed when test diets are supplied in the feeder.

Bird age also affects the determination of amino acid maintenance requirements. Studies have been carried out with growing chickens (Kim *et al*., 1997a,b,c; Bae *et al*., 1999a,b; Edwards and Baker, 1999; Sakomura and Coon, 2003; Samadi and Liebert, 2006a,b, 2007a), mature laying chickens (layers or broiler breeders hens) (McDonald and Morris, 1975; Bowmaker and Gous, 1991) and roosters (Leveille and Fisher, 1958, 1959, 1960; Leveille *et al*., 1960; Gous *et al*., 1984; Gous, 1986; Burnham and Gous, 1992; Nonis and Gous, 2008; Bonato *et al*., 2011). The degree of maturity of a bird should be considered when estimating maintenance requirements since it can represent a larger or smaller proportion of these requirements. Maintenance requirements increase proportionally as the bird matures; upon reaching maturity, it stops growing. For instance, growing birds such as broilers have lower maintenance requirements as compared to mature birds, such as layers or roosters, but have requirements for growth. It is difficult to estimate the maintenance requirements of growing birds because their weight and body composition change daily. On the other hand, in mature birds, maintenance represents most of their requirements. Therefore, it is more useful to measure maintenance requirements in mature birds than in growing broilers. Maintenance requirements should not be measured using laying hens because it is difficult to separate this requirement from that for egg production, so it is better to use mature male chickens to determine maintenance requirements.

According to Emmans and Oldham (1988), several issues need to be considered when determining maintenance requirements: genotypes differ in size at maturity, and birds of the same genotype differ in their requirements at different stages of growth. One further problem is how to deal with changes in body fat content, since there is no requirement for amino acids for the maintenance of lipid reserves.

Maintenance requirements have variously been scaled to body weight of the fasting bird (mg/BW_{kg} day) (Fisher, 1994), to metabolic body weight (mg/$BW_{kg}^{0.75}$ day) (Hurwitz *et al*., 1978; King, 2001 and others) and to feather-free body protein weight scaled to mature body protein (Emmans and Fisher, 1986). The latter authors, based on the work of Brody (1945) and Taylor and Young (1968), showed that amino acid requirements for maintenance are more closely related to body protein content, because there is no demand for amino acids for the maintenance of lipid reserves. These authors proposed the following equation: $MP = (0.008 \times BP_m^{0.73}) \times u$; where MP is maintenance protein requirement (g/day); 0.008 is a constant (kilogrammes of ideal protein/maintenance unit), which assumes that chickens require 8 g protein with adequate composition (ideal) to meet their maintenance requirements; BP_m is body protein weight at maturity (kg); and u is the degree of maturity at time t ($u = BP_t/BP_m = 1$ in adult birds, and therefore, $BP_t = BP_m$).

Several studies have been conducted at the Poultry Science Laboratory of UNESP-Jaboticabal, Brazil, to evaluate the problems and factors discussed above. This chapter describes the methodology and the results obtained in the determination of amino acid requirements of chickens for maintenance.

Materials and Methods

Seven metabolism assays were performed at the Poultry Science Laboratory of the Faculty of Agriculture and Veterinary Sciences, UNESP-Jaboticabal, São Paulo, Brazil, to determine the methionine + cystine (Met+Cys), threonine (Thr), lysine (Lys) and valine (Val) requirements for maintenance of adult roosters using the methodology described by Nonis and Gous (2008). Two assays were performed for Met+Cys and three for Thr. Also, assays were carried out to compare the maintenance requirements for each amino acid between Cobb (meat type) and Bovans White (egg type) roosters in order to determine if these requirements should be expressed in terms of body protein content or body weight (Bonato *et al.*, 2011). A parallelism test (Kaps and Lamberson, 2004) was previously carried out to compare the slopes of the response to increasing amino acid intake on N balance for these genotypes. The regression coefficients obtained for Lys and Val did not differ ($P > 0.05$) between the two genotypes, and hence, only one equation is needed to describe bird response, independently of genotype (Bonato *et al.*, 2011). The responses of Bovans White and Cobb roosters were again compared when determining the maintenance requirements for Lys and Val.

Birds and experimental design

In each experiment, 42 birds of each strain were used, except for the Lys trial (36 birds). Birds were selected in order to obtain the same average body weight at the beginning of the experiments. Bovans White roosters weighed, on average, 2.02 ± 0.2 kg in the Met+Cys trials, 2.11 ± 0.2 kg in the Thr trials and 2.05 ± 0.2 kg in the Lys trial; and Cobb roosters weighed, on average, 5.54 ± 0.6 kg in the Met+Cys trials, 5.78 ± 0.7 kg in the Thr trials and 4.10 ± 0.5 kg in the Val trial.

Roosters were individually housed in metabolism cages (0.4 × 0.5 × 0.6 m) each equipped with a nipple drinker and a trough feeder. In each experiment, birds were fed six diets (treatments) containing graded levels of the test amino acid, with six birds (replicates) per treatment, except for the Lys trial, which included five treatments, but also six replicates each. Birds were randomly distributed among treatments.

Experimental procedures

Feed was withdrawn two days before the experiments started to allow the emptying of the digestive tract. During this period, 60 ml of water with sucrose (1:1) was fed once daily directly into the crop. In the morning of the third day (beginning of 3-day collection period) individual body weight was recorded. Birds were fed the experimental diets directly into crop by gavage every 24 h for the next 72 h. During this period, a N-free diet was supplied *ad libitum* in the feeder and its intake was measured during the 72-h period. Excreta collection started 24 h after the first feeding and ended 24 h after the last feeding. Excreta were weighed per individual bird at the end of the collection period, and then processed.

Experimental diets

The experimental diets were formulated according to the dilution technique (Fisher and Morris, 1970). Two basal diets were formulated in each experiment. One was free of nitrogen (N-free diet) but contained adequate metabolizable energy (ME), mineral and vitamin levels as recommended by Rostagno *et al.* (2005) and Rostagno *et al.* (2011). The other basal diet (concentrated diet) was formulated to contain the same ME, mineral and vitamin levels as the N-free diet, but also included protein, with the test amino acid as the first-limiting amino acid, being 0.2 (Met+Cys, Thr and Lys trials) and 0.4 (Val trial) of the 'ideal' requirement. The N-free and the concentrated basal diets were mixed in different proportions in order to obtain the intermediate amino acid dietary levels.

The composition of the six basal diets used to determine the maintenance requirement for amino acids is presented in Table 15.1. Daily feed allowance consisted of a mixture of N-free and N-containing diets, and changed according to the diets, as shown in Table 15.2. The last amino acid level in each trial, as shown in Table 15.1, was used to verify if indeed the test amino acid was the limiting amino acid in the diet, and not to determine maintenance requirements.

Laboratory analysis

The excreta produced daily were individually weighed and stored in a freezer (–20°C) until the end of the trial. Samples were

Table 15.1. Composition of the basal diets used to determine methionine + cystine (Met+Cys), threonine (Thr), lysine (Lys) and valine (Val) maintenance requirements.

	Met+Cys		Thr		Lys	Val
Ingredients	BW	Cobb	BW	Cobb	BW	Cobb
Corn	355	581	451	370	781	677
Soybean meal 450 g/kg	480	319	392	450	100	225
Soybean oil	73.2	43.8	50.2	60.0	21.8	21.5
Dicalcium phosphate	20.8	21.4	21.3	21.0	8.13	11.3
Limestone	9.30	9.80	9.50	9.30	6.59	7.90
Salt	8.10	8.00	8.00	8.10	4.02	5.34
L-Lysine HCl (785 g/kg)	2.70	–	5.40	6.00	–	5.17
DL-Methionine (980 g/kg)	1.40	0.30	10.1	11.7	8.76	7.33
L-Threonine (906 g/kg)	6.80	0.80	2.00	4.10	8.57	5.62
L-Tryptophan (933 g/kg)	1.60	–	–	3.00	2.51	1.62
L-Valine (980 g/kg)	9.00	1.20	11.0	12.0	10.4	5.19
L-Arginine (931g/kg)	5.10	–	7.80	8.80	11.0	6.26
L-Isoleucine (980 g/kg)	6.40	–	7.90	9.00	8.87	6.23
L-Leucine (985 g/kg)	4.20	–	6.10	9.00	7.45	4.07
L-Phenylalanine (980 g/kg)	1.00	–	2.40	3.00	4.91	4.99
L-Glycine (980 g/kg)	–	–	–	–	–	0.97
Potassium chloride	–	–	–	–	5.00	2.71
Choline chloride 700 g/kg	5.00	5.00	5.00	5.00	1.00	1.00
Vitamin/mineral premix[a]	10.0	10.0	10.0	10.0	10.0	1.00
Calculated nutritional levels						
Metabolizable energy (MJ/kg)	13.0	13.0	13.0	13.0	13.0	13.4
Crude protein (g/kg)[b]	294	204	270	283	166	196
Lysine[c]	15.1	9.31	15.1	16.9	**3.77**	11.1
Methionine + cystine	**7.92**	**5.85**	15.8	17.7	11.9	11.7
Tryptophan	4.37	2.15	4.37	5.57	3.28	3.23
Threonine	14.6	7.2	**7.32**	**11.7**	10.9	10.8
Arginine	21.2	11.9	21.1	23.6	15.9	15.6
Valine	19.4	9.43	20	21.8	14.3	**11.8**
Phenylalanine	12.6	8.98	12.4	13.9	9.44	12.1
Isoleucine	16.4	8.09	16.5	18.5	12.3	12.1
Leucine	23.4	16.3	23.4	27.2	17.5	17.3

[a] Content/kg – vit. A = 12,000,000 IU, vit. D3 = 22,000,000 IU, vit. E = 30,000 mg, vit. B1 = 2200 mg, vit. B2 = 6000 mg, vit. B6 = 3300 mg, vit. B12 = 16,000 mg, Niacin = 53,000 mg, pantothenic acid = 13,000 mg, vit. K = 2500 mg, folic acid = 1000 mg, selenium = 250 mg, antioxidant = 100,000 mg, manganese = 75,000 mg, iron = 50,000 mg, zinc = 70,000 mg, copper = 6500 mg, cobalt = 200 mg, iodine = 1500 mg.

[b] Analysed crude protein levels (N × 6.25).

[c] Digestible amino acid, g/kg.

thawed and homogenized using a blender (RI2008, Walita). A known volume of distilled water was added in order to obtain a proper texture, as described by Burnham and Gous (1992). In this case, the weight corresponding to the volume of distilled water added was summed to the total excreta produced. Aliquots were poured on disposable Petri dishes, weighed, frozen (–20°C) and then vacuum-dried (–80°C; –80 kPa) (VLP20, Thermo Fisher) for 72 h. Dried samples were ground in a micro mill (A11 BASIC – IKA, São Paulo) for 1 min. The experimental diets were submitted to the same procedure. At the end of each trial the roosters were sacrificed, and their carcasses were frozen, plucked, ground, and a sample was collected and freeze-dried. Diet, excreta and carcass samples were analysed for dry matter, ether extract (only carcasses) and total N content,

Table 15.2. Content of basal diet (g) contributing to the total amount fed (TFI) (g) per treatment for the amino acids tested.

Trial		Treatment							TFI
		1	2	3	4	5	6	7[a]	
Met+Cys	BovW[h]	0	20	30	35	37.5	40	20[b]	40
	Cobb	10	22.5	35	47.5	50	60	22.5[c]	60
Thr	BovW	0	20	30	35	37.5	40	20[d]	40
	Cobb	0	10	20	30	45	50	10[e]	50
Lys	BovW	0	10	20	30	40	10[f]	–	40
Val	Cobb	0	8	16	24	32	40	8[g]	40

[a] Additional level to verify the limiting amino acid in each trial.
[b] Treatment 2 + 8.5 mg dl-methionine.
[c] Treatment 2 + 13.1 mg dl-methionine.
[d] Treatment 2 + 28.9 mg l-threonine.
[e] Treatment 2 + 28.9 mg l-threonine.
[f] Treatment 2 + 28 mg l-Lysine.
[g] Treatment 2 + 96 mg l-valine.
[h] Bovans White strain.

which was determined using the Kjeldahl method as described by the AOAC (1990).

Statistical analysis

Nitrogen balance (*NB*) was calculated as the difference between nitrogen intake and nitrogen excretion. Linear regressions between *NB* and amino acid intake, and the requirements were expressed using four different scales (mg/bird day, mg/BW_{kg} day, mg/$BW_{kg}^{0.75}$ day, or mg/$BP_m^{0.73}.u$ day, where *BW* is empty body weight, BP_m is mature body protein content and *u* is the degree of maturity or BP/BP_m). The body protein content of birds was calculated as 184 g/kg and 199 g/kg for Bovans White and Cobb, respectively (Bonato *et al.*, 2011). Because the roosters used in the trial were mature ($u = 1$), mg/$BP_m^{0.73}.u$ day is equal to mg/$BP_m^{0.73}$ day. Based on these equations, digestible amino acid requirement for maintenance was determined as the intake (expressed using the scales described above) that corresponds to zero *NB*.

Statistical analysis was performed using the GLM procedure of the software program SAS 9.2 (2002) at 0.05 significance level. The concentration of each amino acid required to make up the 'ideal' protein for maintenance was calculated based on the results obtained for each amino acid, assuming that a bird requires 8 g of protein per unit of maintenance (Emmans and Fisher, 1986). Daily intake of each amino acid required per maintenance unit was divided by 8 g.

Results

In order to estimate amino acid requirements for maintenance, nitrogen intake and nitrogen excretion need to be measured, and the difference between intake and excretion is the nitrogen balance (*NB*). The maintenance requirement is defined at the point where the line estimated by the regression of amino acid intake (*AAI*) on nitrogen balance intersects the *x*-axis, when $NB = 0$. The results of each trial (Met+Cys, Thr, Lys and Val) are presented in Table 15.3.

The results of the Met+Cys and Thr trials (with both strains) were compared using the parallelism test, and one equation was sufficient to explain Met+Cys and Thr maintenance requirements of both strains (Bonato *et al.*, 2011). Therefore, only one equation was considered for these amino acids. Table 15.4 shows the regression equations for Met+Cys, Thr, Lys and Val according to the scales (mg/bird day, mg/BW_{kg} day, mg/$BW_{kg}^{0.75}$ day, mg/$BP_m^{0.73}$ day), and the maintenance requirement estimated using each of these equations.

Table 15.3. Mean (±SD) amino acid intake (*AAI*) and nitrogen balance (*NB*) of methionine + cystine (Met+Cys), threonine (Thr), lysine (Lys) and valine (Val) trials with Bovans White (BovW) and Cobb genotypes.

AA/ strain		Treatment						
		1	2	7[a]	3	4	5	6
		mg/kg$^{0.73}$ day						
Met +Cys	AAI	0.0 ± 0.0	39.5 ± 0.95	59.8 ± 1.50	84.8 ± 2.52	166 ± 3.84	334 ± 10.1	638 ± 12.1
BovW[c]	NB[b]	–296 ± 102	–162 ± 119	72.1 ± 80.3	–65.7 ± 174	334 ± 155	615 ± 159	1814 ± 124
Met +Cys	AAI	0.00 ± 0.0	55.3 ± 2.07	76.2 ± 1.91	120 ± 4.05	201 ± 10.85	263 ± 10.46	316 ± 9.45
Cobb[c]	NB	–230 ± 55.4	–97.7 ± 85.2	428 ± 46.2	215 ± 96	259 ± 69.1	674 ± 166	695 ± 224
Thr	AAI	0.0 ± 0.0	36.7 ± 0.70	96.4 ± 1.25	73.1 ± 1.58	144 ± 1.39	287 ± 5.89	577 ± 13
BovW[c]	NB	–203 ± 36.8	–37.2 ± 109	342 ± 74.1	132 ± 73.9	393 ± 170	1182 ± 43.8	1620 ± 184
Thr	AAI	0.0 ± 0.0	38.2 ± 0.59	96.4 ± 1.25	74.9 ± 1.79	152 ± 3.22	292 ± 5.56	584 ± 5.34
BovW[c]	NB	–364 ± 186	–130 ± 91.7	342 ± 74.1	117 ± 97.6	487 ± 88.8	509 ± 168	1306 ± 230
Thr	AAI	0.0 ± 0.0	52.6 ± 2.46	95.3 ± 2.49	212 ± 9.33	324 ± 3.1	416 ± 7.74	542 ± 15.9
Cobb[c]	NB	–305 ± 109	–415 ± 105	468 ± 83.2	51.3 ± 144	597 ± 209	514 ± 269	698 ± 196
Lys	AAI	0.0 ± 0.0	88.0 ± 10.5	132 ± 10.6	176 ± 14.9	244 ± 15.9	338 ± 17.5	–
BovW[d]	NB	–387 ± 135	120 ± 8.92	139 ± 19	313 ± 34.1	635 ± 32.7	794 ± 58.3	–
Val	AAI	0.0 ± 0.0	91.8 ± 45.5	218 ± 19.8	222 ± 13.8	329 ± 33.4	439 ± 42.2	553 ± 64.8
Cobb[e]	NB	–548 ± 260	–171 ± 94.9	–157 ± 134	–47.7 ± 224	346 ± 81.5	493 ± 112	761 ± 138

[a] Additional level to verify the limiting amino acid in each trial.
[b] Nitrogen balance = nitrogen intake – nitrogen excretion. Nitrogen intake includes the consumption of a N-free diet offered *ad libitum*.
[c] Bonato *et al*. (2011).
[d] Data not published.
[e] Data not published.

In order to obtain the different scales used to describe the maintenance estimates, nitrogen and amino acid intake data were transformed into their respective scales based on bird weight (actual, metabolic and protein weights). Considering that amino acids are required only for protein, and not for water, fat or mineral maintenance, body protein content (mg/$BP_m^{0.73}$ day) was considered to be the most accurate. Figures 15.1–15.4 show the graphical representation of amino acid intake as a function of *NB* and the regression equations (equation parameter ± standard deviation) on body protein scale (mg/$BP_m^{0.73}$ day).

Discussion

The results obtained in the N balance trials based on the methodology described by Nonis and Gous (2008) showed consistent data, and the scales used helped to improve the accuracy of the requirement estimates. Because maintenance is a state in which the animal is in nitrogen balance; that is, nitrogen intake is equal to the sum of nitrogen losses, thereby maintaining a constant nitrogen content in the body (Fuller *et al*., 1976), amino acids should be supplied at the same rate as which they are lost (Sakomura and Rostagno, 2007).

Table 15.4. Maintenance requirements for methionine + cystine (Met+Cys), threonine (Thr), lysine (Lys) and valine (Val) based on four scales that describe the intake of these amino acids.

Amino acid	Scale	Regression equation	R^2	Requirement estimate
Met+Cys[a]	mg/bird day	$-174\ (\pm 43.8) + 2.92\ (\pm 0.18)\ X$	0.72	59.5
	mg/BW_{kg} day	$-59.8\ (\pm 10.5) + 3.16\ (\pm 0.20)\ X$	0.83	18.9
	mg/$BW_{kg}^{0.75}$ day	$-81.4\ (\pm 14.0) + 3.20\ (\pm 0.20)\ X$	0.82	25.5
	mg/$BP_m^{0.73}$ day	$-279\ (\pm 48.0) + 3.20\ (\pm 0.20)\ X$	0.82	87.2
Thr[a]	mg/bird day	$-82.2\ (\pm 15.3) + 1.83\ (\pm 0.16)\ X$	0.45	44.9
	mg/BW_{kg} day	$-45.8\ (\pm 12.6) + 2.69\ (\pm 0.20)\ X$	0.71	17.1
	mg/$BW_{kg}^{0.75}$ day	$-54.7\ (\pm 9.70) + 2.50\ (\pm 0.20)\ X$	0.60	22.0
	mg/$BP_m^{0.73}$ day	$-191\ (\pm 59.7) + 2.53\ (\pm 0.20)\ X$	0.60	44.7
Lys	mg/bird day	$-155\ (\pm 19.9) + 3.59\ (\pm 0.21)\ X$	0.94	43.0
	mg/BW_{kg} day	$-71.6\ (\pm 9.08) + 3.54\ (\pm 0.20)\ X$	0.94	20.2
	mg/$BW_{kg}^{0.75}$ day	$-86.9\ (\pm 11.0) + 3.56\ (\pm 0.20)\ X$	0.94	24.4
	mg/$BP_m^{0.73}$ day	$-304\ (\pm 38.5) + 3.56\ (\pm 0.20)\ X$	0.94	85.4
Val	mg/bird day	$-456\ (\pm 55.7) + 2.33\ (\pm 0.20)\ X$	0.84	195
	mg/BW_{kg} day	$-105\ (\pm 11.2) + 2.27\ (\pm 0.16)\ X$	0.89	46.1
	mg/$BW_{kg}^{0.75}$ day	$-150\ (\pm 16.0) + 2.29\ (\pm 0.16)\ X$	0.89	65.4
	mg/$BP_m^{0.73}$ day	$-501\ (\pm 53.4) + 2.29\ (\pm 0.16)\ X$	0.89	219

[a] Bonato *et al.* (2011).

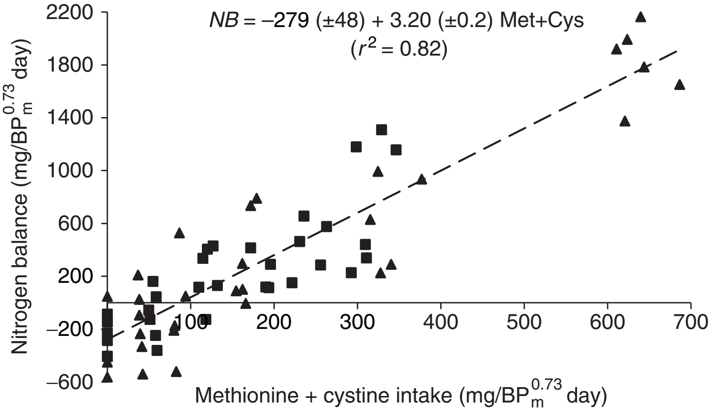


Fig. 15.1. Graphic representation of methionine + cystine intake (mg/$BP_m^{0.73}$ day) as a function of nitrogen balance in two chicken genotypes (Bovans White ▲ and Cobb ■).

The dilution technique (Fisher and Morris, 1970) was used to achieve the amino acid intake interval in each trial in order to maintain a constant ideal amino acid ratio. In order to obtain both negative and positive *NB* values in trials, requirements recommended in the literature were used. Each amino acid was tested at different intake levels. The results shown in Table 15.3 are consistent with the assumption that when amino acid intake is equal to zero, nitrogen balance is negative; the opposite is also true; that is, high amino acid intake results in positive *NB*.

The scales applied in the experiments here (Table 15.4) are commonly used when expressing maintenance requirements, and are independent of bird size. The scale mg/bird does not take into account bird weight; mg/BW_{kg} considers body weight, but not body composition; mg/$BW_{kg}^{0.75}$ also enables a comparison to be made of the requirements of birds of different sizes (mass/surface ratio) but not of different body composition. Since amino

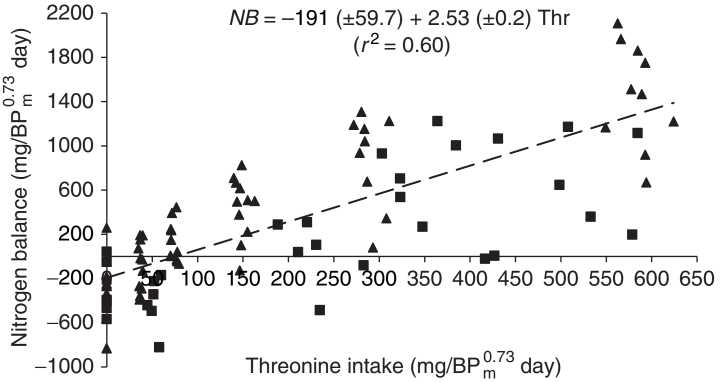


Fig. 15.2. Graphic representation of threonine intake (mg/$BP_m^{0.73}$ day) as a function of nitrogen balance in two chicken genotypes (Bovans White ▲ and Cobb ■).

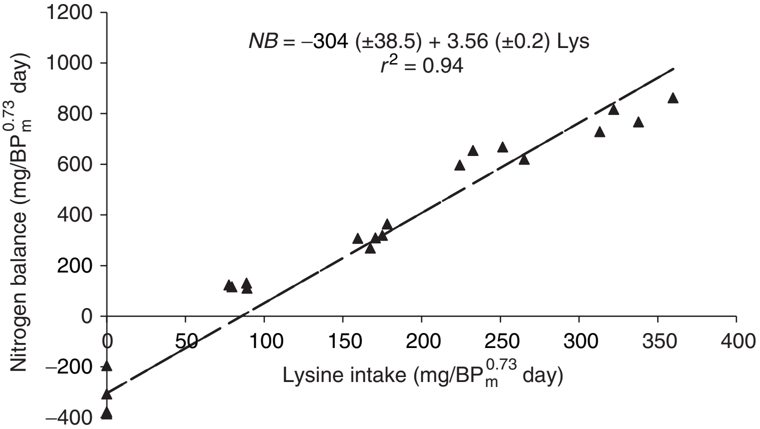


Fig. 15.3. Graphic representation of lysine intake (mg/$BP_m^{0.73}$ day) as a function of nitrogen balance (Bovans White genotype).

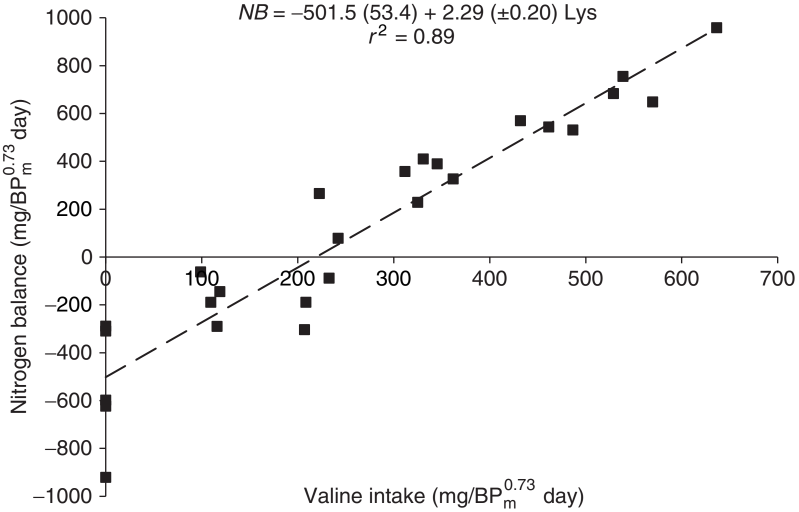


Fig. 15.4. Graphic representation of valine intake (mg/$BP_m^{0.73}$ day) as a function of nitrogen balance (Cobb genotype).

acids are not required to maintain the content of water, fat or minerals in the body (Emmans and Oldham, 1988) the scale mg/$BP_m^{0.73}$ day, which accounts for metabolic protein weight, is the preferred scale for expressing maintenance requirements for amino acids.

Leveille and Fisher (1959) proposed that the requirements of an adult animal are largely determined by the composition of the synthesized tissue, and in the case of roosters, by feather synthesis. It was shown that lysine, threonine, methionine + cystine and valine fit this hypothesis, although the valine requirement level is lower than its content in feathers (Leveille and Fisher, 1958, 1959, 1960; Leveille *et al.*, 1960). Feathers are important body structures that provide body insulation, reduce energy maintenance requirements and prevent skin abrasions and infections (Urdaneta-Rincon and Leeson, 2004). Feather synthesis evidently is not the only factor influencing maintenance requirements of adult roosters, but it is probably very important. Maintenance requirements are also determined by the replacement of endogenous body losses under non-stressful conditions (Mitchell, 1962).

Methionine is an important donor of methyl groups required for the biosynthesis of many essential body compounds (Baker, 1991) and it supplies cystine needs (Graber and Baker, 1971). Cystine plays a special role in keratin synthesis, and therefore is related to feathering (Baker, 1991). Although some studies have considered only methionine requirements, cystine must also be taken into account. The presence of cystine in the diet (42 mg/kg day) reduced the methionine requirement for maintenance by approximately 0.20 (Leveille *et al.*, 1960). In addition, cystine supply helps to reduce endogenous catabolism when the body searches feather follicles for cystine, even to the extent of degrading other tissue proteins (Mitchell, 1962). Therefore, both methionine and cystine deficiencies may impair feathering (Deschutter and Leeson, 1986) because sulphur amino acid content is higher in feathers when compared with muscle protein. Estimates of the sulphur amino acid requirement for maintenance reported in the literature range between 6.62 and 142 mg/kg day (Leveille *et al.*, 1960; Owens *et al.*, 1985; Kim *et al.*, 1997b; Edwards and Baker, 1999). This wide variation may be explained by differences in methodologies, bird age and scale. According to Bonato *et al.* (2011), a single dataset of Met+Cys results from experiments with roosters belonging to different genotypes was used (Table 15.3, 15.4 and Fig. 15.1). The estimated Met+Cys requirement of 18.9 mg/kg day obtained is consistent with the minimum maintenance requirement determined by Leveille *et al.* (1960) of 15 mg/kg day. The small difference may be attributed to a relatively lower cystine content in the experimental diet.

On the other hand, Lys maintenance requirement is lower in adult roosters than in growing chickens because Lys is directed mainly to muscle accretion and not to feather protein synthesis. According to Urdaneta-Rincon and Leeson (2004), feathering is not affected by dietary Lys levels. Dietary lysine deficiencies are more likely to affect body protein than feather development. Therefore, it may be assumed that the largest fraction of Lys maintenance requirement is caused by endogenous protein losses in mature birds (Jansmann *et al.*, 2002). The Lys requirement estimated in this study with Cobb roosters is lower than that found in other studies (Leveille and Fisher, 1958; Edwards *et al.*, 1999; Sakomura and Coon, 2003; Nonis and Gous, 2008; Siqueira *et al.*, 2011), which ranged between 29 mg/kg day and 168 mg/kg day. Although the Lys requirement estimated in the present study was very low (20 mg/kg day) Leveille and Fisher (1958) obtained a Lys requirement of 29 mg/kg day and showed no further improvement in nitrogen retention at higher lysine intake levels in roosters. Although Burroughs *et al.* (1940) proposed that Lys was not essential for the maintenance of nitrogen balance in rats, Leveille and Fisher (1958) showed it to be essential for adult roosters, as found in the present study.

Threonine, as with Lys, is essential for body protein deposition. However, the maintenance requirement for Thr is mainly used to maintain gut integrity (Ball *et al.*, 1999) and immunity (Corzo *et al.*, 2007).

When the gut is exposed to health challenges, Thr requirement increases due to higher mucin secretion (Bequette, 2003) and stimulation of immune functions (Corzo *et al.*, 2007). Threonine requirements reported in the literature range between 5.33 mg/kg day and 56 mg/kg day (Leveille and Fisher, 1960; Edwards *et al.*, 1997; Bae *et al.*, 1999a; Nonis and Gous, 2008). In addition to immune challenges, age, genotype, methodology and environment factors may account for this variation. The same dataset obtained in the Thr assays carried out by Bonato *et al.* (2011) was also used here to estimate requirements (Table 15.3 and 15.4, and Fig. 15.2). Threonine requirement to obtain zero nitrogen body retention was estimated as 17.1 mg/BW_{kg} day, which is much lower than the minimum maintenance requirement of 55 mg/BW_{kg} day determined by Leveille *et al.* (1960) and of 56 mg/BW_{kg} day determined by Nonis and Gous (2008). Possible explanations for this result are the low health challenge promoted by the metabolic-cage environment and low abrasion caused by the experimental diets in the gut.

Valine is potentially limiting in corn and soybean meal-based diets, which may become evident at older ages when dietary protein content decreases (Corzo *et al.*, 2004). Corn protein contains relatively low valine and isoleucine and high leucine levels (Corzo *et al.*, 2004). The structure of these amino acids is very similar; that is, they are branched-chain amino acids (BCAAs) and there is an antagonism between them (Allen and Baker, 1972; Farran and Thomas, 1990; Bae *et al.*, 1999b). This suggests that maintenance requirements for Val are probably not constant and are influenced by its ratio to the other BCAAs in the diet (Bae *et al.*, 1999b). Therefore, leucine and isoleucine requirements should also be taken into account when determining Val requirements. Inadequate dietary Val impairs body weight gain and feed conversion and causes feather abnormalities in broilers (Farran and Thomas, 1992). The valine requirement obtained in the present study is higher (46.1 mg/BW_{kg} day) than the other evaluated amino acids. This may be explained by the importance of maintaining feather synthesis in adult roosters, because the small weight changes (less than 0.05) observed can be attributed to water balance changes and to feather loss (Leveille and Fisher, 1959). The Val requirement determined here is consistent with literature reports, although slightly lower than the minimum maintenance requirement of 55 mg/BW_{kg} day determined by Leveille *et al.* (1960).

As mentioned above, it is difficult to compare studies when different scales are used to express maintenance requirements for amino acids. Nonis and Gous (2008), studying Lys and Thr and working with the same methodology applied in the present study, found higher Lys requirements compared with other studies, and attributed this result to the fact that excreta were collected directly from trays, because the faeces in the trays below the cages are exposed to nitrogen-rich feather residues. However, the results of the present study indicate that excreta collection technique apparently had no influence on the estimated requirements.

The objective of the experiments carried out in the present study was to estimate the maintenance requirements of most essential amino acids in order to apply effective models for the precision feeding of chickens of different ages and genotypes. These maintenance requirements may be used in factorial approaches to determine general requirements, such as the Reading Model (Fisher *et al.*, 1973), or to calculate the maintenance coefficients for broiler breeders (Bowmaker and Gous, 1991). Emmans (1989) calculated amino acid requirements in ideal protein for maintenance (PIM), where the amino acid requirement, expressed per $BP_m^{0.73}\ u$, is divided by eight (assuming that roosters need 8 g of protein with adequate composition to supply their maintenance requirements). From the results of the studies reported here, the concentrations of Met+Cys, Thr, Lys and Val in ideal body protein for maintenance are 10.9 g/kg, 5.59 g/kg, 10.7 g/kg and 27.4 g/kg, respectively.

The daily intake of each amino acid required for maintenance increases proportionately as the bird grows, and even during the reproductive phase the amount required for maintenance is a large proportion of the total required. An accurate estimate of the maintenance requirement of both growing and adult chickens is a necessity when calculating the daily amount of amino acids required by these birds at any stage of life. Therefore, a standardized and reliable methodology should be used that takes into consideration bird age, diet formulation and an appropriate scale used to express the amino acid requirement for maintenance. The methodology used in the trials reported here hopefully provides a more considered theoretical and methodological basis for measuring maintenance requirements of poultry for amino acids.

Acknowledgements

The authors wish to thank Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP) for funding this study.

References

Allen, N.K. and Baker, D.H. (1972) Effect of excessive lysine on the utilization and requirement for arginine by the chick. *Poultry Science* 51, 902.

Armsby, H.P. and Moulton, C.R. (1925) *The Animal as a Converter of Matter and Energy*. The Chemical Catalog Co. Inc., New York.

Association of Official Analytical Chemists (1990). *Official Methods of Analysis*, 15th edn, AOAC, Washington, DC.

Bae, S.H., Kim, J.H., Shin, I.S. and Han, K.I. (1999a) Partition of amino acids requirement of broilers between maintenance and growth. IV. Threonine and glycine. *Asian-Australian Journal of Animal Science* 12, 381–387.

Bae, S.H., Kim, J.H., Shin, I.S. and Han, K.I. (1999b) Partition of amino acids requirement of broilers between maintenance and growth. V. Isoleucine and valine. *Asian-Australian Journal of Animal Science* 3, 388–394.

Baker, D.H. (1991) Partitioning of nutrients for growth and other metabolic functions: efficiency and priority considerations. *Poultry Science* 70, 1797–1805.

Ball, R.O., Law, G., Betolo, R.F.P. and Pencharz, P.B. (1999). Adequate oral threonine is critical for mucin production and mucosal growth by neonatal piglet gut. In: Lobley, G.E., White, A. and Macrae, J.C. (eds) *Proceedings of the VIIIth International Symposium on Protein Metabolism and Nutrition*, EAAP Publication (96). Wageningen, The Netherlands, pp. 31.

Bequette, B.J. (2003) Amino acid metabolism in animals: an overview. In: D'Mello, J.F.P. (ed.) *Absorption and Utilization of Amino Acids*. CAB International, Wallingford, UK, pp. 87–102.

Bonato, M.A., Sakomura, N.K., Siqueira, J.C., Fernandes, J.B.K. and Gous, R.M. (2011) Maintenance requirements for methionine and cysteine, and threonine for poultry. *South African Journal of Animal Science* 41, 209–222.

Bowmaker, J.E. and Gous, R.M. (1991) The response of broiler breeder hens to dietary lysine and methionine. *British Poultry Science* 32, 1069–1088.

Brody, S. (1945) *Bioenergetics and Growth*. Reinhold Publishing Corporation, New York, USA.

Burnham, D. and Gous, R.M. (1992) Isoleucine requirements of the chicken: requirement for maintenance. *British Poultry Science* 33, 59–69.

Burroughs, E.W., Burroughs, H.S. and Mitchell, H.H. (1940) The interdependence among amino acids in their utilization in the endogenous metabolism. *Journal of Nutrition* 19, 385–391.

Corzo, A., Moran, E.T. Jr and Hoehler, D. (2004) Valine needs of male broilers from 42 to 56 days of age. *Poultry Science* 83, 946–951.

Corzo, A., Kidd, M.T. and Dozier, W.A. III (2007). Dietary threonine needs for growth and immunity of broilers raised under different litter conditions. *Journal of Applied Poultry Research* 16, 574–582.

Deschutter, A. and Leeson, S. (1986) Feather growth and development. *World's Poultry Science Journal* 42, 259–267.

Edwards, H.M and Baker, D. (1999) Maintenance sulfur amino acid requirements of young chicks and efficiency of their use for accretion of whole-body sulfur amino acids and protein. *Poultry Science* 78, 1418–1423.

Edwards, H.M., Baker, D.H., Fernandez, S.R. and Parsons, C.M. (1997) Maintenance threonine requirement and efficiency of its use for accretion of whole-body threonine and protein in young chicks. *British Journal of Nutrition* 78, 111–119.

Edwards, H.M., Fernandez, S.R. and Baker, D.H. (1999) Maintenance lysine requirement and efficiency of using lysine for accretion of whole-body lysine and protein in young chicks. *Poultry Science* 78, 1412–1417.

Emmans, G.C. (1989) The growth of turkeys. In: Nixey, C. and Grey, T.C. (eds) *Recent Advances in Turkey Science*. Poultry Science Symposium, Butterworths, London, pp. 135–166.

Emmans, G.C. and Fisher, C. (1986) Problems in nutritional theory. In: Fisher, C. and Boorman, K.N. (eds) *Nutrient Requirements of Poultry and Nutritional Research*. Butterworths, London, pp. 9–39.

Emmans, G.C. and Oldham, J.D. (1988) Modelling of growth and nutrition in different species. In: Korver, S. and Van Arendonk, J.A.M. (eds) *Modelling of Livestock Production Systems*. Kluwer Academic Publishers, Amsterdam, pp. 13–21.

Farran, M.T. and Thomas, O.P. (1990) Dietary requirements of leucine, isoleucine and valine in male broilers during the starter period. *Poultry Science* 69, 757.

Farran, M.T. and Thomas, O.P. (1992) Valine deficiency. 1. The effect of feeding a valine-deficient diet during the starter period on performance and feather structure of male broiler chicks. *Poultry Science* 71, 1879–1884.

Fisher, C. (1994) Responses of laying hens to amino acids. In: J.P.F. D'Mello (ed.) *Amino Acids in Farm Animal Nutrition*. CAB International, Wallingford, UK, pp. 245–279.

Fisher, C. and Morris, T.R. (1970) The determination of the methionine requirements of laying pullets by a diet dilution technique. *British Poultry Science* 11, 67–82.

Fisher, C., Morris, T.R. and Jennings, R.J. (1973) A model for the description and prediction of the response of laying hens to amino acid intake. *British Poultry Science* 14, 469–484.

Fuller, M.F., Webster, A.J.F., Macpherson, R.M. and Smith, J.S. (1976) Comparative aspects of the energy metabolism of Pietrain and Large White X Landrace pigs during growth. In: Vermorel, M. (ed.) *Energy Metabolism of Farm Animals*. European Association for Animal Production Publication, 19. G. Bussac, Clermont-Ferrand, France, pp. 177–180.

Gous, R.M. (1986) Measurement of response in nutritional experiments. In: Fisher C. and Boorman N.K. (eds) *Proceedings of Nutrient Requirements of Poultry and Nutritional Research*. British Poultry Science Symposium, Butterworths, London, pp. 41–57.

Gous, R.M., Fisher, C. and Broadbent, L.A. (1984) Measurement of the amino acid requirement for maintenance of adult cockerels. *Proceedings of XVII World's Poultry Congress*, Helsinki, Finland.

Graber, G. and Baker, D.H. (1971). Sulfur amino acid nutrition of the growing chick: quantitative aspects concerning the efficacy of dietary methionine, cysteine and cystine. *Journal of Animal Science* 33, 1005–1011.

Hurwitz, S., Sklan, D. and Bartov, I. (1978) New formal approaches to determination of energy and amino acid requirements of chickens. *Poultry Science* 57, 197–205.

Jansmann, A.J.M., Smink, W., van Leeuwen, P. and Rademacher, M. (2002) Evaluation through literature data of the amount and amino acid composition of basal endogenous crude protein at the terminal ileum of pigs. *Animal Feed Science Technology* 98, 49–60.

Kaps, M. and Lamberson, W.R. (2004) *Biostatistics for Animal Science*. CAB Internatioanl, Wallingford, UK.

Kim, J.H., Cho, W.T., Yang, C.J., Shin, I.S. and Han, K.I. (1997a) Partition of amino acids requirement for maintenance and growth of broilers. I. Lysine. *Asian-Australian Journal of Animal Science* 10, 178.

Kim, J.H., Cho, W.T., Yang, C.J., Shin, I.S. and Han, K.I. (1997b) Partition of amino acids requirement for maintenance and growth of broilers. II. Methionine. *Asian-Australian Journal of Animal Science* 10, 277.

Kim, J.H., Cho, W.T., Yang, C.J., Shin, I.S. and Han, K.I. (1997c) Partition of amino acids requirement for maintenance and growth of broilers. III. Tryptophan. *Asian-Australian Journal of Animal Science* 10, 284.

King, R.D. (2001) Description of a growth simulation model for predicting the effect of diet on broiler composition and growth. *Poultry Science* 80, 245–253.

Leveille, G.A. and Fisher, H. (1958) The amino acid requirements for maintenance in the adult rooster. *The Journal of Nutrition* 66, 441–452.

Leveille, G.A. and Fisher, H. (1959) Amino acid requirements for maintenance in the adult rooster. II. The requirements for glutamic acid, histidine, lysine and arginine. *The Journal of Nutrition* 69, 289–294.

Leveille, G.A. and Fisher, H. (1960) Amino acid requirements for maintenance in the adult rooster. III. The requirements for leucine, isoleucine, valine and threonine, with reference also to the utilization of the d-isomers of valine, threonine and isoleucine. *The Journal of Nutrition* 70, 135–140.

Leveille, G.A., Shapiro, R. and Fisher, H. (1960) Amino acid requirements for maintenance in the adult rooster. IV. The requirements for methionine, cystine, phenylalanine, tyrosine and tryptophan: the adequacy of the determined requirements. *Journal of Nutrition* 72, 8–15.

Liebert, F. (2008) Modelling of protein metabolism yields amino acid requirements dependent on dietary amino acid efficiency growth response, genotype and age of growing chicken. *Avian Biology Research*, 1(3), 101–110.

McDonald, M.W. and Morris, T.R. (1975) Quantitative review of optimum amino acid intakes for young laying pullets. *British Poultry Science* 26, 253–264.

Mitchell, H.H. (1962) *Comparative Nutrition of Man and Domestic Animals*. Academic Press, New York.

Moughan, P.J. (2003) Simulating the partitioning of dietary amino acids: new directions. *Journal of Animal Science* 81, 60–67.

Nonis, M.K. and Gous, R.M. (2008) Threonine and lysine requirements for maintenance in chickens. *South African Journal of Animal Science* 38, 75–82.

Owens, F.N. and Pettigrew, J.E. (1989) Subdividing amino acid requirements into portions for maintenance and growth. In: Friedman, M. (ed.) *Absorption and Utilization of Amino Acids*. CRC Press, Boca Raton, Florida, USA, pp. 15–30.

Owens, F.N., Pettigrew, J.E., Cornelius, S.G. and Moser, R.L. (1985) Amino acid requirements for growth and maintenance of rats and chicks. *Journal of Animal Science* 61, 312.

Rostagno, H.S., Albino, L.F.T., Donzele, J.L., Gomes, P.C., Oliveira, R.F.M., Lopes, D.C., Ferreira, A.S. and Barreto, S.L.T. (2005) *Tabelas brasileiras para aves e suínos: composição de alimentos e exigências nutricionais*. 2nd edn. Universidade Federal de Viçosa, Viçosa, Minas Gerais, Brazil.

Rostagno, H.S., Albino, L.F.T., Donzele, J.L., Gomes, P.C., Oliveira, R.F.M., Lopes, D.C., Ferreira, A.S., Barreto, S.L.T. and Euclides, R.F. (2011) *Tabelas brasileiras para aves e suínos: composição de alimentos e exigências nutricionais*. 3rd edn. Universidade Federal de Viçosa, Viçosa, Minas Gerais, Brazil.

Sakomura, N.K. and Coon, C. (2003) Amino acid requirements for maintenance of broiler breeder pullets. *Proceedings of European Symposium on Poultry Nutrition*, Lillehammer, Norway, pp. 280–281.

Sakomura, N.K. and Rostagno, H.S. (2007) *Métodos de pesquisa em nutrição de monogástricos*. Funep, Jaboticabal, São Paulo, Brazil.

Samadi and Liebert, F. (2006a) Estimation of nitrogen maintenance requirements and potential for nitrogen deposition in fast-growing chickens depending on age and sex. *Poultry Science* 85, 1421–1429.

Samadi and Liebert, F. (2006b) Modelling threonine requirement depending on age, protein deposition, dietary threonine efficiency and sex of fast growing chickens. *Poultry Science* 85, 1961–1968.

Samadi and Liebert, F. (2007a) Lysine requirement of fast growing chickens: effects of age, sex, level of protein deposition and dietary lysine efficiency. *The Journal of Poultry Science* 44, 63–72.

Samadi and Liebert, F. (2007b) Threonine requirement of slow growing male chickens depends on age and dietary efficiency of threonine utilization. *Poultry Science*, 86, 1140–1148.

Samadi and Liebert, F. (2008) Modelling the optimal lysine to threonine ratio in growing chickens depending on age and efficiency of dietary amino acid utilization. *British Poultry Science* 49, 45–54.

Sibbald, I.R. (1976) A bioassay for true metabolizable energy in feeding stuffs. *Poultry Science* 55, 303–308.

Siqueira, J.C. (2009) Estimativas das exigências de lisina de frangos de corte pelos métodos dose resposta e fatorial. Universidade Estadual Paulista Júlio de Mesquita Filho, Faculdade de Ciências Agrárias e Veterinárias de Jaboticabal, Jaboticabal, São Paulo, Brazil.

Siqueira, J.C., Sakomura, N.K., Rostagno, H.S., Bonato, M.A., Pinheiro, S.R.F. and Nascimento, D.C.N. (2011) Exigência de lisina para mantença determinada com galos de diferentes genótipos. *Revista Brasileira de Zootecnia* 40, 812–820.

Taylor, St C.S. and Young, G.B. (1968) Equilibrium weight in relation to food intake and genotype in twin cattle. *Animal Production* 10, 393–412.

Urdaneta-Rincon, M. and Leeson, S. (2004) Effect of dietary crude protein and lysine on feather growth in chicks to twenty-one days of age. *Poultry Science* 83, 1713–1717.

16 A Model to Estimate the Amino Acid Requirements for Growth and Sexual Development in Laying Pullets

E.P. Silva,[1] N.K. Sakomura,* L. Hauschild[1] and R.M. Gous[2]
[1]*Universidade Estadual Paulista, Jaboticabal, São Paulo Brazil;* [2]*University of KwaZulu-Natal, Pietermaritzburg, South Africa*

Abstract

Growth in a laying pullet prior to sexual maturity can be partitioned into three components: feathers, the feather-free body and reproductive organs. This study aimed to describe the growth of the feathers, the feather-free body, the reproductive organs and the liver of Dekalb White hens for integration into a model to determine the daily requirements for lysine (Lys), methionine + cystine (Met+Cys) and threonine (Thr) of a pullet from 1 day old to sexual maturity. Measurements of feather- and feather-free body protein and, from 15 weeks of age, the ovary, oviduct and liver, were used to describe the growth of these components using the Gompertz equation. Using the rates of amino acid deposition in each of the components and assumed efficiencies of utilization of dietary amino acids, the daily amounts of Lys, Met+Cys and Thr required to sustain this potential growth were calculated. The resultant factorial model facilitates a more accurate estimate of the daily requirements of growing pullets for Lys, Met+Cys and Thr based on the growth phase and sexual maturation.

Introduction

Animal growth has long been the subject of research interest. Early studies (Robertson, 1916; Brody, 1921) suggested that growth occurs in different cycles during the development phase. For birds, three or four cycles of growth were described, the last of which occurred at approximately 24 weeks (Brody, 1921). These findings substantiate the multiphase growth approach. Grossman and Koops (1988) have described the growth of laying hens in three stages: the first stage of growth accounts for 0.80 of growth, the second for 0.18 and the third for 0.02.

Kwakkel *et al.* (1993) applied a model divided into three, four and five phases and observed the best fits with the use of four and five phases. In their four-phase model, 0.69, 0.13, 0.10 and 0.08 of growth occurred in the first, second, third and fourth phases, respectively, while in their five-stage model, the first two phases were similar to those in the four-phase model, while the third, fourth and fifth phases represented 0.11, 0.03 and 0.04 of growth, respectively. The increase in the number of phases implies a higher degree of growth compartmentalization. According to Kwakkel *et al.* (1993) the essential growth of the bird (muscles and vital organs) occurs in

---

*E-mail: sakomura@fcav.unesp.br

Nutritional Modelling for Pigs and Poultry
(eds N.K. Sakomura *et al.*)

the first two phases. The third phase is associated with the growth of the organs involved in sexual maturation and in the fourth phase, weight gain is related to body fat deposition.

The combined effects of genotype and environment can affect the number of phases and generate a few common assumptions that justify the need to use multiple phases to describe growth (Grossman and Koops, 1988; Kwakkel *et al.*, 1993, 1995).

Protein growth in a laying pullet can be partitioned into three compartments, namely feather, feather-free body (Emmans, 1989) and reproductive organs (Bowmaker and Gous, 1989) based on differences in the growth rates of each component, which are specific to each genotype. The resultant growth is the sum of these components.

The aim of this study was to describe the growth of feathers, feather-free body, reproductive organs and liver of Dekalb White laying pullets from 1 day old to sexual maturity for integration into a model to determine the daily requirements for lysine (Lys), methionine + cystine (Met+Cys) and threonine (Thr) of a pullet during growth.

Materials and Methods

The studies were conducted in the Laboratory of Poultry Science, Faculty of Agriculture and Veterinary Sciences, UNESP-Jaboticabal, São Paulo, Brazil.

Description of growth

Dekalb White pullets were weighed and sampled at 0, 14, 28, 56, 70, 98 and 112 days of age in order to determine the weights of feather- and feather-free protein at those ages. Weighing and sampling of the ovary, oviduct and liver took place at 105, 112, 119, 126, 133, 140, 147 and 154 days. The Gompertz (1825) equation (Eqn 16.1) was fitted to these data to determine the potential rates of growth of these components:

$$Pt = Pm \times e^{-e^{-B \times t - t^*}} \qquad (16.1)$$

The parameters estimated for each component were: *Pm*, protein weight at maturity (kg); *B*, rate of maturing (in days); and *t**, the age at maximum growth rate (days), where *Pt* is weight at time *t* (kg), *t* is the bird's age (days) and *e* is Euler's number.

Feather protein weight (*FP*) was corrected for the loss of feathers occurring between sampling periods. This correction consisted of adding feather protein loss to the observed weights. Feather protein loss was defined as 0.04 g/day (Silva, 2012). The corrected feather protein weight (FP_C) was applied to Eqn 16.1 to estimate the corrected growth parameters.

The rate of protein deposition (*PD*) (g/day) of each component was calculated using Eqn 16.2:

$$PD = B \times Pt \times \ln (Pm/Pt) \qquad (16.2)$$

Where ln is the natural log. Given *B*, *Pm* and *e*, the maximum protein deposition (*PDmax*) was calculated in g/day: $PDmax = B \times Pm/e$.

The rates of deposition of Lys, Met+Cys and Thr in each component were obtained by multiplying *PD* by their corresponding amino acid contents in the feather and feather-free protein. The same amino acid composition that was used for the feather-free body was used for the ovary, oviduct and liver.

Description of the model for determining amino acid requirements

To estimate the daily Lys, Met+Cys and Thr requirements for potential protein growth the factorial model of Martin *et al.* (1994) was used, to which was added the growth of ovary, oviduct and liver from 15 weeks of age. The amino acid requirements were established separately by considering the rates of amino acid depositions of five components (feathers, feather-free body, ovary, oviduct and liver) and the efficiency of amino acid utilization. The maintenance requirements of feather and feather-free body protein were also considered in the model. The model is described by Eqn 16.3:

$$AAI = [(AAm_c \times BPm^{0.73} \times u) + (FPL \times FP \times AA_f)] + [(AA_c \times PD_c)/k + (AA_f \times PD_f)/k + AA_c \times (PD_{Ova} + PD_{Ovi} + PD_{Liv})/k] \quad (16.3)$$

Where AAI is the digestible amino acid requirement (mg/day); AAm_c is the amino acid requirement for the maintenance of feather-free body protein (mg × $BPm^{0.73}$ × u); $BPm^{0.73}$ is the metabolic body protein weight at maturity (kg); u is the degree of maturity of feather-free body protein ($u = BPt/BPm$); FPL is the feather protein loss (0.04 g/day); FP or FPc is the feather protein weight (g/day); AAf is the amino acid content of feather protein (mg/g); AA_c is the amino acid content of feather-free body protein (mg/g); PD_c is the rate of deposition of feather-free body (g/day); PD_f is the rate of protein deposition in the feathers (g/day); PD_{Ova} is the rate of protein deposition in the ovary (g/day); PD_{Ovi} is the rate of protein deposition in the oviduct (g/day); PD_{Liv} is the rate of protein deposition in the liver (g/day); and k is the efficiency of utilization of amino acid for protein deposition.

Laying hens lose a significant amount of feathers during growth (Silva, 2012). The daily loss of feathers may be regarded as the maintenance requirement for feathers, as suggested by Emmans (1989). The amino acid composition for feather protein maintenance was considered to be equal to its concentration in feather protein.

Coefficients for calculating the maintenance requirements of the feather-free body for Lys, Met+Cys and Thr were obtained from studies conducted at UNESP-Jaboticabal. The Lys requirement was calculated as 174 mg × $BPm^{0.73}$ × u (Siqueira *et al.*, 2011), the coefficient for Met+Cys requirement was 93.5 and for Thr, 44.7 (Bonato *et al.*, 2011).

The coefficient used to describe the efficiency of utilization of Lys (k_{Lys}), Met+Cys ($k_{Met+Cys}$) and Thr (k_{Thr}) was 0.80 for all three amino acids.

The contents of Lys, Met+Cys and Thr in feathers and in the feather-free body were measured by Silva (2012) to be 18.7 mg/g, 89.2 mg/g and 44.3 mg/g protein, respectively, in feathers (AA_f) and 67.8 mg/g, 33.3 mg/g and 40.4 mg/g, respectively, in the feather-free body (AA_c).

Estimating the requirements

The Lys, Met+Cys and Thr requirements were estimated by applying the parameters for Dekalb White hens using the Martin *et al.* (1994) model (Model 1) and then making corrections for feather growth and the inclusion of organs (Model 2).

Model 1: based on Martin *et al.* (1994) (M1):

$$AAI = [(AAm_c \times BPm^{0.73} \times u) + (FPL \times FP \times AA_f)] + [(AA_c \times PD_c)/k + (AA_f \times PD_f)/k] \quad (16.4)$$

Model 2: corrected for feather loss and the growth of reproductive organs and liver (M2):

$$AAI = [(AAm_c \times BPm^{0.73} \times u) + (FPL \times FP \times AA_f)] + [(AA_c \times PD_c)/k + (AA_f \times PD_f)/k + AA_c \times (PD_{Ova} + PD_{Ovi} + PD_{Liv})/k] \quad (16.5)$$

Results

Description of the growth parameters

The growth parameters for the protein weights of feathers, feather-free body and ovary, oviduct and liver of Dekalb White hens are given in Table 16.1. At maturity (Pm) the total protein weight of the bird was 382 g. Of this, 0.57 corresponded to the feather-free body, 0.35 to feathers, 0.03 to the ovary, 0.03 to the oviduct and 0.02 to the liver.

The correction for feather loss applied to the observed weights resulted in a 4% increase in the protein weight of feathers (PFm; Table 16.1). This correction enabled an approximation to be made of the real feather weight, which is of considerable importance when determining the amount of each amino acid required for the growth of feathers, especially cystine.

Table 16.1. Mean weights of feather-free body protein (*BP*), feather protein (*FP* and *FPc*), ovary, oviduct and liver, and parameters of the Gompertz equation for Dekalb White hens.

Age (weeks)	*BP* (g)	*FP* (g)	*FPc* (g)	Ovary (g)	Oviduct (g)	Liver (g)
0	5	2	2			
2	14	7	8			
4	31	17	17			
6	55	28	29			
8	66	25	26			
10	103	58	61			
12	137	68	71			
14	136	85	88			
15				0	0	4.1
16	162	102	106	0.2	0.2	4.4
17				2	3	4.6
18				5	7	4.8
19				7	9	5.1
20				9	10	5.3
21				10	10.4	5.5
22				10.3	10.4	5.7
Gompertz equation parameter values						
Pm (g)	220	127	133	10.6	10.4	8.2
B (per day)d	0.024	0.023	0.023	0.111	0.176	0.013
*t** (day)	55.0	63.0	63.5	124	120	77

Pm, weight at maturity; *B*, rate of maturing; *t**, age at maximum growth rate; *FP*, without correction for feather loss; *FPc*, with correction for feather loss.

Based on the parameter *t** in the Gompertz equation (Table 16.1) the maximum growth of the different components occurred at: feathers, 63 days; feather-free body, 55 days; ovary, 124 days; and oviduct, 120 days. *PDmax* was 1.08 g/day, 1.94 g/day, 0.43 g/day, 0.68 g/day and 0.04 g/day for the five components, respectively, these being achieved at the following approximate degrees of maturity (*u*): 0.43, 0.37, 0.82, 0.81 and 0.55, respectively.

The rate of maturing, *B* (Table 16.1), determined for feathers, feather-free body and ovary, oviduct and liver showed that feathers grew at a rate similar to that of the feather-free body, while the ovary and oviduct matured 4.6 to 7.3 times faster than the feather-free body. The rate of maturing of the liver corresponds to half that of the feather-free body.

Using the parameters *Pm* and *B* shown in Table 16.1, *PD* was calculated for each component and summed to obtain the total *PD* for each component. The proportion of *PD* for each component over the growing period in relation to the total amount deposited is shown in Fig. 16.1.

The total *PD* to 15 weeks corresponded to the sum of the *PD* of feather-free body and feather protein. At the end of the first week the proportion of feather-free body protein and feather protein corresponded to 0.74 and 0.25, respectively, of the bird's total *PD*. The proportion of feather protein (*pFP*) in the total *PD* increased linearly ($pFP = 0.01064 \times Age_{(week)} + 0.255$) to 15 weeks at a rate close to 0.0011 per week; reciprocally, the proportion of feather-free body protein (*pBP*) decreased.

Between 15 and 17 weeks, *pBP* and *pFP* decreased linearly by approximately 12% and 75% per week; however, during the same period, the proportion of protein in the oviduct (*pPOvi*) and ovary (*pPOva*) increased by 12.8% and 70%, respectively. Between 17 and 18 weeks of age 55% of the total *PD* was due to the growth of the oviduct (25% the *pPOvi*) and ovary (20% the *pPOva*).

The increase in the proportion of liver protein (*pPLiv*) during the growth peak in the sexual maturity phase is less representative when the factors are analysed together, but an analysis of the isolated organ is shown in Fig. 16.2. A separate approach reveals that after the maximum growth rate of the ovary and oviduct, there was an increase in *pPLiv* from the 18th week, according to the broken line equation: $pPLiv\%=1.46 - 0.45 \times (18 - Age_{(weeks)})$ for $Age > 18$th week, when $Age \geq 15$th and ≤ 18th, $pPLiv = 1.46$.

Models used to estimate amino acid requirements

Considering the growth parameters and coefficients obtained, the models for Lys, Met+Cys and Thr are presented below:

For Lys:

$$\begin{aligned} AAI = {} & [(173 \times BPm^{0.73} \times u) \\ & + (0.04 \times FP \times 18.7)] \\ & + [(67.8 \times PD_c)/0.8 \\ & + (18.7 \times PD_f)/0.8 + 67.8 \\ & \times (PD_{Ova} + PD_{Ovi} + PD_{Liv})/0.8] \quad (16.6) \end{aligned}$$

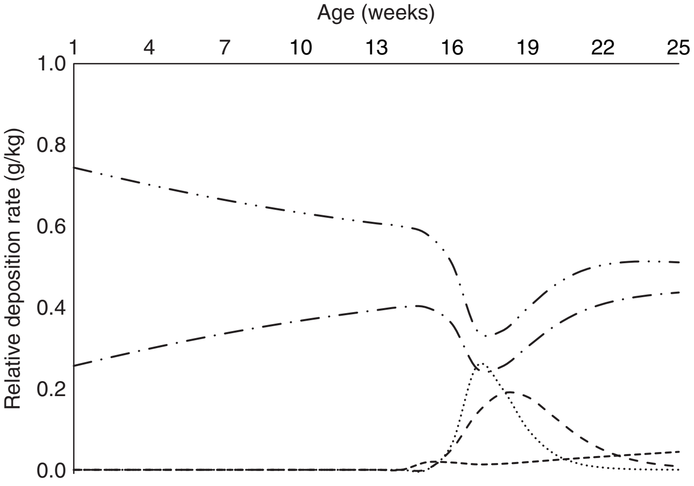


Fig. 16.1. Rate of protein deposition in each of the protein components of the body over time relative to the total amount deposited. Feather-free body —··—·; feathers —·—·–; ovary -----; oviduct ·············; and liver ------.

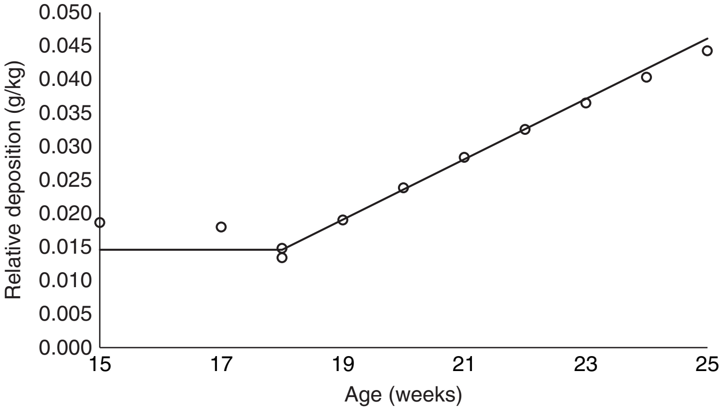


Fig. 16.2. Protein deposition in the liver as a proportion (g/kg) of the total amount deposited in the body (feather-free body + feathers + ovary + oviduct + liver). Observed values ○○○○○; predicted values ——.

For Met+Cys:

$$AAI = [(93.5 \times BPm^{0.73} \times u) + (0.04 \times FP \times 89.2)] + [(33.3 \times PD_c)/0.8 + (89.2 \times PD_f)/0.8 + 33.3 \times (PD_{Ova} + PD_{Ovi} + PD_{Liv})/0.8] \quad (16.7)$$

For Thr:

$$AAI = [(44.7 \times BPm^{0.73} \times u) + (0.04 \times FP \times 44.3)] + [(40.4 \times PD_c)/0.8 + (44.3 \times PD_f)/0.8 + 40.4 \times (PD_{Ova} + PD_{Ovi} + PD_{Liv})/0.8] \quad (16.8)$$

Where AAI is the digestible amino acid requirement (mg/day); 173, 93.5 and 44.7 are the respective Lys, Met+Cys and Thr requirements for maintaining the feather-free protein body weight; BPm is the protein weight of the feather-free body at maturity (kg), u is the degree of maturity of the feather-free body protein ($u = BPt/BPm$); 0.04 is the protein loss of the feathers (0.04 g/day); FP or FPc is feather protein weight (g/day); 18.7, 89.2 and 44.3 mg/g are the respective Lys, Met+Cys and Thr contents in the feather protein; 67.8 mg/g, 33.3 mg/g and 40.4 mg/g are the respective Lys, Met+Cys and Thr contents in the protein of the feather-free body; PD_c, PD_f, PD_{Ova}, PD_{Ovi} and PD_{Liv} are the respective protein depositions of the feather-free body, feathers, ovary, oviduct and liver (g/day); and 0.8 is the efficiency of amino acid utilization for protein deposition.

Models for determining requirements

The factorial model described estimates the intake of Lys, Met+Cys and Thr required to maintain the feather-free body protein, to meet the requirements for feather loss and to deposit protein in the feather-free body, the feathers and the ovary, oviduct and liver using the value 0.8 for the efficiency of utilization of the three amino acids for protein growth. The weekly requirements throughout growth are shown in Table 16.2.

Differences in the estimates of the daily intakes required for Lys, Met+Cys and Thr predicted by models M1 and M2 are illustrated in Fig. 16.3. The correction for feather loss is evident to the 13th week of age and differs for each amino acid. Although the weekly differences appear to be minimal, the cumulative differences for Lys, Met+Cys and Thr to the 13th week of age sum to 6%, 28% and 18%, respectively.

From the 15th week, the differences between models M1 and M2 are greater

Table 16.2. Predicted lysine (Lys), methionine + cystine (Met+Cys) and threonine (Thr) requirements (mg/day) of laying-type pullets during the growing period.

Age	Lysine		Methionine + cystine		Threonine	
(Week)	M1[a]	M2[b]	M1[a]	M2[b]	M1[a]	M2[b]
1	84	84	71	72	61	61
3	143	144	128	130	106	107
5	193	193	179	182	144	146
7	219	220	209	214	165	167
9	221	222	216	222	166	169
11	207	209	205	211	154	156
13	185	186	182	188	134	136
15	161	165	156	163	112	116
17	139	229	131	179	91	147
19	120	163	108	133	74	101
21	104	116	90	98	59	67
23	93	97	75	79	48	51
25	84	86	63	66	40	42

[a] Model 1 based on Martin *et al*. (1994).

[b] Model 2 corrected for feather loss and growth of reproductive organs and liver.

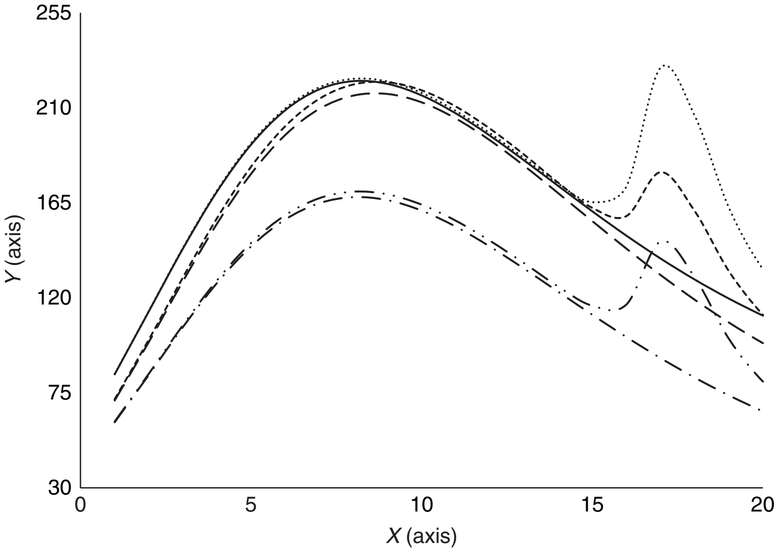


Fig. 16.3. Intakes (mg/day) of lysine (Lys), methionine + cystine (Met+Cys) and threonine (Thr) required by pullets for maintenance and protein deposition over the 20-week growing period. Model M1, based on Martin *et al*. (1994), is uncorrected for feather loss and reproductive organ and liver growth, whereas M2 includes these additional features. Lys M1 ——; Lys M2 ....; Met+Cys M1— — — ·; Met+Cys M2 – – – – –; Thr M1 — · — · –; and Thr M2 — · · — ·

because the requirements for the growth of ovary, oviduct and liver are accounted for in M1 and not in M2. These differences are illustrated in Figs 16.3 and 16.4.

The total amount of each amino acid required, as shown in Table 16.2, was partitioned into maintenance and protein deposition for the different components (the feather-free body, feathers, ovary, oviduct and liver). The proportions of the requirement for each component in relation to the total required for Lys, Met+Cys and Thr are shown in Fig. 16.4a, b and c, respectively.

During the first week more than 0.88 of the Lys required was destined for protein deposition in the feather-free body, 0.08 for protein deposition in feathers and only 0.04 for maintenance. With advancing age, the proportion of Lys needed for protein deposition in the feather-free body was reduced to 0.33 by the 17th week of age. In this week, the total amount of Lys required for protein deposition in the ovary (0.21) and oviduct (0.25) and for maintenance (0.21) was approximately 0.67. After the sexual maturation phase, the Lys required for maintenance increased to 0.66 of the total by the 25th week of age.

Only in the first week of age was the proportion of Met+Cys required for protein deposition in the feather-free body (0.50) higher than the proportion required for that in feathers (0.45). From the 3rd to the 13th week, the proportion of Met+Cys required for deposition in feathers increased from 0.48 to 0.52, while that required for protein deposition in the feather-free body declined from 0.46 to 0.30. During the sexual maturation phase the Met+Cys requirement for protein deposition in the ovary (0.07) and oviduct (0.14) together equalled 0.21 of the total required, while that for maintenance and protein deposition in the feathers amounted to approximately 0.60 of the total required.

The proportion of Thr required in the first week for protein deposition in the feather-free body, feathers and maintenance amounted to 0.71, 0.27 and 0.03 of the total, respectively. As the birds grew, these proportions changed and by the 17th week 0.28 of the protein deposited was in the feather-free body and feathers, whereas maintenance accounted for 0.38, and the ovary and oviduct accounted for 0.32 of the total.

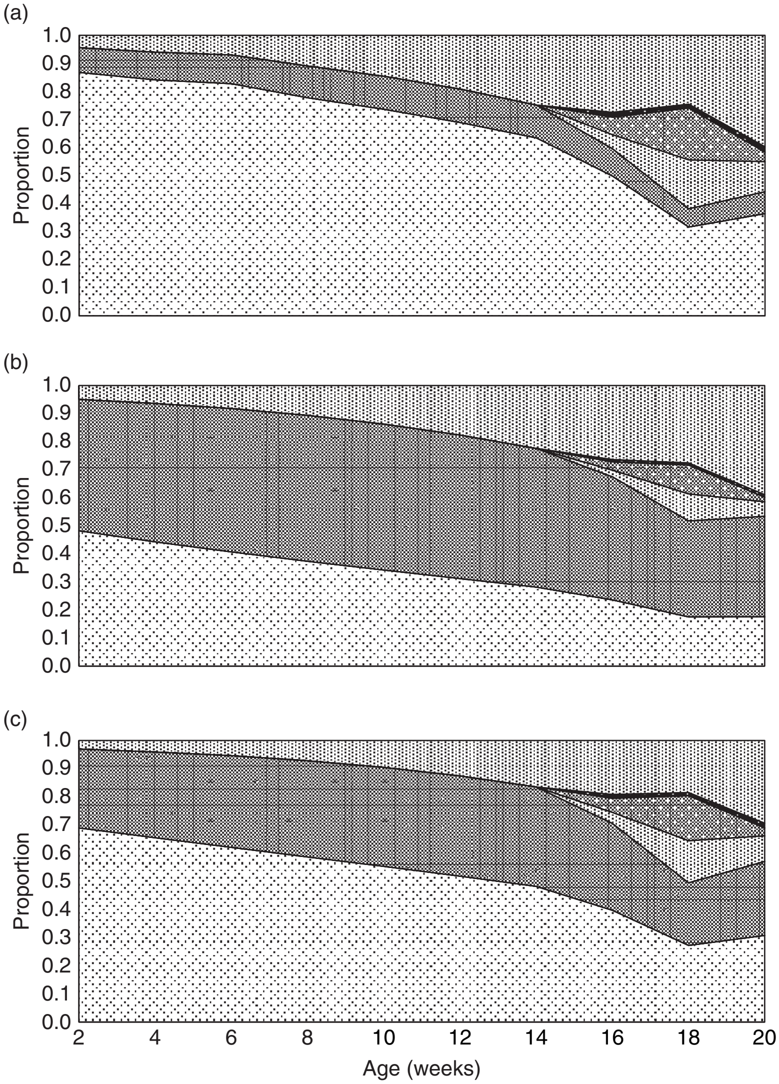


Fig. 16.4. The proportions of lysine (a: Lys), methionine + cystine (b: Met+Cys) and threonine (c: Thr) intake required over time for maintenance and for the deposition of protein in feather-free body, feathers, ovary, oviduct and liver. Feather-free body ☐; feather ▩; ovary ▨; oviduct ▩; liver ■; and maintenance ▨.

The ratio of Met+Cys to Lys changed from 0.86 in the first week to 0.78 in the 17th week (Fig. 16.5) but over the same period the Thr:Lys ratio changed very little, remaining at about 0.72 throughout.

Discussion

The parameters *Pm*, *B* and *t** of the Gompertz function were used in this exercise to compare the growth of different body components of laying pullets from hatching to the onset of lay. Because of differences in the rates of growth and amino acid composition of feather and non-feather protein, these two components have traditionally been treated separately when determining the daily amino acid requirements of growing pullets (Martin *et al.*, 1994). In this exercise the rates of maturing of these two components were very similar (0.023 vs 0.024/day), which is

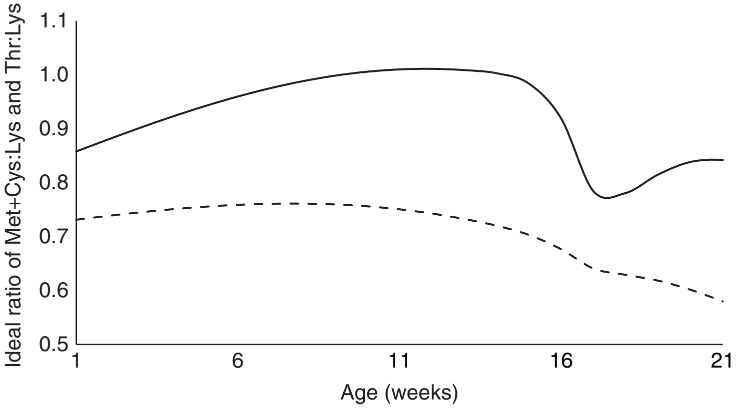


Fig. 16.5. Ratios of methionine + cystine (Met+Cys) to lysine (Lys) and threonine (Thr) to Lys required by growing pullets to maximize protein growth over time. Met+Cys:Lys ————; and Thr:Lys - - - - - - -.

unusual, as the rate of maturing of feather protein has been reported to be 1.30 of body protein in growing pullets (Martin *et al.*, 1994), and 1.36 (Hancock *et al.*, 1995) and 1.35 (Sakomura *et al.*, 2005) in broilers. The similarity in rate of maturing of these components in this exercise is in spite of taking account of feather loss during growth, which had no effect on the rate of maturing of feathers, which remained at 0.023/day after correction.

There is no doubt that feathers are lost during growth due mainly to damage and moulting, so a correction for feather loss is essential when the rate of feather growth is estimated by serially sampling birds during growth and measuring the weight of feathers on the bird at each sampling, as was done in this exercise. These losses may also be seen as a measure of the requirement for the maintenance of feathers (Emmans, 1989). The rate of loss used in this exercise (0.04 g/day) is equivalent to a daily loss of 0.04% given the mature weight of feather protein of 104 g measured here. This is four times the rate suggested by Emmans (1989) for broilers and turkeys, but is based on the measurements made by Silva (2012).

The contribution made by feathers to the daily amino acid needs of the growing pullet is substantial, especially for sulphur amino acids (Figs 16.1 and 16.4), the protein deposited in feathers representing 0.50 of the Met+Cys requirement of the pullet during growth. However, because the concentration of Thr in feather- and body protein is similar, partitioning between these tissues when calculating the Thr requirement during growth is unnecessary.

The magnitude of the increase in amino acid requirement during the sexual maturity phase was related to the amino acid content of the protein being deposited, thus Lys showed the greatest increase during this phase compared with the other amino acids. Protein deposition in the ovary and oviduct increased the overall requirements of Lys, Thr and Met+Cys during growth by 65%, 60% and 37%, respectively, only during the sexual maturity phase. This additional amount of each of the three amino acids required during the development of the reproductive organs is substantial and warrants consideration when calculating the amino acid requirements of the growing pullet.

The liver was the component that showed the lowest rate of maturing (0.013/day), being approximately half that of the feather-free body protein. However, this increase in liver protein growth occurs only after the ovary and oviduct have reached their mature state (Fig. 16.2) and when feather and body protein would also have stopped growing, as no further body protein growth occurs once the hen starts laying (Fisher and Gous, 2008). The spurt in liver protein growth after the 18th week of age in this trial is in preparation for the task of synthesizing lipoproteins in the yolk, with the mature state being achieved at around the 30th week of age. Although its contribution to overall protein deposition is small, nevertheless there is a need to supply the bird with additional protein during this phase of growth.

The factorial model of Martin *et al.* (1994) does not consider the loss of feathers during growth or the development of the three additional body components measured in this trial, so the daily requirements for amino acids predicted by that model were expected to differ from the improved model proposed here. Accounting for feather loss of 0.04 g/day, which may be regarded as feather maintenance, makes only a small addition to the amino acid requirements initially, but the cumulative effect (1st to the 13th week of age) amounted to an additional 28% of the Met+Cys requirements, but less for the other amino acids because of their lower concentrations in feathers. The accumulated amount of each of the three amino acids (Lys, Met+Cys and Thr) required by a pullet from the 15th to 21st week of age was 913 mg/bird, 846 mg/bird and 586 mg/bird when the model (M1) of Martin *et al.* (1994) was used. These totals were increased to 1185 mg/bird, 1004 mg/bird and 757 mg/bird, or 1.30, 1.19 and 1.29 times, when the additional requirements for feather loss and ovary, oviduct and liver growth (Model M2) were added.

These results suggest that the amount of each of the three amino acids required to replace lost feathers and to ensure the successful development of the reproductive organs is not insubstantial and therefore should be included together with the requirements for the growth of feather and non-feather body protein when calculating the daily amino acid requirements of pullets during growth. By ignoring the daily amounts of amino acids needed to support the growth of these additional components the predicted supply of amino acids required in the weeks prior to the onset of lay will be insufficient to meet the needs of the developing pullet.

The results presented are based on the suggestions of Emmans (1989) and Gous *et al.* (1999) that in order to determine the amount of each amino acid that a growing bird would need to consume in order to grow to its potential, a complete description is required of its growth potential. Though the daily requirements calculated in this study for Lys, Met+Cys and Thr are specific to the current Dekalb White hens, the approach used here may successfully be used for other laying strains.

Acknowledgements

The authors thank Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP) for funding this study.

References

Bonato, M.A., Sakomura, N.K., Siqueira, J.C., Fernandes, J.B.K. and Gous, R.M. (2011) Maintenance requirements for methionine and cysteine, and threonine for poultry. *South African Journal of Animal Science* 41, 209–222.

Bowmaker, J.E. and Gous, R.M. (1989) Quantification of reproductive changes and nutrient requirements of broiler breeder pullets at sexual maturity. *British Poultry Science* 30, 663–676.

Brody, S. (1921) The rate of growth of the domestic fowl. *The Journal of General Physiology* 60, 765–770.

Emmans, G.C. (1989) The growth of turkeys. In: Nixey, C. and Grey T.C. (eds) *Recent Advances in Turkey Science*. Poultry Science Symposium, Butterworths, London, pp. 135–166.

Fisher, C. and Gous, R.M. (2008) Recent evidence about the protein and amino acid nutrition of broiler breeder hens. *XXIII World's Poultry Congress*. WPSA, Brisbane, Australia.

Gompertz, B. (1825) On the nature of the function expressive of the law of human mortality, and on a new mode of determining the value of life contingencies. *Philosophical Transactions of the Royal Society of London* 115, 513–583.

Gous, R., Moran, E. Jr. Stilborn, H., Bradford, G. and Emmans, G. (1999) Evaluation of the parameters needed to describe the overall growth, the chemical growth, and the growth of feathers and breast muscles of broilers. *Poultry Science* 78, 812–821.

Grossman, M. and Koops, W.J. (1988) Multiphasic analysis of growth curves in chickens. *Poultry Science* 67, 33–42.

Hancock, C.E., Bradford, G.D., Emmans, G.C. and Gous, R.M. (1995) The evaluation of the growth parameters of six strains of commercial broiler chickens. *British Poultry Science* 36, 247–264.

Kwakkel, R.P., Ducro, B.J. and Koops, W.J. (1993) Multiphasic analysis of growth of the body and its chemical components in white leghorn pullets. *Poultry Science* 72, 1421–1432.

Kwakkel, R.P., Van Esch, J.A.W., Ducro, B.J. and Koops, W.J. (1995) Onset of lay related to multiphasic growth and body composition in white leghorn pullets provided ad libitum and restricted diets. *Poultry Science* 74, 821–832.

Martin, P.A., Bradford, G.D. and Gous, R.M. (1994) A formal method of determining the dietary amino acid requirements of laying-type pullets during their growing period. *British Poultry Science* 35, 709–724.

Robertson, T.B. (1916) Experimental studies on growth: II. The normal growth of the white mouse. *Journal of Biological Chemistry* 24, 363–383.

Sakomura, N., Longo, F., Oviedo-Rondon, E., Boa-Viagem, C. and Ferraudo, A. (2005) Modeling energy utilization and growth parameter description for broiler chickens. *Poultry Science* 84, 1363–1369.

Silva, E.P. (2012) Modelos de crescimento e das respostas de frangas de postura submetidas a diferentes ingestões de aminoácidos sulfurados. PhD Thesis, Faculdade de Ciências Agrárias e Veterinárias de Jaboticabal, São Paulo, Brazil.

Siqueira, J.C., Sakomura, N.K., Rostagno, H.S., Bonato, M.A., Pinheiro, S.R.F. and Nascimento, D.C.N. (2011) Exigência de lisina para mantença determinada com galos de diferentes genótipos. *Revista Brasileira de Zootecnia* 40, 812–820.

17 Responses of Broilers to Amino Acid Intake

D.C.Z. Donato, N.K. Sakomura* and E.P. Silva
Universidade Estadual Paulista, Jaboticabal, São Paulo, Brazil

Abstract

The main objective of this research was to measure the responses of broilers to methionine + cysteine and to threonine intake, to determine their efficiencies of utilization for growth and their intake for optimum response in the starter, grower and finisher phases. Six dose–response trials were conducted with male and female Cobb broilers in these three phases of growth. Measurements included body weight gain, digestible amino acid intake, feed conversion ratio, the proportion of feathers in the protein deposited and the amino acid and lipid deposition in the body. The efficiency of utilization of the amino acids studied was calculated by linear regression of amino acid deposition and the amino acid intake for each phase. Despite the differences between sexes and phases, the efficiency of utilization remained unchanged, being 0.56 and 0.73 for methionine + cysteine and threonine, respectively. The methionine + cysteine intakes estimated for optimum feed conversion ratio were 231 mg/day and 524 mg/day in the starter and grower phases, respectively, for both males and females, and 923 mg/day and 1053 mg/day for females and males, respectively, in the finisher phase. For threonine these intakes were 184 mg/day, 612 mg/day and 823 mg/day in the three phases, for both males and females.

Introduction

To maintain the increasing production and productivity of broilers, in addition to health care and management, nutrition is of great importance. All nutrients should be supplied in sufficient quantities so that nutrient deficiencies do not occur, as these lead to low productivity, and excesses should be avoided as these lead to an increased cost of production, the excretion of waste products into the environment and losses in productivity.

Protein is considered to be one of the most important nutrients in the feed of broilers, since their productivity depends mainly on an efficient conversion of feed protein into muscle protein (Costa *et al.*, 2001). However, now that synthetic amino acids are being produced on a commercial scale by industries, nutritionists have reduced levels of dietary crude protein and now formulate diets in order to meet the specific needs for essential amino acids. Therefore, it is of importance to know how broilers respond to the intake of specific amino acids so that the optimum economic intakes of these amino acids can be determined. Maintenance requirements and the

---

*E-mail: sakomura@fcav.unesp.br

efficiency of utilization of amino acids necessary for protein deposition are essential to the development of models to estimate amino acid responses (Edwards *et al*., 1997, 1999).

Methionine + cysteine (Met+Cys) and threonine (Thr) stand out as two of the first three limiting essential amino acids. Methionine has a specific role in protein synthesis, being the first amino acid to be incorporated into the peptide structure, and its deficiency may inhibit this early stage (Kino and Okumura, 1987). Thr is important in various metabolic processes such as protein synthesis and maintenance of body protein turnover; it has a role in antibody production, as well as in the maintenance associated with the digestive tract, where it plays an important role in the synthesis of mucins.

There are two main approaches for studying the response of poultry to essential amino acids: the dose–response method, which measures the response in performance to increasing intakes of the nutrient under test; and the factorial method, which is based on the principle that the animal needs amino acids to maintain vital processes and activities, as well as for growth and/or production (Sakomura and Rostagno, 2007).

The dose–response method has traditionally been used to study the responses of poultry to increasing concentrations of amino acids in the diet. It is useful as a means of providing components for the factorial models (D'Mello, 2003a) such as the efficiency of amino acid utilization, and also to evaluate the factors that influence this efficiency, thereby contributing to the development of generalized models of nutrient responses.

This chapter describes the studies conducted at the Poultry Science Laboratory of the Faculdade de Ciências Agrárias e Veterinárias (FCAV) at UNESP-Jaboticabal that have been aimed at assessing responses of broilers to increasing levels of Met+Cys and Thr in the diet, their efficiencies of utilization for growth and their estimated intakes for optimum responses in the starter, grower and finisher phases.

Materials and Methods

Six trials were conducted at the Poultry Science Laboratory of FCAV, UNESP-Jaboticabal, designed to measure the response of broiler chickens during three phases of growth (1–14 days, 15–28 days and 29–42 days) to dietary amino acids.

Five hundred and sixty male and 560 female broilers (totalling 1120 broilers) were distributed in a completely random design, according to a 7 × 2 factorial (seven levels of dietary amino acids and two sexes) totalling 14 treatments, with four replicates. Each experimental unit comprised 20 birds. Cobb 500 broilers were used in all the trials. At the beginning of each trial, birds were individually weighed and distributed such that each experimental unit had a homogeneous weight.

The experimental diets were formulated using the dilution technique. A high protein summit diet was formulated to contain approximately 1.2 times the digestible Met+Cys and Thr levels suggested by Rostagno *et al*. (2005) for broilers during the respective phases, and all other essential amino acids were set at a minimum of 1.4 times their suggested levels. These summit diets were diluted sequentially with isoenergetic, protein-free diets (nitrogen free) (Fisher and Morris, 1970) (Table 17.1), to create a range of feeds increasing in content of the studied amino acids (Met+Cys: 1–14 days: 3.05 to 10.88 g Met+Cys/kg; 15–28 days: 2.72 to 9.79 g Met+Cys/kg and 29–42 days: 2.50 to 9.03 g Met+Cys/kg) (Thr: 1–14 days: 1.49 to 9.96 g Thr/kg; 15–28 days: 1.30 to 8.86 g Thr/kg and 29–42 days: 1.20 to 8.17 g Thr/kg).

To verify whether the studied amino acid was limiting in the dilution series, a pilot trial for each amino acid was conducted with 30 male Cobb broilers from 1 to 14 days for Met+Cys and from 7 to 21 days for Thr. They were distributed in a completely random design with two treatments in each trial: the lowest studied levels for each amino acid and the control treatment. This treatment had the same nutritional composition as the lowest treatment in the dilution series, but it was supplemented

Table 17.1. Composition (g/kg) and analysed nutrient content (g/kg) of the summit and nitrogen-free diets used in each phase of the trial.

	Diets		
Ingredients (g/kg)	Met+Cys summit	Thr summit	Nitrogen-free
Soybean meal (450 g/kg)	510	510	–
Maize	339	339	–
Soybean oil	65.0	65.0	100
Maize gluten meal (600 g/kg)	37.3	36.8	
Dicalcium phosphate	20.3	20.3	27.0
Limestone	9.45	9.45	5.07
Salt	4.38	4.38	5.13
DL-methionine (990 g/kg)	3.28	5.12	–
L-lysine (785 g/kg)	4.89	4.87	–
L-threonine (990 g/kg)	2.01	0.33	–
L-valine (965 g/kg)	1.40	1.40	–
Choline chloride (600 g/kg)	1.00	1.00	1.00
L-arginine (985 g/kg)	0.54	0.53	
Mineral premix[a]	0.50	0.50	0.50
Vitamin premix[b]	0.50	0.50	0.50
Potassium chloride	–	–	11.4
Starch	–	–	428
Sugar	–	–	150
Rice husk	–	–	150
Anti-coccidial	0.50	0.50	0.50
Growth promotor	0.05	0.05	0.05
Antioxidant	0.10	0.10	0.10
Washed sand	–	–	121
Nutrients (g/kg)			
Metabolizable energy (kcal/kg)[c]	3050	3050	3050
Crude protein	294	298	8.90
Methionine + cysteine[d]	9.04	10.8	–
Methionine[d]	5.82	7.48	–
Lysine[d]	15.8	17.1	–
Tryptophan[d]	3.14	2.81	–
Threonine[d]	10.2	9.99	–
Arginine[d]	16.1	16.7	–
Valine[d]	12.3	14.1	–
Isoleucine[d]	9.70	11.3	–
Leucine[d]	21.2	23.1	–
Phenylalanine[d]	12.9	13.7	–
Calcium	10.0	10.0	10.0
Sodium	2.20	2.20	2.20
Available phosphorus	5.00	5.00	5.00

[a] Content/kg of product: Mn = 150,000 mg; Fe = 100,000 mg; Zn = 100,000 mg; Cu = 16,000 mg; and I = 1500 mg.

[b] Content/kg of product: folic acid = 1000 mg; pantothenic acid = 15,000 mg; niacin = 40,000 mg; Biotin = 60 mg; vitamin B1 = 1800 mg; vitamin B12 = 12,000 mg; vitamin B2 = 6000 mg; vitamin B6 = 2800 mg; vitamin D3 = 2,000,000 UI; vitamin E = 15,000 mg; vitamin K3 = 1800 mg; Se = 300 mg; antioxidant = 500 mg.

[c] Predicted value.

[d] Digestible amino acid composition.

with the test amino acid to reach the same level as the second treatment. Body weight gain (BWG) and feed conversion ratio (FCR) were evaluated.

Digestible amino acid contents of the summit diets were determined through a digestibility trial using the method described by Sakomura and Rostagno (2007).

Total amino acid concentrations in the diets and excreta were determined by high performance liquid chromatography (HPLC).

BWG (g/bird/day), digestible amino acid intake (Met+Cys$_i$ or Thr$_i$, mg/day, calculated from the feed intake), feed conversion ratio (FCR, g/g) and the proportion of feathers in the body weight (PF) were calculated from the measurements of body weight and feed intake taken during each phase of growth. The deposition of protein and lipid (g/day) in the feather-free body and in the feathers was determined using the comparative slaughter technique. The number of birds sampled at the beginning of each phase was six, while two birds in each experimental unit were sampled at the end of each phase of the trials.

The amino acid content of protein in the feather-free body and in the feathers was measured in birds sampled at the beginning and the end of each phase and was analysed by HPLC, from which the amount of amino acids deposited during each phase was calculated.

The efficiency of utilization of Met+Cys and Thr was obtained by linear regression of the amino acid deposited in the whole body (feather-free body + feathers) on digestible amino acid intake. The amino acid intake for growth was calculated by subtracting the maintenance requirement from the total consumed. To ensure that only the linear portion of the response was used for this regression the lowest four levels of Met+Cys and Thr were used.

The amino acid requirements for maintenance used in the calculations were those measured by Bonato *et al.* (2011), namely 24 mg Met+Cys/kg$^{0.75}$/day and 50 mg Thr/kg$^{0.75}$/day.

A statistical analysis of variance was conducted on each of the variables measured. Linear response plateau and quadratic polynomial models were fitted to the data. To estimate the optimum amino acid intake both models were used, since the point where the quadratic curve first intersects the plateau of the broken line is considered ‘a realistic and objective estimate of the requirement for a population of animals’ (Baker, 2003). To express optimum amino acid intakes as concentrations in the diet, the mean feed intakes suggested by Cobb-Vantress (2009) were used, these being 31 g/day, 107 g/day and 175 g/day for females and 34 g/day, 116 g/day and 195 g/day for males, during the starter, grower and finisher phases, respectively.

Results

The mean amino acid intakes, body weight gains, feed conversions and feather proportions in broilers subjected to increasing dietary levels of Met+Cys are presented in Table 17.2 and of Thr are in Table 17.3. Figure 17.1 illustrates the response in terms of weight gain as a proportion of its maximum value, to the reduction in intake of each amino acid.

Results of the pilot trials confirmed that Met+Cys and Thr were the limiting amino acids in the respective dilution series. The addition of synthetic Met+Cys and Thr to the feed with the lowest contents of these amino acids improved both BWG (7.79 g/bird/day vs 5.18 for Met+Cys and 30.1 g/bird/day vs 27.6 for Thr) and FCR (2.65 g/g vs 2.98 g/g for Met+Cys and 2.28 g/g vs 2.45 g/g for Thr).

For Met+Cys (Table 17.2) gender influenced the responses in BWG after 14 days, but with FCR this effect was only significant in the last phase. The reduction to 0.19 of the maximum Met+Cys intake in the starter phase reduced BWG to 0.36 of the maximum response. For the grower and finisher phases, reducing Met+Cys intake to approximately 0.32 of the maximum, regardless of sex, reduced BWG to 0.48 and 0.54 of the maximum gain for both males and females, respectively, in the grower phase, and to 0.65 and 0.57 of the maximum gain for both males and females, in the finisher phase. These responses are illustrated in Fig. 17.1.

Gender differences in the responses in BWG in the Thr trial (Table 17.3) are apparent in all phases, but no such effect was observed in FCR. A reduction to 0.06 of the maximum Thr intake resulted in a reduction to 0.13 of maximum BWG in the starter phase, regardless of sex. In the grower and finisher phases, reducing Thr intake to approximately 0.13 of the maximum reduced BWG to 0.20 of maximum gain, regardless of sex during grower phase, and to 0.30 and 0.28 of maximum gain for males and females, respectively, in the finisher phase.

Table 17.2. Body weight gain (BWG; g/bird/day), feed conversion ratio (FCR; g/g) and proportion of feathers (PF) of broiler males and females in response to intakes of methionine + cysteine (Met+Cys$_i$, mg/bird/day) during three phases of growth.

	Starter				Grower							Finisher							
	Combined				Females		Males		Combined			Females			Males			Combined	
Levels	Met+ Cys$_i$	BWG	FCR	PF	Met+ Cys$_i$	BWG	M+Ci	BWG	Met+ Cys$_i$	FCR	PF	Met+ Cys$_i$	BWG	FCR	Met+ Cys$_i$	BWG	FCR	Met+ Cys$_i$	PF
1	56	10.0	2.2	0.334	194	30.4	197	30.4	195	2.8	0.362	377	56.5	3.2	427	59.8	3.4	402	0.505
2	116	19.3	1.7	0.324	293	43.4	314	46.5	304	2.1	0.356	548	72.5	2.5	646	83.9	2.6	597	0.447
3	167	25.6	1.4	0.324	381	51.6	411	56.1	396	1.7	0.347	693	81.4	2.2	796	94.2	2.2	745	0.466
4	209	28.7	1.3	0.365	456	54.8	498	62.5	477	1.6	0.452	823	86.2	2.0	945	101.4	1.9	884	0.520
5	242	29.4	1.2	0.336	495	56.7	537	62.0	516	1.4	0.393	943	87.2	1.9	1078	103.7	1.8	1011	0.476
6	276	29.4	1.2	0.370	557	57.5	611	65.1	584	1.3	0.471	1062	87.0	1.9	1213	105.7	1.7	1137	0.534
7	295	28.1	1.2	0.336	601	56.5	661	63.1	631	1.3	0.453	1153	86.4	1.8	1331	105.1	1.7	1242	0.497
Sex × Met+Cys		0.61	0.68	0.17		<0.01		<0.01		0.13	0.17		<0.01	<0.01		<0.01	<0.01		0.53
CV (%)[a]		6.55	2.43	25.76		2.88		3.62		2.14	17.51		3.85	2.12		4.18	2.68		12.21
P		<0.01	<0.01	0.91		<0.01		<0.01		<0.01	<0.01		<0.01	<0.01		<0.01	<0.01		0.07

[a] CV = coefficient of variation.

Table 17.3. Body weight gain (BWG; g/bird/day), feed conversion ratio (FCR; g/g) and proportion of feathers (PF) of broiler males and females in response to intakes of threonine ($\mathrm{Thr_i}$, mg/bird/day) during different phases of growth.

	Starter								Grower								Finisher						
	Females			Males			Combined		Females			Males			Combined		Females		Males		Combined		
Levels	$\mathrm{Thr_i}$	BWG	PF	$\mathrm{Thr_i}$	BWG	PF	$\mathrm{Thr_i}$	FCR	$\mathrm{Thr_i}$	BWG	PF	$\mathrm{Thr_i}$	BWG	PF	$\mathrm{Thr_i}$	FCR	$\mathrm{Thr_i}$	BWG	$\mathrm{Thr_i}$	BWG	$\mathrm{Thr_i}$	FCR	PF
1	16	2.6	0.404	18	2.9	0.313	17	4.2	86	11.8	0.266	103	13.3	0.336	94	5.8	163	25.0	189	28.7	176	5.5	0.453
2	117	15.1	0.766	113	14.5	0.503	115	1.9	377	45.3	0.332	444	48.8	0.256	411	2.5	554	67.0	666	84.1	610	2.5	0.450
3	160	18.9	0.726	159	18.3	0.551	159	1.7	479	55.0	0.351	522	59.6	0.295	501	1.9	689	78.9	848	95.7	769	2.1	0.429
4	185	19.9	0.586	203	21.5	0.609	194	1.5	567	58.1	0.359	626	64.7	0.293	597	1.7	833	86.7	964	101	899	1.8	0.430
5	221	21.3	0.624	220	20.6	0.802	221	1.4	629	57.8	0.467	706	67.5	0.383	668	1.6	923	85.5	1112	108	1017	1.7	0.478
6	252	21.2	0.547	265	22.3	0.681	259	1.4	713	59.2	0.478	803	68.3	0.331	758	1.5	1048	85.5	1261	108	1154	1.7	0.451
7	266	19.4	0.689	291	22.0	0.772	279	1.4	776	57.6	0.470	850	64.7	0.345	813	1.5	1128	83.0	1359	103	1243	1.6	0.502
Sex × Thr		<0.05	<0.05		<0.05	<0.05		0.83		<0.01	<0.05		<0.01	<0.05		0.23		<0.01		<0.01		0.99	0.07
CV (%)[a]		6.81	23.62		6.81	21.23		4.85		2.51	12.56		3.32	16.99		8.27		5.96		4.06		8.62	10.06
P		<0.01	<0.05		<0.01	<0.01		<0.01		<0.01	<0.01		<0.01	0.07		<0.01		<0.01		<0.01		<0.01	<0.05

[a] CV = coefficient of variation.

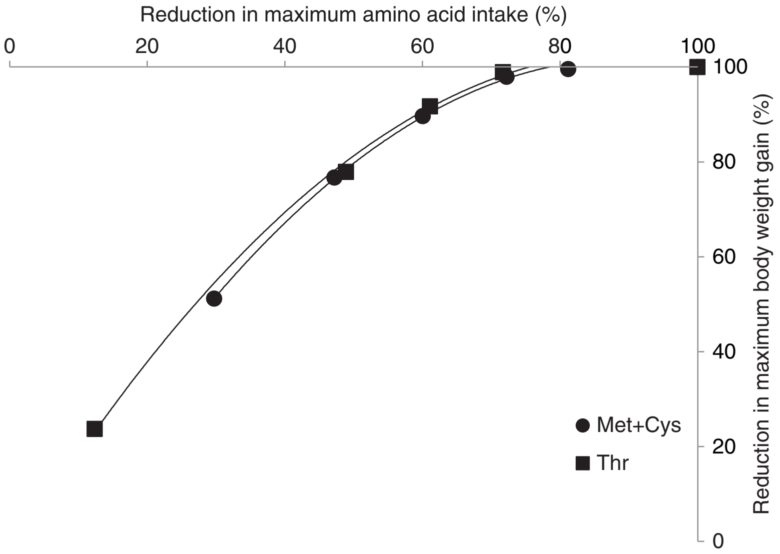


Fig. 17.1. Reduction in maximum body weight gain of male broilers as a proportion of the reduction in intakes of methionine + cysteine (Met+Cys) and threonine (Thr) for the whole rearing period (42 days).

The analysed amino acid contents of the feather-free body and feathers were, respectively, 29 Met+Cys/kg and 54 g Met+Cys/kg and 36 Thr/kg and 45 g Thr/kg.

In Tables 17.4 and 17.5 the rates of protein deposition are presented together with the body lipid contents of broilers fed Met+Cys and Thr. Although there is no interaction between gender and level of Met+Cys or Thr for these variables in some of the phases studied, they are nevertheless presented separately, so that protein deposition can be examined and hence the amino acids for each gender, and the efficiency of amino acid utilization for each sex can be evaluated.

In general, in all phases, the deposition of protein increased with amino acid intake until it reached a plateau (Fig. 17.2). The rate of deposition of each amino acid (Met+Cys, Thr) was calculated for each treatment during each phase of the experiment taking account of the content of amino acids in the protein of body and feathers. Despite the differences in rates of deposition between genders and phases, the efficiency of utilization of Met+Cys and Thr did not differ, being 0.56 ($\text{Met+Cys}_d = 28.01 + 0.56\ \text{Met+Cys}_i$; $R^2 = 0.94$) for Met+Cys and 0.73 ($\text{Thr}_d = 10.87 + 0.73\ \text{Thr}_i$; $R^2 = 0.91$) for Thr.

Body lipid content decreased as amino acid intake increased (Tables 17.4 and 17.5). The responses in body lipid to increasing amino acid intake over the whole period (1–42 days) for each amino acid are shown in Fig. 17.3. Birds fed Met+Cys-limiting feeds, at the end of 42 days, had less body fat than those birds fed Thr-limiting feeds.

The fitted equations relating body weight gain and body fat content to amino acid intake are presented in Tables 17.6 and 17.7 for Met+Cys and Thr, respectively. Also shown in the tables are body weight gain and body lipid content at the optimum intake, as well as the calculated optimum intakes of methionine + cysteine and threonine when measured in males and females in the starter, grower and finisher phases. The estimated intakes for maximum BPd (body protein deposition) are closer to those estimated for maximal BWG. However, the estimated requirements for minimum BLc (body lipid content) are higher than those for maximal BWG and BPd, this difference being more pronounced in the older birds.

Other aspects of interest are the optimum responses predicted by the models. BWG, BPd and FCR are quite close to Met+Cys and Thr in all phases, being closer with advancing

Table 17.4. Body protein deposition (BPd; g/bird/day) and body lipid content (BLc; g/kg) of broiler males and females as a function of methionine + cysteine intake (Met+Cys$_i$; mg/bird/day).

	Starter						Grower						Finisher					
	Females			Males			Females			Males			Females			Males		
Levels	Met+ Cys$_i$	BPd	BLc	Met+ Cys$_i$	BPd	BLc	Met+ Cys$_i$	BPd	BLc	Met+ Cys$_i$	BPd	BLc	Met+ Cys$_i$	Met+ Cys$_i$	BLc	Met+ Cys$_i$	BPd	BLc
1	53	1.25	177	60	1.59	142	194	5.27	175	197	4.75	174	377	10.2	207	427	9.02	185
2	107	2.67	155	124	3.25	128	293	7.48	149	314	7.34	146	548	10.3	172	646	13.0	163
3	162	3.57	133	171	3.92	118	381	8.66	140	411	8.75	122	693	15.0	153	796	15.9	138
4	205	4.31	101	214	4.57	102	456	9.18	104	498	10.4	104	823	15.0	158	945	17.9	119
5	237	4.85	62.7	248	5.02	60.8	495	9.65	85.7	537	9.87	83.8	943	16.0	127	1078	17.2	90.9
6	271	4.69	55.2	282	4.82	61.8	557	10.8	70.6	611	10.6	59.0	1062	14.9	115	1213	18.2	101
7	289	4.71	61.0	302	4.70	42.4	601	10.3	55.8	661	10.9	48.0	1153	14.0	134	1331	18.3	110
Sex × Met+Cys		0.34	0.30		0.34	0.30		<0.05	<0.01		<0.05	<0.01		<0.01	0.12		<0.01	0.12
CV (%)[a]		7.06	11.2		6.05	9.04		4.52	6.17		6.03	10.5		6.54	14.6		10.5	11.0
P		<0.01	<0.01		<0.01	<0.01		<0.01	<0.01		<0.01	<0.01		<0.01	<0.01		<0.01	<0.01

[a] CV = coefficient of variation.

Table 17.5. Body protein deposition (BPd; g/bird/day) and body lipid content (BLc; g/kg) of broiler males and females as a function of threonine intake (Thr_i; mg/bird/day).

	Starter						Grower						Finisher					
	Females			Males			Females			Males			Females			Males		
Levels	Thr_i	BPd	BLc	Thr_i	BPd	BLc	Thr_i	BPd	BLc	Thr_i	BPd	BLc	Thr_i	BPd	BLc	Thr_i	BPd	BLc
1	16	0.40	154	18	0.40	181	86	1.31	282	103	1.51	248	163	5.48	344	189	4.95	330
2	117	2.83	135	113	2.46	175	377	6.78	183	444	7.13	214	554	12.3	294	666	14.0	278
3	160	3.42	138	159	3.21	149	479	8.60	172	522	8.85	180	689	14.8	252	848	15.5	251
4	185	3.41	114	203	3.87	132	567	8.74	161	626	9.61	140	833	15.5	237	964	17.3	185
5	221	3.72	111	220	4.06	120	629	9.22	145	706	10.3	131	923	16.1	192	1112	18.5	183
6	252	3.40	90.5	265	3.88	95.7	713	9.62	128	803	10.1	101	1048	15.0	229	1261	19.7	221
7	266	3.47	83.2	291	4.08	78.3	776	9.51	111	850	9.87	111	1128	15.0	192	1359	18.3	157
Sex × Thr		<0.01	<0.01		<0.01	<0.01		0.26	<0.01		0.26	<0.01		<0.05	<0.01		<0.05	<0.01
CV (%)[a]		15.2	9.06		9.79	7.86		5.90	4.58		4.21	9.34		7.01	10.6		9.67	8.14
P		<0.01	<0.01		<0.01	<0.01		<0.01	<0.01		<0.01	<0.01		<0.01	<0.01		<0.01	<0.01

[a] CV = coefficient of variation.

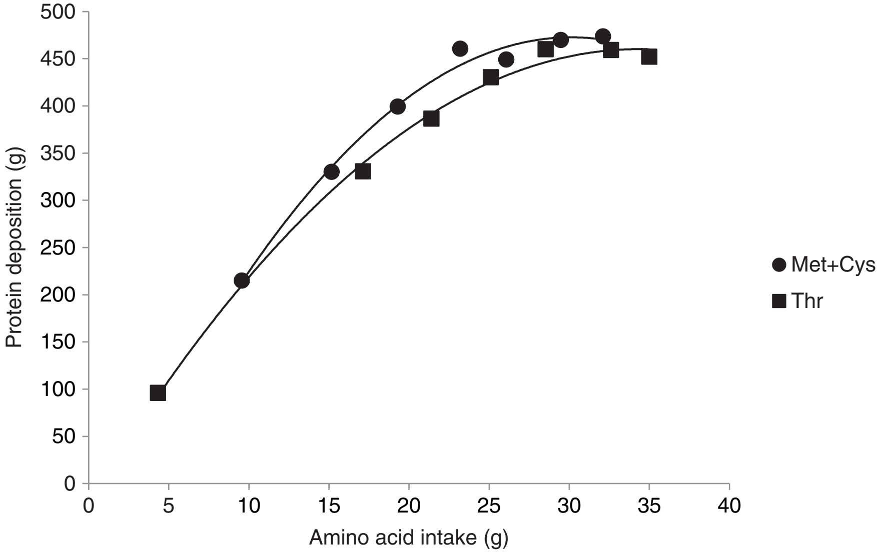


Fig. 17.2. Protein deposition in male broilers after 42 days as a function of methionine + cysteine (Met+Cys) or threonine (Thr) intake.

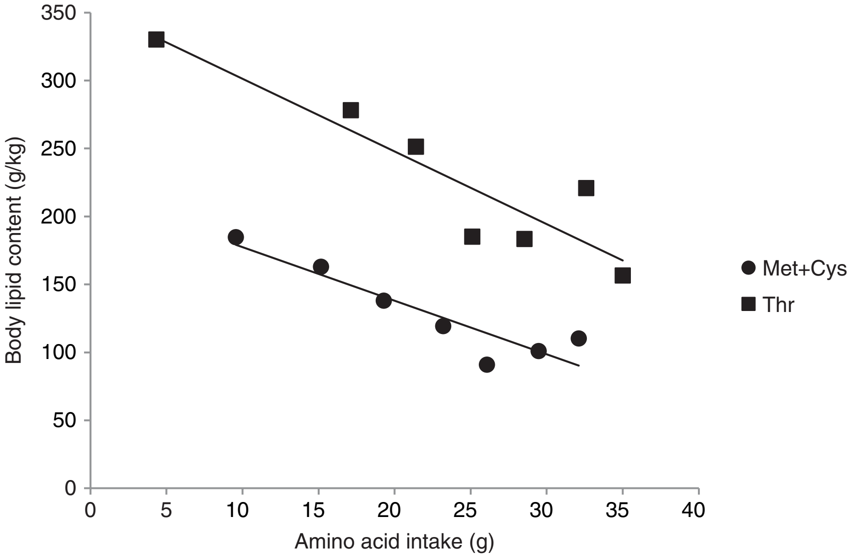


Fig. 17.3. Body lipid content of male broilers after 42 days as a function of threonine (Thr) or methionine + cysteine (Met+Cys) intake.

age. But the optimum response in BLc, as expected, was lower for males in all phases and for both amino acids, and was much greater for Thr, as already observed in the Thr responses.

Discussion

In this study, based on the responses of broilers to Met+Cys and Thr intake, the efficiency of utilization of these amino acids

Table 17.6. Fitted equations describing responses to methionine + cysteine, body weight gain (BWG, g/day), feed conversion ratio (FCR, g/g), body protein deposition (BPd, g/day) and body lipid content (BLc, g/kg) at optimum intake, and optimum intakes (Met+Cys$_i$, mg/day) and contents (Met+Cys$_i$, g/kg) of methionine + cysteine when fed to broiler males and females in starter, grower and finisher phases.

Equation	Optimum response	Met+Cys$_i^a$	Met+Cys$_i^b$
Starter phase			
Females			
$\text{BPd} = -0.00006 \times \text{Met+Cys}_i^2 + 0.04 \times \text{Met+Cys}_i - 5.28$	4.75	268	8.65
$\text{BLc} = 0.0004 + \text{Met+Cys}_i^2 - 0.68 \times \text{Met+Cys}_i + 161.49$	57.7	279	9.00
Males			
$\text{BPd} = -0.00007 \times \text{Met+Cys}_i^2 + 0.04 \times \text{Met+Cys}_i - 5.26$	4.78	245	7.21
$\text{BLc} = 0.001 \times \text{Met+Cys}_i^2 - 0.92 \times \text{Met+Cys}_i + 183.33$	31.5	344	10.1
Combined			
$\text{BWG} = -0.0005 \times \text{Met+Cys}_i^2 + 0.25 \times \text{Met+Cys}_i - 31.39$	28.9	224	6.79
$\text{FCR} = 0.00002 \times \text{Met+Cys}_i^2 - 0.01 \times \text{Met+Cys}_i + 1.57$	1.20	231	7.00
Grower phase			
Females			
$\text{BWG} = -0.0002 \times \text{Met+Cys}_i^2 + 0.23 \times \text{Met+Cys}_i - 62.53$	56.4	486	4.54
$\text{BPd} = -0.00002 \times \text{Met+Cys}_i^2 + 0.03 \times \text{Met+Cys}_i - 9.77$	9.97	510	4.77
$\text{BLc} = 0.0002 \times \text{Met+Cys}_i^2 - 0.45 \times \text{Met+Cys}_i + 204.07$	61.0	620	5.79
Males			
$\text{BWG} = -0.0002 \times \text{Met+Cys}_i^2 + 0.23 \times \text{Met+Cys}_i - 71.314$	63.2	543	4.68
$\text{BPd} = -0.00002 \times \text{Met+Cys}_i^2 + 0.03 \times \text{Met+Cys}_i - 11.32$	10.4	564	4.86
$\text{BLc} = 0.0002 \times \text{Met+Cys}_i^2 - 0.45 \times \text{Met+Cys}_i + 218.28$	39.8	810	6.98
Combined			
$\text{FCR} = 0.000008 \times \text{Met+Cys}_i^2 - 0.01 \times \text{Met+Cys}_i + 3.04$	1.40	524	4.68
Finisher phase			
Females			
$\text{BWG} = -0.00008 \times \text{Met+Cys}_i^2 + 0.17 \times \text{Met+Cys}_i - 80.51$	86.7	853	4.87
$\text{FCR} = 0.000003 \times \text{Met+Cys}_i^2 - 0.006 \times \text{Met+Cys}_i + 3.18$	1.87	923	5.27
$\text{BPd} = -0.00002 \times \text{Met+Cys}_i^2 + 0.03 \times \text{Met+Cys}_i - 16.13$	15.0	822	4.70
$\text{BLc} = 0.0001 \times \text{Met+Cys}_i^2 - 0.33 \times \text{Met+Cys}_i + 188.29$	132	986	5.63
Males			
$\text{BWG} = -0.00008 \times \text{Met+Cys}_i^2 + 0.18 \times \text{Met+Cys}_i - 107.69$	104	1033	5.30
$\text{FCR} = 0.000003 \times \text{Met+Cys}_i^2 - 0.006 \times \text{Met+Cys}_i + 3.83$	1.80	1053	5.40
$\text{BPd} = -0.00001 \times \text{Met+Cys}_i^2 + 0.04 \times \text{Met+Cys}_i - 21.31$	17.9	1063	5.45
$\text{BLc} = 0.0001 \times \text{Met+Cys}_i^2 - 0.38 \times \text{Met+Cys}_i + 250.15$	90.0	1161	5.95

[a] mg/bird/day.

[b] g/kg.

was measured and their intakes required to maximize performance was estimated.

The diet formulation technique directly affects the responses of animals to amino acid intake. Gous and Morris (1985) favoured the use of the dilution technique for dose–response experiments involving individual amino acids, since it favours the expression of the productive potential of the poultry. According to Gous (1980), when this technique is used the balance of amino acids remains constant between treatments so that

Table 17.7. Fitted equations describing responses to threonine, body weight gain (BWG, g/day), feed conversion ratio (FCR, g/g), body protein deposition (BPd, g/day) and body lipid content (BLc, g/kg) at optimum intake, and optimum intakes (Thr_i, mg/day) and contents (Thr_i, g/kg) of threonine when fed to broiler males and females in starter, grower and finisher phases.

Equation	Optimum response	Thr_i^a	Thr_i^b
Starter phase			
Females			
$BWG = -0.0004 \times Thr_i^2 + 0.18 \times Thr_i - 20.73$	20.5	204	6.58
$BPd = -0.00007 \times Thr_i^2 + 0.03 \times Thr_i - 3.57$	3.49	182	5.87
$BLc = 0.001 \times Thr_i^2 - 0.58 \times Thr_i + 91.89$	88.7	277	8.95
Males			
$BWG = -0.0003 \times Thr_i^2 + 0.16 \times Thr_i - 21.36$	21.6	228	6.71
$BPd = -0.00005 \times Thr_i^2 + 0.03 \times Thr_i - 4.14$	3.97	235	6.91
$BLc = 0.001 \times Thr_i^2 - 0.75 \times Thr_i + 158.72$	65.1	344	10.1
Combined			
$FCR = 0.00006 \times Thr_i^2 - 0.03 \times Thr_i + 3.19$	1.44	184	5.58
Grower Phase			
Females			
$BWG = -0.0001 \times Thr_i^2 + 0.18 \times Thr_i - 61.11$	58.2	600	5.61
$BPd = -0.00002 \times Thr_i^2 + 0.03 \times Thr_i - 10.25$	9.27	624	5.83
$BLc = 0.0001 \times Thr_i^2 - 0.35 \times Thr_i + 191.13$	117	777	7.26
Males			
$BWG = -0.0001 \times Thr_i^2 + 0.18 \times Thr_i - 70.94$	66.7	743	6.41
$BPd = -0.00002 \times Thr_i^2 + 0.03 \times Thr_i - 11.23$	9.96	722	6.22
$BLc = 0.0003 \times Thr_i^2 - 0.53 \times Thr_i + 270.63$	105	909	7.84
Combined			
$FCR = 0.00001 \times Thr_i^2 - 0.02 \times Thr_i + 5.48$	1.60	612	5.46
Finisher Phase			
Females			
$BWG = -0.00009 \times Thr_i^2 + 0.18 \times Thr_i - 86.71$	85.2	884	5.05
$BPd = -0.00002 \times Thr_i^2 + 0.03 \times Thr_i - 14.35$	15.2	835	4.77
$BLc = 0.000009 \times Thr_i^2 - 0.17 \times Thr_i + 174.64$	200	1077	6.15
Males			
$BWG = -0.00007 \times Thr_i^2 + 0.18 \times Thr_i - 106.59$	105	1070	5.49
$BPd = -0.00001 \times Thr_i^2 + 0.03 \times Thr_i - 18.31$	18.6	1220	6.26
$BLc = 0.00002 \times Thr_i^2 - 0.17 \times Thr_i + 180.79$	188	1218	6.25
Combined			
$FCR = 0.000006 \times Thr_i^2 - 0.01 \times Thr_i + 5.36$	1.76	823	4.45

[a] mg/bird/day.
[b] g/kg.

the responses are the consequence of the limiting amino acid being tested without being confounded by imbalances or antagonisms. The responses obtained in this study appeared to be a true reflection of changes in the intake of the amino acids being tested. It was confirmed that the responses were to the amino acids under test by the positive response obtained to the supplementation of the lowest level of each of the amino acids with the synthetic form of the amino acid.

The results of protein deposition and body lipid content presented in this chapter confirm the reports of Leclercq (1998) and Gous (1998, 2007), that increasing the content of a limiting amino acid in the diet enhances deposition of protein and reduces the body lipid content in broilers, thereby changing the composition of the body weight gain. But this statement is only valid for birds fed diets formulated with the dilution technique. According to D'Mello (2003a), when comparing the dilution and graded supplementation techniques, it is possible to observe contrasting effects on carcass fat content of chicks fed levels of individual amino acids, and it is important to consider methodological aspects when interpreting carcass fat responses to amino acid intake. This is due to the fact that the birds have a genetic potential for growth and protein deposition, and offering them a diet with the same energy content, but deficient in protein or amino acid, will force them to consume more feed in an attempt to reach their potential growth, and in so doing consume more energy than necessary and deposit more fat (Emmans, 1981, 1989).

Results of the Thr response trial indicate that even the highest levels of this amino acid were not sufficient to decrease body lipid content to the same level as was measured in the Met+Cys trial. This lack of effect of Thr on carcass fat has been reported previously (Leclercq, 1998; Kidd *et al.*, 1999; Dozier *et al.*, 2000a,b, 2001). The abdominal fat depot is suggested to be the least sensitive response criterion for dietary Thr, but not for Met+Cys (Dozier, 2000b). This fact is related to the utilization of Thr by broilers, since this amino acid is heavily involved in feather formation, although the percentage of Thr in the whole carcass is similar to that of feathers (Fisher *et al.*, 1981; Stilborn *et al.*, 1997). Once assimilated in feathers, there is no turnover of Thr for reutilization in protein synthesis (Dozier, 2000a). On the other hand, Met+Cys acts as a lipotropic agent (Andi, 2012), playing a role in carnitine synthesis, which stimulates the oxidative metabolism of lipids (Schutte *et al.*, 1997) thus reducing abdominal fat (Andi, 2012) and consequently, body lipid content.

For the reason cited above, protein or amino acid deposition was used to calculate the efficiency of utilization of each amino acid, rather than body weight gain. In the present study, the contents of Met+Cys and Thr measured in the feather-free body and feathers are consistent with the literature (Sklan and Noy, 2004; Stilborn *et al.*, 2010; Silva, 2012).

Some authors suggest that the efficiencies of utilization are different for each amino acid and that differences must be due to species and genotype (Edwards *et al.* 1999; Fatufe *et al.*, 2004). Other authors report that these factors and some others like age, sex, environmental temperature, immunological stress and diet nutritional composition exert their effects by affecting food intake, and not specifically the efficiency of utilization of the amino acids (D'Mello, 2003a).

In the case of poultry, feathers grow at a different rate to that of the rest of the body (Emmans, 1989; Gous *et al.*, 1999) and also the rates differ between sexes, since birds are feather-sexable, thus females have feather growth rates greater than males (Marcato *et al.*, 2009). Therefore, we expected that there would be differences in the efficiency of utilization of amino acids, especially Met+Cys, between phases and between the sexes. However, no differences were observed for any of the amino acids studied, since the slopes of the lines were similar for both sexes, as well as in the different growth phases. Therefore we determined a single efficiency of utilization to describe the average daily requirement of these amino acids.

Heger and Frydrych (1989) reported that the relative concentration of the amino acid in the diet is the main factor that affects the efficiency of utilization, the efficiency being higher when the amino acid is deficient, and the increased consumption of the limiting amino acid reduces its efficiency of utilization, because a greater proportion of this amino acid is allocated to alternative metabolic processes that do not deposit protein. For this reason, we used only the results of the four most deficient levels of Met+Cys and Thr to obtain their efficiencies of utilization. We obtained similar values to those found in the literature for Met+Cys and an intermediate value for Thr (Edwards *et al.* 1997; Edwards and Baker, 1999; Stilborn *et al.*, 2010).

Edwards *et al.* (1997) also reported that the efficiencies of utilization of individual amino acids are different, as observed in this study. One explanation for this difference is that essential amino acids have different degradation rates. When studying Thr requirements for maintenance in the chick, Edwards *et al.* (1997) found negative Thr retention for the groups that received diets with 0.05, 0.10 and 0.15 of the ideal requirements, and an efficiency of Thr utilization of 0.82. In another study, Edwards and Baker (1999) observed only positive retention in chicks fed graded levels of Met+Cys. But in this case the efficiency of utilization was only 0.52, a reflection of the diverse functions of methionine beyond its role in protein synthesis (D'Mello, 2003b).

The Met+Cys intakes for maximum response reported here are in accordance with the findings of some other authors. The intake to maximize FCR exceeded that for maximizing body weight gain (Schutte and Pack, 1995; Baker *et al.*, 1996; Mack *et al.*, 1999) suggesting that at marginal deficiencies of methionine birds consume more feed to meet their requirement. Chamruspollert *et al.* (2002) have also reported a higher methionine intake to maximize protein synthesis in broiler chicks when compared to that for maximum growth, as found in this trial, suggesting that methionine should be supplemented in starter diets so as to reach the maximum protein synthesis and maximum lean body yield, but that this was not as important in the grower and finisher phases, as these requirements are very close to each other.

However, the intake of Thr to maximize body weight gain exceeded that for maximum FCR. This result is contrary to the findings of Kidd and Kerr (1997) and Baker *et al.* (2002) who found that the intake required to maximize BWG and FCR was the same. On the other hand, Mack *et al.* (1999) and Ahmadi and Golian (2010) found that intake of Thr had to be higher to maximize FCR than that required to maximize BWG. This could be due to the formulation technique used in the present trial, which resulted in less change in carcass composition over the range of Thr intakes than in the case of Met+Cys. More energy is required for fat deposition than for protein deposition (Wallis, 1999), which may also explain the difference in intake of Thr required to maximize body weight gain and protein gain, especially for female broilers, which deposited more fat than males.

In conclusion, the efficiency of utilization of Met+Cys and Thr as measured in these trials for both male and female broilers are, respectively, 0.56 and 0.73. The Met+Cys intakes for minimum FCR were 231 mg/day (7.00 g/kg) and 524 mg/day (4.68 g/kg) in the starter and grower phases, for both males and females, and 923 mg/day (5.27 g/kg) and 1053 mg/day (5.40 g/kg) for females and males, respectively, in the finisher phase. Thr intakes were 184 mg/day (5.58 g/kg), 612 mg/day (5.46 g/kg) and 823 mg/day (4.45 g/kg) in the starter, grower and finisher phases, respectively, for both males and females.

The knowledge of how broilers respond to incremental intakes of amino acids enables the nutritionist to define optimum economic intakes of different amino acids, but to convert these into dietary concentrations for feed formulation purposes the expected food intake of broilers needs first to be predicted.

Acknowledgements

The authors would like to acknowledge Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP) for financial support for this project and scholarship.

References

Ahmadi, H. and Golian, A. (2010) The integration of broiler chicken threonine responses data into neural network models. *Poultry Science* 89, 2535–2541.

Andi, M.A. (2012) Effects of additional DL-methionine in broiler starter diet on blood lipids and abdominal fat. *African Journal of Biotechnology* 11, 7579–7581.

Baker, D.H. (2003) Ideal amino acid patterns for broiler chicks. In: D'Mello, J.P.F. (ed.) *Amino Acids in Animal Nutrition*. 2nd edn. CAB International, Wallingford, UK, pp. 223–236.

Baker, D.H., Fernandez, S.R., Webel, D.M. and Parsons, C.M. (1996) Sulfur amino acid requirement and cysteine replacement value of broiler chicks during the period three to six weeks posthatching. *Poultry Science* 75, 737–742.

Baker, D.H., Batal, A.B., Parr, T.M., Augspurger, N.R. and Parsons, C.M. (2002) Ideal ratio (relative to lysine) of tryptophan, threonine, isoleucine and valine for chicks during the second and third week of life. *Poultry Science* 81, 485–494.

Bonato, M.A., Sakomura, N.K., Siqueira, J.C., Fernandes, J.B.K. and Gous, R.M. (2011) Maintenance requirements for methionine and cysteine, and threonine for poultry. *South African Journal of Animal Science* 41, 209–222.

Chamruspollert, M., Pesti, G.M. and Bakalli, R.I. (2002) Determination of the methionine requirement of male and female broiler chicks using an indirect amino acid oxidation method. *Poultry Science* 81, 1004–1013.

Cobb-Vantress (2009) *Suplemento de crescimento e nutrição para frangos de corte Cobb 500*. Cobb-Vantress, Siloam Springs, Arkansas, USA.

Costa, F.G.P., Rostagno, H.S., Albino, L.F.T., Gomes, P.C., Toledo, R.S. and Vargas, J.G. Jr (2001) Níveis Dietéticos de Proteína Bruta para Frangos de Corte de 1 a 21 e 22 a 42 Dias de Idade. *Revista Brasileira de Zootecnia* 30, 1498–1505.

D'Mello, J.P.F. (2003a) Responses of growing poultry to amino acids. In: D'Mello, J.P.F. (ed.) *Amino Acids in Animal Nutrition*. 2nd edn. CAB International, Wallingford, UK, pp. 237–264.

D'Mello, J.P.F. (2003b) Amino acids as multifunctional molecules. In: D'Mello, J.P.F. (ed.) *Amino Acids in Animal Nutrition*. 2nd edn. CAB International, Wallingford, UK, pp. 1–14.

Dozier III, W.A., Moran, E.T. Jr and Kidd, M.T. (2000a) Responses of fast- and slow-feathering male broilers to dietary threonine during 42 to 56 days of age. *Journal of Applied Poultry Research* 9, 460–467.

Dozier III, W.A., Moran, E.T. Jr and Kidd, M.T. (2000b) Threonine requirement for broiler males from 42 to 56 days of age. *Journal of Applied Poultry Research* 9, 214–222.

Dozier III, W.A., Moran, E.T. Jr and Kidd, M.T. (2001) Male and female broiler responses to low and adequate dietary threonine on nitrogen and energy balance. *Poultry Science* 80, 926–930.

Edwards, H.M. and Baker D. (1999) Maintenance sulfur amino acid requirements of young chicks and efficiency of their use for accretion of whole-body sulfur amino acids and protein. *Poultry Science* 78, 1418–1423.

Edwards, H.M., Baker, D.H., Fernandez, S.R. and Parsons, C.M. (1997) Maintenance threonine requirement and efficiency of its use for accretion of whole-body threonine and protein in young chicks. *British Journal of Nutrition* 78, 111–119.

Edwards, H.M., Fernandez, S.R. and Baker, D.H. (1999) Maintenance lysine requirement and efficiency of using lysine for accretion of whole-body lysine and protein in young chicks. *Poultry Science* 78, 1412–1417.

Emmans, G.C. (1981) A model of the growth and feed intake of *ad libitum* fed animals, particularly poultry. In: Hillyer, G.M., Whittemore, C.T. and Gunn, R.G. (eds) *Computers in Animal Production*. British Society of Animal Production, Edinburgh, UK, pp. 106–110.

Emmans, G.C. (1989) The growth of turkeys. In: Nixey, C. and Grey, T.C. (eds) *Recent Advances in Turkey Science*. Butterworths, London, pp. 135–166.

Fatufe, A.A., Timmber, R. and Rodehutscord, M. (2004) Response to lysine in composition of body weight gain and efficiency of lysine utilization of growing male chickens from two genotypes. *Poultry Science* 83, 1314–1324.

Fisher, C. and Morris, T.R. (1970) The determination of the methionine requirements of laying pullets by a diet dilution technique. *British Poultry Science* 11, 67–82.

Fisher, M.L., Leeson, S., Morrison, W.D. and Summers, J.D. (1981) Feather growth and feather composition of broiler chickens. *Canadian Journal of Animal Science* 61, 769–773.

Gous, R.M. (1980) An improved method for measuring the response of broiler chickens to increasing dietary concentrations of an amino acid. *Proceedings of European Poultry Conference*. World's Poultry Science Association, Hamburg, Germany, pp. 32–39.

Gous, R.M. (1998) Making progress in the nutrition of broilers. *Poultry Science* 77, 111–117.

Gous, R.M. (2007) Methodologies for modeling energy and amino acid responses in poultry. *Revista Brasileira de Zootecnia* 36, 263–275 (Supplement).

Gous, R.M. and Morris, T.R. (1985) Evaluation of a diet dilution technique for measuring the response of broiler chickens to increasing concentrations of lysine. *British Poultry Science* 26, 147–161.

Gous, R.M., Moran, E.T. Jr, Stilborn, H.R., Bradford, G.D. and Emmans, G.C. (1999) Evaluation of the paramenters needed to describe the overall growth, the chemical growth, and the growth of feathers and breast muscles of broilers. *Poultry Science* 78, 812–821.

Heger, J. and Frydrych, Z. (1989) Efficiency of utilization of amino acids. In: Friedman, M. (ed.) *Absorption and Utilization of Amino Acids*. CRC Press, Boca Raton, Florida, USA, pp. 31–56.

Kidd, M.T. and Kerr, B.J. (1997) Threonine responses in commercial broilers at 30 to 42 days. *Journal of Applied Poultry Research* 6, 362–367.

Kidd, M.T., Lerner, S.P., Allard, J.P., Rao, S.K. and Halley, J.T. (1999) Threonine needs of finishing broilers: an evaluation of growth, carcass, and economic responses. *Journal of Applied Poultry Research* 8, 160–169.

Kino, K. and Okumura, J.-I. (1987) Whole-body protein turnover in chicks fed control, histidine, or methionine plus cysteine-free diets. *Poultry Science* 66, 1392–1397.

Leclercq, B. (1998) Specific effects of lysine on broiler production: comparison with threonine and valine. *Poultry Science* 77, 118–123.

Mack, S., Bercovici, D., Degroote, G., Leclercq, B., Lippens, M., Pack, M., Schutte, J.B. and Van Cauwenberghe, S. (1999) Ideal amino acid profile and dietary lysine specification for broiler chickens of 20 to 40 days of age. *British Poultry Science* 40, 257–265.

Marcato, S.M., Sakomura, N.K., Fernandez, J.B.K., Nascimento, D.C.N., Furlan, R.L. and Piva, G.H. (2009) Crescimento e deposição de nutrientes nas penas, músculo, ossos e pele de frangos de corte de duas linhagens comerciais. *Ciência e Agrotecnologia* 33, 1159–1168.

Rostagno, H.S., Albino, L.F.T., Donzele, J.L., Gomes, P.C., Oliveira, R.F.M., Lopes, D.C., Ferreira, A.S. and Barreto, S.L.T. (2005) *Tabelas Brasileiras para Aves e Suínos: Composição de Alimentos e Exigências Nutricionais*. 2nd edn. Universidade Federal de Viçosa, Viçosa, Minas Gerais, Brazil.

Sakomura, N.K. and Rostagno, H.S. (2007) *Métodos de Pesquisa em Nutrição de Monogástricos*. Funep, Jaboticabal, São Paulo, Brazil.

Schutte, J.B. and Pack, M. (1995) Sulfur amino acid requirement of broiler chicks from fourteen to thirty eight days of age. 1. Performance and carcass yield. *Poultry Science* 74, 480–487.

Schutte, J.B., De Jong, J., Smink, W. and Pack, M. (1997) Replacement value of betaine for DL-methionine in male broiler chicks. *Poultry Science* 76, 321–325.

Silva, E.P. (2012) Modelos de crescimento e das respostas de frangas de postura submetidas a diferentes ingestões de aminoácidos sulfurados. Phd Thesis, Universidade Estadual Paulista 'Júlio de Mesquita Filho', Jaboticabal, São Paulo, Brazil.

Sklan, D. and Noy, Y. (2004) Catabolism and deposition of amino acids in growing chicks: effect of dietary supply. *Poultry Science* 83, 952–961.

Stilborn, H.L., Moran, E.T. Jr, Gous, R.M. and Harrison, M.D. (1997) Effect of age on feather amino acid content in two broiler strain crosses and sexes. *Journal of Applied Poultry Research* 6, 205–209.

Stilborn, H.L., Moran, E.T. Jr, Gous, R.M. and Harrison, M.D. (2010) Influence of age on carcass (feather-free) amino acid content for two broiler strain-crosses and sexes. *Journal of Applied Poultry Research* 19, 13–23.

Wallis, I.R. (1999) Dietary supplements of methionine increase breast meat yield and decrease abdominal fat in growing broiler chickens. *Australian Journal of Experimental Agriculture* 39, 131–141.

18 Description of the Growth of Body Components of Broilers and Laying Pullets

E.P. Silva,[1] N.K. Sakomura,[1]* S.M. Marcato[2] and R. Neme[3]
[1]*Universidade Estadual Paulista, Jaboticabal, São Paulo, Brazil*; [2]*Universidade Estadual de Maringá, Maringá, Paraná, Brazil*; [3]*Ilender Pharmaceutical Corporation, Campinas, São Paulo, Brazil*

Abstract

This review presents a description of the growth of broiler and laying chicken strains studied at the Laboratory of Poultry Science, Universidade Estadual Paulista (UNESP)-Jaboticabal. Two commercial broiler strains and four laying strains were assessed. Ross 308® and Cobb 500® broilers were reared to 56 days of age using 1920 broiler chicks divided into four groups (two strains × two sexes), each with four replicates of 120 birds, resulting in 16 experimental units. The four laying strains studied, to 126 days of age, were Hy-Line Brown, Hisex Brown, Hy-Line White W-36 and Hisex White. Three hundred chicks of each strain, all females, were separated into groups to create four replicates of 75 birds, resulting in 16 experimental units. Every week, the birds were weighed and a sample was selected for carcass analysis based on the average weight of the experimental unit. Measurements were made of their chemical components (water, protein, lipid and ash) from which the growth of each component was described using the Gompertz function. Allometric coefficients were determined for the chemical components of the body in relation to the feather-free protein weight of the body. Differences between the broiler and laying strains were observed in some parameters of the Gompertz function. Among the broiler strains, differences were observed in the protein content of the body and in the weight of the feathers. Differences between laying strains were in protein weight and rate of maturing. The allometric coefficients revealed little difference between the genotypes, in both broiler and laying strains, indicating that it is possible to use generalized parameters to describe the growth of chemical components of the body using allometry. The different rates of growth between genotypes indicate that the intakes of energy and amino acids required to enable them to reach their genetic potential would differ between genotypes.

Introduction

Body composition was suggested as a means of estimating the amino acid requirements of poultry in the 1950s (Williams *et al.*, 1954), and later it was applied in a factorial model to predict the protein and amino acid requirements of poultry (Hurwitz and Bornstein, 1973). The factorial model described by these authors separates the requirements for maintenance and weight gain, which introduces the need to predict the growth of the animal because many modifications can occur in the physical and chemical composition of the bird from birth to maturity (Emmans, 1981). Therefore, applying a mathematical description of growth assists in describing the changes in body composition as the animal

---

*E-mail: sakomura@fcav.unesp.br

Nutritional Modelling for Pigs and Poultry (eds N.K. Sakomura *et al.*)

advances in age (Gous *et al.*, 1999) and allows for a more precise estimation of the nutritional requirements.

Although there was already a mathematical description of growth (Winsor, 1932) a new method was introduced in the 1980s (Emmans, 1981) that integrated growth with factorial models to calculate the nutritional requirements of the bird. Protein is used to define the genetic potential for growth and, in the growth model of Emmans (1981), it is the preferred variable to be used in the factorial model to predict maintenance requirements and the requirement for growth, as there is a close relationship between protein and the other physical and chemical components of the bird. Therefore, the first step in estimating the nutritional requirements of a growing bird is to describe the potential growth of protein, which has traditionally been determined using the Gompertz function (Gous *et al.*, 1999).

The parameters of the Gompertz equation: the mature protein weight, rate of maturing and t^*, the age when protein deposition is greatest, can be used to differentiate between genotypes together with knowledge of the ratio of lipid to protein in the mature bird (Hancock *et al.*, 1995). These parameters, which are subject to genetic selection, influence the energy and amino acid requirements needed to achieve the bird's genetic potential (Gous *et al.*, 1999).

Taking into account the proposal of Emmans (1981) for the application of factorial models, it is necessary to know the potential for growth and nutrient deposition in the body. Based on this approach, the Laboratory of Poultry Science of UNESP-Jaboticabal has developed models to predict the energy (Sakomura *et al.*, 2011) and amino acid requirements (Siqueira *et al.*, 2011) of growing chickens. Studies were carried out to determine the growth parameters of two broiler and four laying strains raised in Brazil, and these are presented in this review.

Materials and Methods

The studies were conducted in the Laboratory of Poultry Science, Faculty of Agriculture and Veterinary Sciences, UNESP-Jaboticabal, São Paulo, Brazil. The genetic parameters of two broiler strains and four laying strains were characterized. The broiler strains included Ross 308® and Cobb 500®, and both sexes were studied. In this study, 1920 broiler chicks were separated into four groups with four replicates of 120 birds each, resulting in 16 experimental units. The birds were housed in pens with wood shavings as litter at a density of 10 birds/m². The groups consisted of Ross 308 males (RM) and females (RF), Cobb 500 males (CM) and females (CF). The experimental period was 56 days.

The laying strains studied included Hy-Line Brown (HLB), Hisex Brown (HSB), Hy-Line White W-36 (HLW) and Hisex White (HSW) strains, and only pullets were evaluated in this case. Three hundred chicks of each strain were housed first in brooding cages (1st to 6th week) and then rearing cages (7th to 18th week). These birds were divided into four groups, each with four replicates of 75 birds, resulting in 16 experimental units. The experimental period was 126 days.

The broiler strains were fed diets based on maize and soybean meal to meet their nutritional requirements, following the breeders' recommendations for the strains during each phase of development. The levels of metabolizable energy (AME_n) and crude protein (CP) were: 3010 kcal AME_n/kg and 220 g CP/kg from the 1st to the 7th day; 3150 kcal AME_n/kg and 215 g CP/kg from the 8th to the 28th day; 3200 kcal AME_n/kg and 200 g CP/kg from the 29th to the 49th day; and 3245 kcal AME_n/kg and 180 g CP/kg from the 50th to the 56th day.

The laying strains were fed diets based on maize, soybean meal and wheat bran to meet their nutritional requirements, following the recommendations of Rostagno *et al.* (2005) for each phase of development. The lightweight strains were given the following levels of metabolizable energy (AME_n) and crude protein (CP): 2950 kcal AME_n/kg and 210 g CP/kg from the 1st to the 6th week; 2850 kcal AME_n/kg and 180 g CP/kg from the 7th to the 12th week; and 2800 kcal AME_n/kg and 160 g CP/kg from the 13th to the 18th week. For the semi-heavy weight strains, the following values were used: 2950 kcal AME_n/kg and 210 g CP/kg from the 1st to the 6th week; 2850 kcal AME_n/kg and 170 g CP/kg from the 7th to the 12th week; and 2750 kcal AME_n/kg and 160 g CP/kg from the 13th to the 18th week.

Every week, the birds were weighed and sample animals were selected for slaughter based on the average weight of each experimental unit. After a fasting period of 24 h the sampled birds were individually weighed and euthanized using CO_2, and feather samples were collected. The weight of feathers was determined by the difference between the weight of the fasted bird and the weight of the defeathered carcass.

The defeathered carcasses were ground to obtain homogeneous samples. An aliquot of each sample was set aside for subsequent pre-drying. The samples were then ground in a micro-mill and analysed for nitrogen content (Kjeldahl method, crude protein = nitrogen × 6.25), ether extract (petroleum ether in Soxhlet equipment), dry matter (oven at 105°C) and ash (muffle at 550°C). The feather samples were chopped with scissors and subjected to the same chemical analyses.

To describe the growth of the major body components, the Gompertz function was used (Gompertz, 1825).

$$Wt = Wm \times e^{\{-e^{[-B \times (t-t^*)]}\}}$$

Where t is the age in days; Wt is the weight at time t, kg; Wm is the weight at maturity, kg; B is the rate of maturing per day; t^* is the age at which the growth rate peaks, days; and e is the numerical base of *Euler*.

The absolute growth rate (dW/dt) and weight gain or deposition of various chemical components (g/day) can be calculated using the following equation:

$$dW/dt = B \times Wt \times \ln(Wm/Wt)$$

The absolute growth rate increases until it reaches a maximum rate, at which point Wt is 0.368 of Wm and t coincides with t^*. After this age, growth rate decreases as Wt approaches Wm.

Considering B, Wm and the numerical base e, the maximum rate of deposition ($dW/dtmax$) is calculated to be $dW/dtmax = B \times Wm/e$, in kg/day. The maximum weight ($Wmax$) is $Wmax = Wm/e$.

Allometric coefficients were obtained from the relationship between the natural logarithm (ln) of the chemical component weights ($\ln Cq$): protein, water, lipid and ash as a function of the natural logarithm of the protein weight ($\ln BP$), according to the following equation:

$$\ln Cq = a + b \times \ln BP$$

The feathering factor (FFc) was calculated as described by Gous *et al.* (1999), considering the relationship of the weight at maturity (Wm) of the feathers (FW) and body protein (BP).

$$FFc = 0.84 \times FWm/BPm^{2/3}$$

Results

Growth of the body

The results presented here describe the growth potential of broiler and laying strains in terms of body weight, feather weight and chemical composition. The parameters of the Gompertz function fitted for each genotype have biological meaning and therefore allow comparisons to be made between the growth parameters of each strain and sex. Table 18.1 shows the values of empty body weight (EBW) and empty feather-free weight (EFFW) for each strain.

The parameter Wm for EBW of males and females differed by approximately 2.08 kg. Females were smaller; however, the parameters B and t^* indicate that their growth was more precocious than that of males. The broiler lines can be ranked by precocity in the following order: CF, RF, CM and RM, with maximum weight gain ($WGmax$) occurring at 28, 35, 35 and 42 days, respectively.

For the laying strains, the brown (HLB and HSB) and white (HLW and HSW) strains showed distinct patterns of growth. Based on Wm, white strains were lighter by approximately 0.5 kg or 0.75 relative to the brown strains. The parameter B is related to early growth and consequently to a decrease in the time required to reach sexual maturity. The HLW strain showed higher B and t^* values compared to the other strains for both EBW and EFFW. No differences were observed among the brown strains regarding

Table 18.1. Estimates of the three parameters of the Gompertz equation for body weight and empty feather-free weight of strains of commercial broiler chickens and laying-type pullets.

	Broiler chickens				Pullets			
Variables	RM	CM	RF	CF	HLB	HSB	HLW	HSW
	Empty body weight, EBW							
EBWm, kg	6.560	6.544	4.658	4.283	2.060	2.064	1.533	1.598
B, per day	0.042	0.042	0.047	0.051	0.023	0.023	0.026	0.023
*t**, days	39	39	34	32	59	59	52	55
	Empty feather free weight, EFFW							
EFFWm, kg	6.239	6.374	4.319	3.977	1.769	1.764	1.261	1.345
B, per day	0.042	0.041	0.047	0.051	0.024	0.024	0.026	0.024
t*, days	39	39	34	32	60	60	51	55

RM = Ross 308 males; RF = Ross 308 females; CM = Cobb 500 males; CF = Cobb 500 females; HLB = Hy-Line Brown; HSB = Hisex Brown; HLW = Hy-Line White W-36; HSW = Hisex White.

the parameters for early growth (*B* and *t**) in EBW and EFFW.

Growth of the chemical components of the body

The parameters that describe the growth of the four chemical components are shown in Table 18.2. For the broiler strains, the parameters *Wm*, *B* and *t** fitted for protein weight revealed clear differences in the growth patterns between strains and sexes.

The results indicate that Ross is the largest bird, with a protein deposition rate that is better distributed throughout the rearing period of 42 days. The Cobb strain, despite being smaller by approximately 0.250 kg, presents a more rapid rate of maturing, indicating higher precocity.

The parameters obtained for lipid growth reveal similarities (*Wm*, *B* and *t**) between broiler strains and sexes. The difference in *Wm* between the two strains was less than 0.006, and between the sexes, CM showed a higher lipid weight by approximately 0.044 compared to RM. For the females, Ross showed a difference of 0.037 compared to Cobb.

The parameter *Wm* fitted to the component body water (BWA) indicates that Cobb broilers have a higher water content (0.06). This difference in composition was driven by a greater water weight in males. For body ash (BA) content, the greatest differences were observed between RM and CF for the parameters *Wm* and *B*. The RM group showed higher *Wm* and lower *B* values, whereas the CF group showed lower *Wm* and higher *B* values.

The parameters *Wm*, *B* and *t** fitted to the chemical components of the laying strains (Table 18.2) indicated that the *Wm* of brown and white strains differed. The values obtained for *B* reveal similarities between the strains, with the exception of HLW, which had the highest rates of maturation for all body components.

The rates of maturation of water, protein and ash were similar, whereas body lipid deposition occurs at a lower rate, and the other components are relatively delayed.

Mature protein weights of white and brown strains of laying pullets differed. The *B* and *t** values indicate that the maximum protein deposition rates (*PDmax*) for the HLB, HSB, HLW and HSW strains were 3.36 g/day, 3.15 g/day, 2.93 g/day and 2.37 g/day at 77 days, 57 days, 58 days and 63 days, respectively.

Allometric relationship non-isometric

The ratios of water:protein at maturity (WPRm), lipid:protein (LPRm) and ash:protein (APRm) are shown in Table 18.3. The average value for WPRm in strains RM and RF was 2.63, and for CM and CF 3.47. The average WPRm for all broiler strains was 3.05, with the values for Ross and Cobb falling between –0.137 and +0.137, respectively, around the overall mean value.

Table 18.2. Estimates of Gompertz parameters for protein, water, lipid and ash weight of commercial and laying type pullets strains.

	Broiler chickens				Pullets			
Variables	RM	CM	RF	CF	HLB	HSB	HLW	HSW
	Body protein, BP							
BPm, kg	1.313	1.023	0.866	0.657	0.365	0.329	0.284	0.248
B, per day	0.036	0.047	0.044	0.056	0.025	0.026	0.028	0.026
*t**, days	44	37	38	31	77	57	58	63
	Body water, BWA							
BWAm, kg	3.216	3.653	2.269	2.342	0.931	0.983	0.606	0.771
B, per day	0.052	0.045	0.057	0.054	0.026	0.025	0.0316	0.025
*t**, day	32	36	29	29	52	55	40	50
	Body lipid, BL							
BLm, kg	0.892	0.931	0.810	0.781	0.368	0.389	0.226	0.237
B, per day	0.039	0.041	0.041	0.043	0.022	0.022	0.028	0.022
*t**, days	47	46	44	43	79	79	60	75
	Body ash, BA							
BAm, kg	0.360	0.174	0.115	0.087	0.073	0.068	0.050	0.052
B, per day	0.038	0.051	0.061	0.081	0.024	0.026	0.028	0.025
*t**, days	52	34	29	24	63	58	55	56

RM = Ross 308 males; RF = Ross 308 females; CM = Cobb 500 males; CF = Cobb 500 females; HLB = Hy-Line Brown; HSB = Hisex Brown; HLW = Hy-Line White W-36; HSW = Hisex White.

Table 18.3. Water to protein (WPRm), lipid to protein (LPRm) and ash to protein (APRm) ratios at maturity in broiler chickens and laying type pullets and allometric regression coefficient.[a]

	Broiler chickens				Pullets			
Items	RM	CM	RF	CF	HLB	HSB	HLW	HSW
	Ratio							
WPRm	2.753	3.571	2.511	3.370	2.553	2.983	2.133	3.105
LPRm	0.845	0.868	0.978	0.977	1.011	1.182	0.795	0.953
APRm	0.248	0.169	0.127	0.248	0.200	0.206	0.175	0.211
	Allometric regression coefficient							
Water vs protein, b^W	0.921	0.925	0.910	0.929	0.850	0.862	0.835	0.885
Lipid vs protein, b^L	1.210	1.164	1.263	1.243	1.275	1.281	1.277	1.277
Ash vs protein, b^A	0.923	0.916	0.923	0.865	1.001	1.008	1.066	1.017

[a] Calculated using estimates of mature component weights in Table 18.2.

RM = Ross 308 males; RF = Ross 308 females; CM = Cobb 500 males; CF = Cobb 500 females; HLB = Hy-Line Brown; HSB = Hisex Brown; HLW = Hy-Line White W-36; HSW = Hisex White.

Table 18.2 shows differences in *Wm* for protein and lipid contents between the broiler sexes. Females had higher lipid weights in the carcass compared to males per unit of protein weight.

Average APRm was similar between broiler strains and sexes, with the exception of RF (Table 18.3), which exhibited the greatest difference from the overall mean of 0.198.

The allometric regression coefficient *b* for water, ash and lipid contents of RM, CM, RF and CF reveal similarities between the strains and sexes (Table 18.3). The overall means for each chemical component were 0.921, 0.907 and 1.220 for water, ash and lipid, respectively. Despite the similarities, major differences were found in lipid contents for RF and CM, being 0.04 and 0.05, respectively.

For the laying strains, WPRm, LPRm and APRm showed average values of 2.694, 0.985 and 0.198, respectively. The Hy-Line birds showed a lower proportion of water per unit of protein weight compared to the Hisex line. For lipid, the brown strains showed the highest lipid retention per unit of protein weight. Based on these relationships, the HLW line showed the greatest deviation from the mean values, including APRm (Table 18.3).

These results suggest that the growth patterns of the chemical components are similar in the laying strains; mean *b* values were 0.858, 1.278 and 1.023 for water, lipid and ash, respectively (Table 18.3). The biggest difference in this parameter was recorded for the ash content of HLW, with a growth rate that was 0.042 higher than the overall mean.

Feather growth

The parameters of the Gompertz function fitted for feather growth and feather protein weight of the broiler and laying strains are in Table 18.4.

In broilers, the proportion of feathers at maturity (FWm) in EBWm was 0.07 and 0.08 for males and females and 0.08 and 0.07 for Ross and Cobb, respectively, and in the laying strains, 0.08 and 0.1 for the white and brown strains and 0.09 and 0.1 for the Hisex and Hy-Line strains, respectively. The protein content of feathers at maturity in both broilers and laying pullets was 840 g/kg.

The values of parameter *B* fitted to BW (Table 18.1) and BP (Table 18.2) indicate that FW and FP grow approximately 1.22 and 1.13 times faster than BW and BP, respectively.

The results obtained for the feathering factor (FFc) indicate similarities between the broiler genotypes and sexes, with an average value of 0.343. For laying pullets the difference in FFc was less than 0.05 when grouped by colour, with an overall mean of 0.303.

Discussion

According to the theory of Emmans (1997) animals will attempt to consume enough of a given food to meet their growth potential. This concept suggests that a description of the growth potential is essential to initiate nutritional studies of growing birds (Gous *et al.*, 1999).

Table 18.4. Estimates of three parameters of the Gompertz equation for feather weight of commercial broiler chickens and laying type pullets.

	Broiler chickens				Pullets			
Variables	RM	CM	RF	CF	HLB	HSB	HLW	HSW
	Feather weight, FW							
FWm	0.482	0.420	0.383	0.298	0.172	0.167	0.164	0.147
B	0.035	0.035	0.036	0.044	0.032	0.032	0.026	0.028
*t**	49	44	45	37	55	55	57	55
	Feather protein, FP							
FPm	0.405	0.0353	0.321	0.250	0.144	0.140	0.138	0.124
B	0.035	0.0350	0.036	0.044	0.032	0.033	0.026	0.028
*t**	49	44	45	37	55	56	58	55
Feathering factor, FFc	0.337	0.347	0.354	0.332	0.284	0.295	0.320	0.314

RM = Ross 308 males; RF = Ross 308 females; CM = Cobb 500 males; CF = Cobb 500 females; HLB = Hy-Line Brown; HSB = Hisex Brown; HLW = Hy-Line White W-36; HSW = Hisex White.

Major differences were evident (Table 18.1) between broiler and laying strains and between sexes in body weight gain, and this relates to the rates of growth of BP and BL. Despite differences in the lipid weight at maturity, the growth of BP was greater than that of BL in all strains. From a nutritional perspective, the rate of protein deposition directly affects the amino acid requirements, and when associated with a lower rate of lipid deposition, the protein requirements tend to increase at a greater rate than do the energy requirements. Likewise, it is expected that strains with higher lipid weight at maturity will have a greater energy requirement to meet the requirement for body lipid deposition.

However, the lipid content of the bird reflects not only the genotype of that bird but also the environmental conditions and feed to which it has been subjected (Hancock *et al.*, 1995; Emmans and Kyriazakis, 1997). Therefore, the calculated growth parameters can be interpreted as fitting a certain desired pattern for lipid growth. Moreover, the animal will attempt to correct a deviation from the desired rate of lipid deposition as soon as the limiting condition is removed (Ferguson, 2006).

The fitted parameters for BWA and BA (Table 18.2) indicate that water and ash exhibited higher growth rates than the other components, but this is contrary to the definition of allometry, which implies that all chemical components of the body that are allometrically related share the same rate of maturity. These differences are likely to be the result of terminating the growth trial with broilers at a very early stage of maturity and then extrapolating to maturity to obtain estimates of the parameters. The values obtained for broilers and laying hens of 2.9 for WPRm and 0.2 for APRm are close to the coefficients that have been suggested for all species (Emmans and Kyriazakis, 1995; Ferguson, 2006), and these similarities indicate that these values can be considered to be nearly constant (Emmans and Kyriazakis, 1995).

The growth rate of allometrically related components (dC/dt) can be estimated from protein growth rate (dBP/dt) using $dC/dt = dC/dP \times dBP/dt$ (Martin *et al.*, 1994). In this equation, dC/dP represents the relationship between protein and water (WPRm and b^W), lipid (LPRm and b^L) or ash (APRm and b^A); therefore, EFFW weight gain can be obtained by summing the gains in protein, lipid, water and ash.

The slopes of the logarithmic relationship between protein weight and water (b^W), lipid (b^L) and ash (b^A) components showed similar values for broilers and laying hens. The largest difference observed was 0.104 for ash, whereas the water and lipid slopes were 0.061 and 0.68, respectively. It was expected that the values obtained for b^L would vary between genotypes (Emmans and Fisher, 1986), but the observed variation was similar to those of the other components. These results are supported by other findings in the literature (Martin *et al.*, 1994).

In general, the allometric coefficients indicate that as protein weight increases there is an increase in the proportion of lipid and a decrease in the proportions of water and ash in the body. These relationships explain the sequence of nutrient deposition in the body of the bird; ash and water are deposited to a greater extent during the immediate post-hatching phase (Marcato *et al.*, 2008).

The amino acid composition of feather protein differs from that of body protein so the growth of these two components should therefore be separately modelled if their requirements for amino acids are to be calculated. The differences in feather weight between the various genetic groups of broiler and laying birds may be related to the natural loss of feathers that occurs during the growth period, which seems to be specific to the genotype, and also a consequence of damage to the feathers (Hancock *et al.*, 1995). These factors affect the actual feather weight and are consequently reflected in the adjustment to the growth parameters.

FFc describes feather growth according to the various rate values of the Gompertz function (Gous *et al.*, 1999). The average values of 0.343 and 0.303 for broilers and laying hens, respectively, indicate that broilers undergo a more rapid rate of feathering than do laying hens. For broilers, the FFc rates were higher relative to other findings in the literature (Hruby *et al.*, 1994; Gous *et al.*, 1999), indicating precocity in the feathering observed in this study.

The differences presented for the growth patterns of body and feather protein imply variations in the pattern of protein deposition in the body of the bird during growth, especially during the post-hatching phase when feathering rate is strictly positive (Emmans, 1989). Feathers have an amino acid composition that varies from that of body protein, and these differences affect the amino acid requirements of the bird. Therefore, it is necessary to calculate the requirements of the feathers separately from those of the body (Emmans and Fisher, 1986; Emmans, 1989, 1997). Furthermore, a coherent model should assess the maintenance and growth of the body and feathers separately (Emmans, 1989). The growth patterns described in this work can be combined with other nutritional constants to calculate the nutritional and feed intake requirements of broilers and laying pullets (Emmans and Fisher, 1986; Emmans, 1989, 1997).

References

Emmans, G.C. (1981) A model of the growth and feed intake of *ad libitum* fed animals, particularly poultry. In: Hillyer, G.M., Whittemore, C.T. and Gunn, R.G. (eds) *Computers in Animal Production*. British Society of Animal Production, Edinburgh, UK, pp. 106–110.

Emmans, G.C. (1989) The growth of turkeys. In: Nixey, C.G. and Grey, T.C. (eds) *Recent Advances in Turkey Science*. Butterworths, London, pp. 135–166.

Emmans, G.C. (1997) A method to predict the food intake of domestic animals from birth to maturity as a function of time. *Journal of Theoretical Biology* 186, 189–200.

Emmans, G.C. and Fisher, C. (1986) Problems in nutritional theory. In: Fisher, C. and Boorman, K.N. (eds) *Nutrient Requirements of Poultry and Nutritional Research*. Butterworths, London, pp. 9–40.

Emmans, G.C., and Kyriazakis, I. (1995) A general method for predicting the weight of water in the empty bodies of pigs. *Animal Science* 61, 103–108.

Emmans, G.C. and Kyriazakis. I. (1997) Models of pig growth: problems and proposed solutions. *Livestock Production Science* 51, 119–129.

Ferguson, N.S. (2006) Basic concepts describing animal growth and feed intake. In: Gous, R., Morris T. and Fisher C. (eds) *Mechanistic Modelling in Pig and Poultry Production*. CAB International, Wallingford, UK, pp. 22–53.

Gompertz, B. (1825) On the nature of the function expressive of the law of human mortality, and on a new mode of determining the value of life contingencies. *Philosophical Transactions of the Royal Society of London* 115, 513–583.

Gous, R., Moran, E. Jr, Stilborn, H., Bradford, G. and Emmans, G. (1999) Evaluation of the parameters needed to describe the overall growth, the chemical growth, and the growth of feathers and breast muscles of broilers. *Poultry Science* 78, 812–821.

Hancock, C.E., Bradford, G.D., Emmans, G.C. and Gous R.M. (1995) The evaluation of the growth parameters of six strains of commercial broiler chickens. *British Poultry Science* 36, 247–264.

Hruby, M., Hamre, M.L. and Coon, C.N. (1994) Growth modelling as a tool for predicting amino acid requirements of broilers. *Journal of Applied Poultry Research* 3, 403–415.

Hurwitz, S. and Bornstein, S. (1973) The protein and amino acid requirements of laying hens: suggested models for calculation. *Poultry Science* 52, 1124–1134.

Marcato, S.M., Sakomura, N.K., Munari, D.P., Fernandes, J.B.K., Kawauchi, I.M. and Bonato, M.A. (2008) Growth and body nutrient deposition of two broiler commercial genetic lines. *Brazilian Journal of Poultry Science* 10, 117–123.

Martin, P.A., Bradford, G.D. and Gous, R.M. (1994) A formal method of determining the dietary amino acid requirements of laying-type pullets during their growing period. *British Poultry Science* 35, 709–724.

Rostagno, H.S., Albino, L.F.T., Donzele, J.L., Gomes, P.C., Oliveira, R.F., Lopes, D.C., Ferreira, A.S., Barreto, S.L.T. and Euclides, R.F. (2005) *Tabelas Brasileiras para Aves e Suínos – Composição de alimentos e exigências nutricionais*. 2nd edn. UFV, Viçosa, Minas Gerais, Brazil.

Sakomura, N.K., Fernandes, J.B.K., Resende, K.T., Rabello, C.B., Longo, F.A. and Neme, R. (2011) Modelling energy utilization in poultry. In: Sauvant, D., Van Milgen J., Faverdin, P. and Friggens N. (eds) *Modelling Nutrient Digestion and Utilisation in Farm Animals*. Wageningen Academic Publishers, Wageningen, The Netherlands, pp. 299–307.

Siqueira, J.C., Sakomura, N.K., Gous, R.M., Teixeira, I.A.M.A., Fernandes, J.B.K. and Malheiros, E.B. (2011) Model to estimate lysine requirements of broilers. In: Sauvant, D., Van Milgen J., Faverdin, P. and Friggens N. (eds) *Modelling Nutrient Digestion and Utilisation in Farm Animals*. Wageningen Academic Publishers, Wageningen, The Netherlands, pp. 308–316.

Williams, H.H., Curtin, L.V., Abraham, J., Loosli, J.K. and Maynard, L.A. (1954) Estimation of growth requirements for amino acids by assay of the carcass. *Journal of Biological Chemistry* 208, 277–286.

Winsor, C.P. (1932) The Gompertz curve as a growth curve. *Proceedings of the National Academy of Sciences* 18, 1–8.

19 Response of Laying Hens to Amino Acid Intake

**H.C.P. Bendezu,[1]* N.K. Sakomura,[1] K.S. Venturini,[1] J. Sato,[1]
L. Hauschild,[1] E.B. Malheiros[1] and R.M. Gous[2]**
[1]*Universidade Estadual Paulista, Jaboticabal, São Paulo, Brazil;*
[2]*University of KwaZulu-Natal, Pietermaritzburg, South Africa*

Abstract

This study was designed to measure the responses of Dekalb laying hens to three amino acids such that the optimum economic amino acid intakes of these hens could be determined, taking into account variation in body weight and potential egg output in the population as well as changes in egg revenue and feed price. Three experiments were conducted with Dekalb White laying hens during the period from 33 to 48 weeks of age, with each trial being divided into four periods of 28 days. Responses were measured to intakes of lysine, methionine + cysteine and threonine. The laying hens were distributed in a completely randomized design among eight treatments and six replicates. The treatments consisted of increasing levels of each of the amino acids under test to obtain a response curve. These levels were obtained using a dilution technique, and a control treatment was included to confirm that responses were due to the test amino acid. Egg production (%), feed intake (g), body weight (kg), egg output (g/day) and egg weight (g) were measured. The control treatment confirmed that the amino acid under test was limiting in each assay. The Reading model was fitted to the data in each trial using the relevant amino acid intakes and egg outputs. The coefficients of response obtained were 8.58 mg/g, 7.96 mg/g and 6.73 mg/g egg output, and 36.6 mg/kg, 50.8 mg/kg and 37.2 mg/kg body weight for lysine, methionine + cysteine and threonine, respectively. Assuming a maximum egg output of 55 ± 12.5 g/day, an average body weight of 1.45 ± 0.2 kg and a cost ratio of the amino acid (c/mg) and egg (c/g) of 0.0023 (lysine), 0.0025 (methionine + cysteine) and 0.0034 (threonine), the optimum economic intakes of each amino acid under current Brazilian conditions were 746, 717 and 593 mg/bird/day for the three amino acids, respectively.

Introduction

Feed represents more than 70% of the cost of production of eggs. In this context, protein is one of the most costly nutrients and therefore there is benefit in reducing any excess protein in the feed by making use of synthetic amino acids wherever feasible to reduce both the excess waste of nitrogen and the production cost.

Synthetic amino acids such as methionine (Met), lysine (Lys) and threonine (Thr) are commonly used in the poultry industry because they are limiting in diets based on maize and soybean meal and because they are now readily available at a competitive cost. Their inclusion represents 7% of the cost of the feed (MDIC, 2012).

Responses to amino acids have been studied extensively because of their nutritional

---

*E-mail: hldplm@gmail.com

Nutritional Modelling for Pigs and Poultry
(eds N.K. Sakomura *et al.*)

and economic importance in promoting growth and egg production. However, the methods used to measure these responses and the interpretation of the results of such trials have been the subject of much discussion and critical analysis in the literature (Gous and Morris, 1985; D'Mello, 2003). Nevertheless, in all cases a factorial approach, based on requirements for maintenance and for production, has been used to describe these responses, thereby allowing for differences in body weight and potential performance between strains and populations (Sakomura and Rostagno, 2007).

The optimum intake of amino acids will differ between strains as a result of genetic selection being applied differentially to rate of egg production, egg size and body weight (Pilbrow and Morris, 1974). For this reason, responses to amino acids may need periodic updating, but it is more important to determine the optimum economic intake of the limiting amino acids on a regular basis, taking into account not only the potential laying performance of the flock but also the relationship between the marginal cost of the amino acids and the marginal revenue for eggs.

One of the many advantages of the Reading model (Fisher *et al.*, 1973) is that it is a generalized model that describes the response of any population of laying hens to different amino acid intakes. Additionally, by considering the inherent variation in egg output and body weight the additional amount of amino acid worth feeding above the mean for the flock may be determined by considering the marginal cost and revenue associated with the feeding of the limiting amino acid(s). Pilbrow and Morris (1974) suggested that there was an advantage in having the result expressed as a daily intake (mg/g) and not as a relative quantity (%) as this eliminates the intrinsic factors that affect food intake. However, as the specifications in a least-cost feed formulation exercise are expressed as concentrations and not intakes, the prediction of food intake becomes essential if the optimum intake of the limiting amino acid by the flock is to be assured.

The objective of this research project was to estimate the Lys, Met+Cys and Thr requirements of a modern strain of laying hen for maintenance (mg/kg) and for egg output (mg/g) using a dilution technique, and to use the resultant coefficients of response to determine the optimum economic intakes of these amino acids to achieve maximum profit.

Materials and Methods

Three trials were conducted over a period of 2 years at the Laboratory of Poultry Science, Faculty of Agriculture and Veterinary Sciences, Universidade Estadual Paulista (UNESP), Jaboticabal, São Paulo, to determine the optimum economic amino acid intakes of Lys, Met+Cys and Thr.

Three hundred and eighty four Dekalb White laying hens were used in the Lys trial and 476 in the Met+Cys and Thr experiments. In each experiment the birds were 32 weeks of age at the start of the trial, and in each case the experimental period was divided into four periods of 28 days (33–36, 37–40, 41–44 and 45–48 weeks of age). A completely randomized design with eight treatments and six replicates was used in each case. All birds were distributed according to body weight and egg production to provide the same conditions for all treatments at the beginning of the experiment. The first 4-week period was considered as an adaptation period.

The lighting programme (16L:8D) used was that recommended for the Dekalb White. Temperature fluctuated during the Lys trial between 32.9 ± 0.71°C and 12.8 ± 0.47°C and the relative humidity between 90.9 ± 0.96% and 35.3 ± 1.81%; for the Met+Cys trial the numbers were 33.1 ± 0.45°C to 17.7 ± 0.3°C and 77.0 ± 1.19% to 32.5 ± 1.42%; and for the Thr trial, 31.7 ± 0.66°C to 19.1 ± 0.65°C and 80.2 ± 1.88% to 36.8 ± 2.69%.

The levels of each of the test amino acids required in the test feeds were achieved by blending a high protein summit basal with a protein-free basal (Fisher and Morris, 1970). Three summit basal diets were formulated based on maize and soybean meal, the first to contain 9.09 g Lys/kg, the second to contain 8.95 g Met+Cys/kg and the third to contain 7.48 g Thr/kg feed (Table 19.1). The minimum

Table 19.1. Composition of the summit (high protein) and nitrogen-free basal feeds used in the lysine (Lys), methionine + cysteine (Met+Cys) and threonine (Thr) response trials.

	Lys		Met+Cys		Thr	
Ingredients	Summit	Nitrogen-free	Summit	Nitrogen-free	Summit	Nitrogen-free
Maize	478		447		443	
Soybean meal 45%	285		390		393	
Maize gluten meal	88.4					
DL-methionine	3.00		3.20		4.60	
L-valine			1.60		1.50	
L-threonine			1.20			
L-lysine HCl			0.40		0.30	
L-tryptophan	0.30		0.10		0.10	
Soybean oil	30.1	100	49.6	48.8	50.1	48.8
Limestone	93.1	87.3	90.1	86.7	90.1	86.7
Dicalcium phosphate	14.7	19.8	10.9	16.9	10.9	16.9
Salt	5.30	5.10	5.10	5.20	5.10	5.20
Vitamin premix[a]	1.50	1.50	1.00	1.00	1.00	1.00
Choline chloride 60%	0.50	0.50	0.50	0.50	0.50	0.50
BHT[b]	0.10	0.10	0.10	0.10	0.10	0.10
Starch		368		500		500
Rice husk		205		120		120
Sugar		150		150		150
Sand		50.0		58.6		58.6
Potassium chloride		12.7		12.3		12.3
Calculated nutrient content						
Metab. energy (Mcal/kg)	2.85	2.85	2.85	2.85	2.86	2.85
Crude protein	224	8.70	219	6.50	221	6.50
Calcium	40.2	40.2	39.0	39.0	39.0	39.0
Available phosphorus	3.80	3.80	2.90	2.90	2.90	2.90
Lysine[c] (g/kg)	9.09		11.4		11.4	
Methionine+cysteine[c] (g/kg)	9.65		8.95		10.3	
Methionine[c] (g/kg)	6.51		6.07		7.43	
Tryptophan[c] (g/kg)	2.44		2.61		2.61	
Threonine[c] (g/kg)	7.46		8.63		7.48	

[a] Content/kg vitamin A = 7,500,000 UI; vitamin E = 5000 UI; vitamin B1 = 1800 mg; vitamin B2 = 4000 mg; vitamin B6 = 3500 mg; vitamin B12 = 7500 µg; pantothenic acid = 15 g; vitamin B3 = 35 g; selenium = 250 mg; antioxidant = 250 mg; excipient 87.0439%; manganese = 65 g; iron = 45 g; zinc = 50 g; copper = 7500 mg; and iodine = 700 mg.

[b] Butyl hydroxy toluene.

[c] Digestible amino acid composition.

content of all amino acids in the summit basal other than the test amino acid was specified as 1.4 times the recommendations for laying hens for the Lys trial and 1.5 times for the Met+Cys and Thr trials based on Rostagno *et al.* (2011), whereas the level of the test amino acid was kept at 1.2 times the recommended level for the Lys trial and 1.3 times for Met+Cys and Thr. The blending proportions are given in Table 19.2.

A control treatment was included in each trial: The feed with the lowest content of the test amino acid (level 7) was supplemented with synthetic L-lysine HCl (78.5%), DL-methionine (99%) or L-threonine (90.6%) such that the content of the test amino acid was the same as that at the next-highest level but with all other nutrients the same as in the lowest dilution.

Feed and water were available *ad libitum*. Feed intake (g/bird/day) was measured at the end of each week, eggs were collected and recorded daily and egg weight (g) was measured three times a week. These data were used

Table 19.2. Proportion of summit basal used with the corresponding protein-free basal in the lysine (Lys), methionine + cysteine (Met+Cys) and threonine (Thr) trials and the concentrations of limiting amino acid in the resultant feed.

	Summit basal			Levels[a]		
Trial	Lys	Met+Cys	Thr	Lys	Met+Cys	Thr
1	1.00	1.00	1.00	9.09	8.95	7.48
2	0.90	0.89	0.90	8.18	7.92	6.73
3	0.70	0.77	0.70	6.36	6.89	5.24
4	0.60	0.62	0.60	5.46	5.51	4.49
5	0.50	0.46	0.50	4.55	4.14	3.74
6	0.40	0.31	0.35	3.64	2.75	2.62
7	0.30	0.15	0.25	2.73	1.37	1.87
Control				+0.91[b]	+1.39[b]	+1.16[b]

[a] Digestible amino acid in g/kg.

[b] Amount of amino acid added to control treatment.

to calculate egg output (g/bird/day). At the end of each experiment all the birds were weighed.

The data were analysed using a completely random design. All the variables had their residuals tested for normality and homoscedasticity using a Cramer–Von Mises and Levene test. Data were analysed using SAS PROC GLM 9.2 (SAS, 2008). The Reading model (Fisher *et al.*, 1973) was fitted to the egg output and amino acid intake data using EFG Software (2003) to obtain the relevant coefficients of response according to the model. Because the correlation between egg output and body weight in laying hens ($r_{E.BW}$) is close to zero (Fisher *et al.*, 1973) a simplified version of the Reading model was used in this case:

$$A_{opt}\left(\frac{\text{mg}}{\text{day}}\right) = a \times E_{max} + b \times BW + x\sqrt{a^2 \times \sigma^2\, E_{max} + \text{b}^2 \cdot \sigma^2\, BW}$$

E_{max} = mean maximum egg output, g/day; σE_{max} = standard deviation of E_{max}; BW = mean body weight, kg; σBM = standard deviation of BW; a = intake of amino acid required per gramme of egg output, mg; b = intake of amino acid required per kilogramme of body weight, mg.

The optimum intake of the amino acid (mg/bird/day) is that which leaves a proportion, *ak*, of the individual requirements unsatisfied (Fisher *et al.*, 1973). The value of x in the Reading model describes the point of truncation, which cuts off an area equal to *ak* in one tail of the normal distribution of egg output. That is, it is the number of standard deviations above the mean that omits an area equal to *ak* in one tail, where k = marginal cost of 1 mg amino acid (Brazilian Reais (R) $/mg)/marginal revenue of 1 g of egg output (R$/g).

Results

In all three experiments, responses obtained with the control diet were significantly higher than with treatment 7, the lowest dilution in the series, confirming that the amino acids tested were limiting in the respective basal diets evaluated.

The levels of the amino acids influenced both feed intake and production as shown in Table 19.3. The maximum feed intakes in the three assays were 106 g/bird/day, 105 g/bird/day and 104 g/bird/day for Lys, Met+Cys and Thr, respectively, these intakes occurring on the fourth-highest level of amino acid contents in each case. The mean intakes at the lower amino acid levels were 0.32, 0.64 and 0.71 of the highest value observed, respectively. However, higher inclusions of the three test amino acids resulted in a reduction of only 0.01, 0.03 and 0.06 of the highest intake recorded.

Only the three lowest levels of each test amino acid resulted in significant decreases in rate of lay, egg weight and egg

Table 19.3. Mean (± standard error) feed intake (g/day), amino acid intake (mg/bird/day), rate of lay (%), egg weight (g) and egg output (g/bird/day) from 35 to 48 weeks in response to lysine, methionine + cysteine and threonine.

Amino acid intake	Feed intake	Rate of lay	Egg weight	Egg output
Lysine				
952	105 ± 2.45	96.2 ± 1.78	64.5 ± 1.67	62.0 ± 1.21
847	103 ± 2.29	95.1± 2.71	64.4 ± 0.80	61.2 ± 1.62
659	104 ± 3.42	94.8 ± 2.21	62.9 ± 1.53	59.6 ± 2.42
579	106 ± 3.41	92.1 ± 2.74	61.3 ± 2.14	56.4 ± 3.07
439	96.6 ± 7.08	75.5 ± 4.55	59.3 ± 0.99	44.7 ± 3.08
289	79.6 ± 9.73	51.5 ± 3.67	55.4 ± 1.99	28.5 ± 1.36
190	69.6 ± 5.67	28.0 ± 1.32	52.1 ± 2.44	14.6 ± 0.91
254[a]	70.3 ± 3.96	31.3 ± 1.78	53.2 ± 0.78	16.6 ± 0.86
Methionine + cysteine				
899	100 ± 2.36	96.5 ± 2.88	66.3 ± 1.58	63.4 ± 1.81
791	99.8 ± 3.54	95.1 ± 3.14	66.9 ± 1.41	63.1 ± 2.80
690	100 ± 4.73	95.2 ± 3.20	64.9 ± 1.25	61.1 ± 2.47
580	105 ± 3.74	93.9 ± 5.02	62.7 ± 1.30	58.2 ± 2.93
302	72.8 ± 6.22	50.0 ± 6.80	57.7 ± 1.34	30.2 ± 3.62
168	61.0 ± 2.05	20.5 ± 1.84	54.0 ± 1.69	11.2 ± 1.22
51.9	37.9 ± 5.52	3.27 ± 0.90	47.5 ± 1.63	2.86 ± 0.55
114[a]	41.5 ± 3.35	6.27 ± 2.22	49.0 ± 2.33	3.42 ± 1.37
Threonine				
737	98.6 ± 3.36	96.0 ± 2.30	66.7 ± 0.97	62.6 ± 1.89
672	99.9 ± 3.09	95.9 ± 2.48	66.3 ± 1.13	62.2 ± 2.05
578	100 ± 3.52	93.7 ± 3.00	66.3 ± 1.15	61.0 ± 2.58
480	104 ± 2.99	93.4 ± 2.95	63.6 ± 1.86	56.9 ± 2.62
247	71.4 ± 4.67	47.6 ± 5.54	58.4 ± 1.52	29.2 ± 3.11
132	57.2 ± 4.46	20.5 ± 1.99	52.8 ± 3.66	11.9 ± 1.30
35.1	30.5 ± 6.39	5.22 ± 0.85	46.7 ± 2.54	3.60 ± 0.57
104[a]	45.1 ± 8.87	6.40 ± 1.68	50.6 ± 2.40	3.80 ± 0.86

[a] Control treatment.

output (Table 19.3; Fig. 19.1) with the lowest levels of Met+Cys and Thr resulting in egg outputs close to zero. The four highest levels used in the three assays produced outputs that probably represent the potential for the strain used.

Estimates of the coefficients *a* and *b* of the Reading model are given in Table 19.4.

The current marginal costs of the three amino acids in this study were R$10/kg for Lys, R$12/kg for Met+Cys and R$15/kg for Thr. Current prices for the four egg grades used in Brazil were R$ 0.22, 0.23, 0.24 and 0.25 per gramme for small (45 g), medium (50 g), large (55 g) and extra-large (60 g) eggs, respectively. From these values *k* (g/mg) was calculated to be 0.0023, 0.0025 and 0.0034 for the three amino acids, and the additional amount of Lys, Met+Cys and Thr worth feeding above the mean was therefore 221 mg, 206 mg and 169 mg, respectively. The optimum economic amino acid intake of the three test amino acids was calculated to be 746 mg/bird/day, 717 mg/bird/day and 593 mg/bird/day, respectively.

A range of cost ratios (*k*) representing 0.15, 0.30 and 0.45 above and below the current value for each amino acid was used to calculate the optimum economic intakes of the three amino acids under test for three maximum egg outputs (45 g/bird/day, 50 g/bird/day and 55 g/bird/day) and three mean body weights (1.45 kg, 1.55 kg and 1.75 kg) and the results are given in Table 19.5. The optimum intakes decreased in all cases as the cost ratio increased, but in all cases the optimum intake increased with potential egg output and mean body weight.

Table 19.4. Mean maximum egg output (E_{max}), standard deviation of egg output (σ_E), mean body weight (W), standard deviation of body weight (σ_W), milligrammes of amino acid required per gramme of egg output *(a)* and per kilogramme of body weight *(b)*.

Amino acid	E_{max}	σ_E	W	σ_W	a	b
Lysine	59.9	12.5	1.53	0.2	8.58	36.6
Methionine + cysteine	63.9	12.5	1.53	0.2	7.96	50.8
Threonine	64.0	12.5	1.53	0.2	6.73	37.2

Table 19.5. Optimum economic amino acid intake (mg/bird/day) as influenced by potential egg output (g/hen/day), mean body weight (kg) and cost ratios (k).[a]

Egg output	Body weight	Cost ratio (k)						
Lysine		0.0013	0.0016	0.002	0.0023	0.0026	0.003	0.0033
45	1.45	685	676	667	660	655	648	644
	1.55	688	680	670	664	659	652	655
	1.75	696	687	678	671	666	659	655
50	1.45	728	719	709	703	698	691	687
	1.55	731	723	713	707	702	695	691
	1.75	739	730	720	714	709	702	698
55	1.45	771	762	752	746	741	734	730
	1.55	774	766	756	750	744	738	741
	1.75	782	773	763	757	752	745	741
Methionine + cysteine		0.0014	0.0018	0.0021	0.0025	0.0029	0.0033	0.0036
45	1.45	660	651	645	637	631	626	622
	1.55	666	656	650	643	636	631	637
	1.75	676	666	660	653	647	641	637
50	1.45	700	691	684	677	671	666	662
	1.55	705	696	689	682	676	671	667
	1.75	715	706	700	692	686	681	677
55	1.45	740	730	724	717	711	705	702
	1.55	745	735	729	722	716	710	717
	1.75	755	746	739	732	726	721	717
Threonine		0.0019	0.0024	0.0029	0.0034	0.0039	0.0044	0.0049
45	1.45	545	538	531	525	521	516	512
	1.55	549	541	535	529	524	520	523
	1.75	556	549	542	537	532	527	523
50	1.45	579	571	565	559	554	550	546
	1.55	583	575	568	563	558	553	549
	1.75	590	582	576	570	565	561	557
55	1.45	613	605	598	593	588	583	579
	1.55	616	609	602	596	592	587	591
	1.75	624	616	610	604	599	595	591

[a] k = marginal cost of amino acid (R$/mg)/marginal revenue for egg output (R$/g).

Discussion

The main purpose of this study was to measure the coefficients of response to three amino acids and to compare these with previously reported coefficients. The coefficients represent the intake of amino acid required per gramme of egg output (*a*) and per kilogramme of body weight (*b*). The method used, known as the dilution technique (Fisher *et al.*, 1973), has been shown to provide an accurate measure of the response to amino acid supply from which these two coefficients may be derived. One of the many advantages of this technique is that it is possible to verify that the amino acid under test is first limiting in the dilution series, unlike the situation with the graded supplementation technique (Gous and Morris, 1985). In all cases the control treatment confirmed that the amino acid under test was indeed first limiting in the dilution series used.

Fitting the Reading model to response data such as those measured here has many advantages over other curve-fitting procedures used to interpret response data (Morris, 1983, 1999) particularly because the coefficients generated have biological meaning, and the optimum economic intake of the limiting amino acid may be determined by considering the marginal cost of amino acid and the marginal revenue for eggs. This model has thus been used widely to describe responses of laying hens to limiting amino acid intake.

The intakes of Lys, Met+Cys and Thr required per gramme of egg output (*a* coefficient) were calculated to be 8.58, 7.96 and 6.73, respectively. These values are very close to those reported by Fisher and Morris (1970) for Met (4 mg/g), McDonald and Morris (1985) for Lys (9 mg/g) and Met (4.7 mg/g), Pilbrow and Morris (1974) for Lys (9.5 mg/g), Gous *et al.* (1987) for Lys (11.03 mg/g) and Met (3.02 mg/g) and Huyghebaert and Butler (1991) for Thr (8.7 mg/g) despite these authors having worked with different strains. That the coefficients have biological meaning is apparent when comparing the intake required with the amount of each amino acid in the egg. The efficiency of utilization of the digestible amino acids for egg production calculated in this study was 0.97, 0.87 and 0.85 for Lys, Met+Cys and Thr, respectively.

The Reading model is not the ideal means of determining the maintenance requirement for amino acids. It has been argued that the maintenance requirement should be based on body protein and not body weight (Nonis and Gous, 2008), and that this should be measured independently of egg production (Burnham and Gous, 1992). Nevertheless, the *b* coefficients obtained here for Met+Cys and for Thr are close to those reported in the literature (Fisher and Morris (1970) obtained a value of 25 mg/kg for Met; McDonald and Morris (1985) obtained a value of 31 mg/kg for Met and Huyghebaert and Butler (1991) obtained a value of 43.5 mg/kg for Thr). The Lys required for maintenance obtained in this study (36.6 mg/kg) was considerably lower than that reported by Pilbrow and Morris (90 mg/kg), but the same as that reported by Gous *et al.* (1987) (37.0 mg/kg). The coefficients measured by Bonato *et al.* (2011) using a direct method of measurement differed from those reported here for Met+Cys (19 mg/kg) and for Thr (17 mg/kg). Clearly, more research needs to be conducted to resolve the issue of maintenance requirements for laying hens.

The pattern of food intake measured, namely, a marginal increase and then a severe decrease as the feed amino acid content was reduced has been reported in all of the response trials in which the dilution technique has been used (Fisher and Morris, 1970; Pilbrow and Morris, 1974; Gous *et al.*, 1987; Huyghebaert and Butler, 1991). The initial increase in intake is an attempt by the birds to consume sufficient of the limiting amino acid to enable them to continue to lay at their potential, but as the deficiency becomes more severe, an increase in intake is no longer possible presumably because the bird would become too hot, or the bulkiness of the food would prevent the bird from consuming what was required. The reason for the reduction in intake has not been established, but it is presumably linked to the ovulatory control mechanism in some way, such that yolk synthesis no longer takes place continuously, ovulation becomes more sporadic, and the requirement for amino acids for egg production declines.

As a consequence of the reduced intake of the limiting amino acid both rate of laying and egg weight decline. The rates of decline are, however, not the same, as has been demonstrated by Morris and Gous (1988) with laying hens and by Bowmaker and Gous (1991) with broiler breeders. A graph similar to that produced in the preceding references indicates that the relative change in rate of lay is greater than that in egg weight (Fig. 19.1) and that the reductions in both rate of lay and egg weight were very similar in the three amino

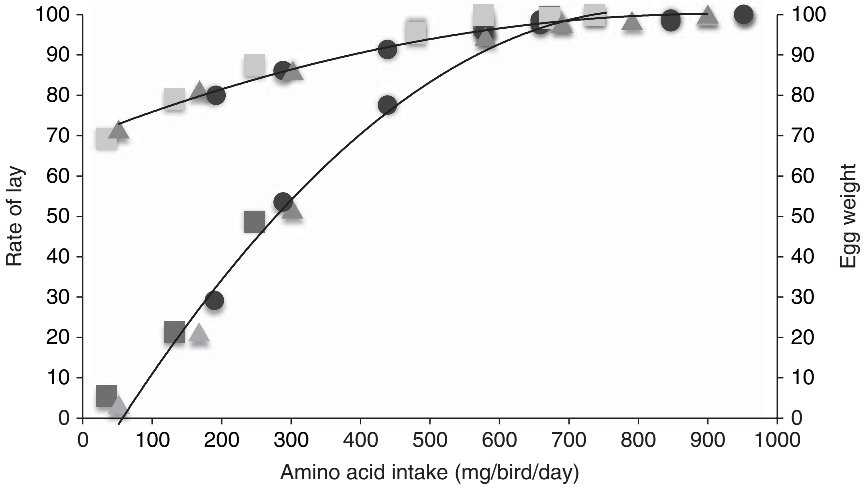


Fig. 19.1. The relationships between amino acid intake and egg production and egg weight, where these are expressed as a proportion of the maximum rate of lay and maximum egg weight, respectively. Lys (●), Met+Cys (▲) and Thr (■).

acids studied, similar to the conclusion drawn by Morris and Gous (1988). This again shows the futility of reducing the amino acid supply in an attempt to alter egg weight without reducing the rate of laying.

The three response trials reported here were conducted when the hens were producing their maximum egg output so the distribution of egg outputs was close to a normal distribution. At a later stage of lay, and in most broiler breeder flocks, egg output is not normally distributed, making conventional statistical analyses difficult if not invalid (Zhang and Coon, 1994; Morris, 2004).

The optimum economic amino acid intake decreased as the ratio of marginal cost to marginal revenue increased (Table 19.5). Egg producers should be aware that the optimum economic supply of essential nutrients is not static but varies according to supply and demand, hence the need to recalculate this optimum whenever the cost:benefit ratio changes. But the optimum economic amino acid intakes were not only a function of the cost ratio (k) but also of body weight and potential egg output. As these variables increase, so the rate of protein synthesis increases and more amino acids are required. Considering Lys as an example, for a hen with a 55-g potential egg output and a body weight of 1.45 kg the optimum Lys intake ranged from 730 to 771 mg/bird/day as a function of k (Table 19.5) and for a fixed k value of 0.0023, the current value in Brazil, the optimum intakes ranged from 660 to 757 mg/day depending on maintenance and potential egg output. This demonstrates the wide range of intakes that could be regarded as optimal depending on the prevailing conditions and strain used. The optimum intake of 771 mg Lys/day is nevertheless lower than that recommended in the Brazilian Tables (Rostagno *et al.*, 2011) for laying hens weighing 1.5 kg and producing 55.5 g of egg output. However, the purpose of this series of response trials was to describe the responses of laying hens to amino acids and not to determine their ‘requirement’, which is a concept that should not be applied to populations or flocks of laying hens.

The optimum intakes of the three amino acids derived in this way are expressed in mg/bird/day, but to formulate a feed it is necessary to know how much the hen is likely to consume. Unfortunately, food intake does not remain constant as the amino acid concentration is varied, so food intake needs to be predicted before the amount of each amino acid can be accurately supplied to the birds. If an intake of 104 g were to be guaranteed, and the mean body weight of the flock was 1.45 kg with a mean maximum egg output of

55 g, the concentrations of Lys, Met+Cys and Thr required in the feed would be 7.17 g/kg ($k = 0.0023$), 6.89 g/kg ($k = 0.0025$) and 5.93 g/kg ($k = 0.0034$), respectively.

Depending on the ingredients available, and their prices, the marginal cost of each amino acid will vary, but not all amino acids need necessarily be limiting in the feed and hence their marginal costs may not be realistic. It is not necessary to attempt to restrict all the essential amino acids to their lower boundary as defined using the Reading model approach: only those amino acids that are limiting in the formulation would be at the lower boundary, while all others should be unlimited. In feed formulations for laying hens that are based on maize and soybean meal, Met+Cys are the first limiting amino acids.

In conclusion, the Reading model is a strategic tool that may be used to estimate the optimum amino acid intakes for laying hens under different genetic and economic circumstances. The values of the coefficients derived in the trials reported here add further evidence that these coefficients have biological meaning and that they can be universally applied for the purpose of defining the optimum economic intakes of amino acids.

Acknowledgements

We would like to acknowledge the Fundação de Apoio a Pesquisa do Estado de São Paulo (FAPESP) for financing the research and for providing student scholarships. We also thank the Programa de Estudante Convenio de Pós Graduação (PEC-PG) for providing a scholarship.

References

Bonato, M.A., Sakomura, N.K., Siqueira, J.C., Fernandes, J.B.K. and Gous, R.M. (2011) Maintenance requirements for methionine & cysteine and threonine for poultry. *South African Journal of Animal Science* 41, 209–222.

Bowmaker, J.E. and Gous, R.M. (1991) The response of broiler breeder hens to dietary lysine and methionine. *British Poultry Science* 32, 1069–1088.

Burnham, D. and Gous, R.M. (1992) Isoleucine responses in broiler chickens. The requirement for maintenance. *British Poultry Science* 33, 59–69.

D'Mello, J.P.F. (2003) Responses of growing poultry to amino acids. In: D'Mello, L.P.F. (ed.) *Amino Acids in Poultry Nutrition*, 2nd edn. CAB International, Wallingford, UK. pp. 237–263.

EFG Software (2003) Amino acid optimizer. Available at: www.efgsoftware.net (accessed October 2013).

Fisher, C. and Morris, T.R. (1970) The determination of the methionine requirement of laying pullets by a diet dilution technique. *British Poultry Science* 11, 67–82.

Fisher, C., Morris, T.R. and Jennings, R.C. (1973) A model for the description and prediction of the response of laying hens to amino acid intake. *British Poultry Science* 14, 469–484.

Gous, R.M. and Morris, T.R. (1985) Evaluation of a diet dilution technique for measuring the response of broiler chickens to increasing concentrations of lysine. *British Poultry Science* 26, 147–161.

Gous, R.M., Griessel, M. and Morris, T.R. (1987) Effect of dietary energy concentration on the response of laying hens to amino acids. *British Poultry Science* 28, 427–436.

Huyghebaert, G. and Butler, E.A. (1991) Optimum threonine requirement of laying hens. *British Poultry Science* 32, 575–582.

McDonald, M.W. and Morris, T.R. (1985) Quantitative review of optimum amino acid intakes for young laying pullets. *British Poultry Science* 26, 253–264.

MDIC (2012) Estudo da Viabilidade Técnica e Econômica destinado à implantação do Parque Produtivo Nacional de Aditivos da Indústria de Alimentação de Animais de Produção. Available at: http://www.desenvolvimento.gov.br/arquivos/dwnl_1347635101.pdf (accessed 21 March 2013).

Morris, T.R. (1983) The interpretation of response data from animal feeding trials. In: Haresign, W. (ed.) *Recent Advances in Animal Nutrition*. Butterworths, London, pp. 12–23.

Morris, T.R. (1999) *Experimental Design and Analysis in Animal Sciences*. CAB International, Wallingford, UK.

Morris, T.R. (2004) Nutrition of chicks and layers. *World's Poultry Science Journal* 60, 5–18.

Morris, T.R. and Gous, R.M. (1988) Partitioning of the response to protein between egg number and egg weight. *British Poultry Science* 29, 93–99.

Nonis, M.A. and Gous, R.M. (2008) Threonine and lysine requirements for maintenance in chickens. *South African Journal of Animal Science* 38, 75–82.

Pilbrow, P.J. and Morris, T.R. (1974) Comparison of lysine requirements amongst eight stocks of laying fowl. *British Poultry Science* 15, 51–73.

Rostagno, H.S., Albino, L.F.T., Donzele, J.L., Gomes, P.C., Oliveira, R.F.M., Lopes, D.C., Ferreira, A.S. and Barreto, S.L.T. (2011) *Tabelas brasileiras para aves e suínos: composição de alimentos e exigências nutricionais*, 2nd edn. UFV, Departamento de Zootecnia, Viçosa, Brazil.

Sakomura, N.K. and Rostagno, H.S. (2007) *Métodos de pesquisa em nutrição de monogástricos*, 1st edn. FUNEP, Jaboticabal, Brazil.

SAS (2008) *SAS User's Guide: Statistics*. Statistical Analysis System Institute, Cary, North Carolina, USA.

Zhang, B. and Coon, C.N. (1994) Nutrient modelling for laying hens. *Journal of Applied Poultry Research* 3, 416–431.

20

Amino Acid Requirements for Pullets Based on Potential Protein Deposition and the Efficiency of Amino Acid Utilization

M.A. Bonato,[1] N.K. Sakomura,[1]* E.P. Silva,[1] J.A. Araújo,[1]
A. Sünder[2] and F. Liebert[2]
[1]*Universidade Estadual Paulista, Jaboticabal, São Paulo, Brazil;*
[2]*Georg-August-University, Goettingen, Germany*

Abstract

The aim of this study was to estimate lysine (Lys), methionine (Met) and threonine (Thr) requirements for pullets based on protein deposition and efficiency of amino acid dietary, based on the Goettingen University approach. Three assays of nitrogen balance were conducted with White Dekalb pullets, in periods I (14 to 28 days), II (56 to 70 days) and III (96 to 112 days). In each experiment, 56 pullets were distributed in a completely randomized design, with five treatments and six replications. The treatments were five diets with different nitrogen levels keeping constant the ideal ratio (amino acid/Lys), except for the amino acid being tested. Each trial included a control treatment in which a small amount of the amino acid under investigation was added to a diet with the same composition as the diet with the lowest content of the test amino acid to verify that the amino acid under test was first limiting in each trial. The data for nitrogen intake (*NI*) and nitrogen excretion (*NEX*) were collected and fitted by an exponential equation for each period to determine the nitrogen maintenance requirement (*NMR*). The maximum theoretical potential for nitrogen retention ($NR_{max}T$) was determined by the exponential relation between *NI* and nitrogen deposited (*ND*) for each period. Based on diets limiting in Lys, Met and Thr, the efficiency (bc^{-1}) was obtained. The quality of dietary protein (*b*) is dependent on concentration of the limiting amino acid in the protein of the diet (*c*). Intake limiting amino acid (*LAAI*) was calculated. All fitted equations were significant ($P < 0.01$). The *NMR* values determined were 270 mg/kg$^{0.67}$/day, 303 mg/kg$^{0.67}$/day and 348 mg/kg$^{0.67}$/day, and the $NR_{max}T$ values were 3208 mg/kg$^{0.67}$/day, 2353 mg/kg$^{0.67}$/day and 1739 mg/kg$^{0.67}$/day for each period. The bc^{-1} values were: 50, 90 and 100 for Lys; 170, 230 and 350 for Met; and 100, 160 and 180 for Thr, for periods I, II and III, respectively. These parameters were used in the formula and *LAAI* was determined considering 40%, 50% and 60% of $NR_{max}T$ for the periods I, II and III, respectively. In general, based on 50% of the $NR_{max}T$ values the requirements are lower than recommended in the literature, which is due to the methodology applied in this study (factorial model, type of approach), although the requirements are consistent for pullets.

Introduction

Poultry is one of the most important providers of animal protein to human diets (EMBRAPA, 2011). The egg is the main product of laying hens in commercial enterprises and contributes to the food protein supply. To ensure optimal development of layers (including

---

*E-mail: sakomura@fcav.unesp.br

Nutritional Modelling for Pigs and Poultry (eds N.K. Sakomura *et al.*)

their reproductive organs) pullets need an adequate supply of nutrients during growth; the supply of amino acids is particularly important for body protein synthesis.

To achieve the optimal content and dietary ratio of amino acids it is necessary to determine both the efficiency of amino acid utilization and the rate of protein deposition (Baker *et al.*, 2002). Several methodologies have been proposed to determine these parameters (Emmans, 1989; Martin *et al.*, 1994; Edwards and Baker 1999; Sakomura and Rostagno, 2007). However, these procedures utilize large numbers of animals and require the slaughter of a relatively large number of birds to measure their responses. Researchers at Georg-August-University in Goettingen, Germany, have proposed another approach. They have published studies based on factorial models using dose–response parameters obtained in nitrogen balance trials (Samadi and Liebert, 2006 a,b, 2007a,b, 2008; Liebert, 2008, 2013; Wecke and Liebert, 2013).

This approach makes use of a non-linear mathematical model to estimate the efficiency of amino acid utilization (bc^{-1}) taking into account the theoretical maximum for daily nitrogen deposition ($ND_{max}T$) and the nitrogen maintenance requirement (NMR) for determination of amino acid requirements.

Most studies have been conducted using broiler chickens (Samadi and Liebert, 2006b, 2007a,b, 2008; Wecke and Liebert, 2013), swine (Thong and Liebert, 2004; Wecke and Liebert, 2009, 2010) or fish (Liebert, 2009). However, up to now no studies have been performed using pullets. The current study was designed to determine the amino acid requirements of pullets based on the Goettingen approach.

Materials and Methods

Four nitrogen balance trials were conducted in the Laboratory of Poultry Sciences of the Faculty of Agriculture and Veterinary Sciences, Universidade Estadual Paulista, Jaboticabal, São Paulo, Brazil.

The model parameters determined in these four nitrogen balance (NB) trials were the nitrogen maintenance requirement (NMR) and the theoretical maximum for daily nitrogen retention ($NR_{max}T$). The last three NB trials were performed both to determine the efficiency of lysine (Lys), methionine (Met) and threonine (Thr) utilization (bc^{-1}) and to estimate the requirements for these amino acids of Dekalb White pullets in various growth phases (I: 14 to 28 days; II: 56 to 70 days; and III: 96 to 112 days). The procedures applied in this study are in accordance with earlier reports (Thong and Liebert, 2004; Samadi and Liebert, 2006a, b, 2007a,b, 2008; Liebert, 2008, 2009; Wecke and Liebert, 2009, 2013) performed to estimate the NMR, $NR_{max}T$, efficiency of amino acid utilization and amino acid requirements making use of NB trials.

Animals, housing and experimental design

A total of 360 Dekalb White birds was used in the trials. Management of the pullets and the lighting programme used followed the recommendations of the pullet management guide. The experimental design was completely randomized, with six treatments and five replicates of one bird per cage. At the beginning of each phase the body weight of the birds in the experimental units was standardized. Pullets were housed in metabolic cages with a floor space of 0.25 m^2/bird.

Dietary treatments

Prior to the start of each experimental period the birds received diets formulated according to the recommendations of the Brazilian Tables for Poultry and Swine (Rostagno *et al.*, 2005).

The first trial (T1) was conducted using graded dietary protein supply to determine the NMR and $NR_{max}T$ of the Dekalb White genotype (Table 20.1). Three trials (T2–T4) were conducted to estimate the model parameters (NMR, $NR_{max}T$) and efficiency of utilization of Lys, Met and Thr, respectively. The dietary treatments consisted of five levels of graded amino acid supply from equal protein

Table 20.1. Nutritional composition of the experimental diets (g/kg) in the four trials.

Nutritional composition	First trial (T1)						Lysine trial (T2)					Methionine trial (T3)					Threonine trial (T4)			
	L1	L2	L3	L4	L5	$L_{Lys}1$	$L_{Lys}2$	$L_{Lys}3$	$L_{Lys}4$	$L_{Lys}5$	$L_{M}1$	$L_{M}2$	$L_{M}3$	$L_{M}4$	$L_{M}5$	$L_{Thr}1$	$L_{Thr}2$	$L_{Thr}3$	$L_{Thrr}4$	$L_{Thr}5$
ME (MJ/kg)[a]	12.4	12.4	12.4	12.4	12.4	12.4	12.4	12.4	12.4	12.4	12.4	12.4	12.4	12.4	12.4	12.1	12.1	12.1	12.1	12.1
Crude protein[b]	**62.4**	**125**	**187**	**250**	**312**	**75.3**	**150**	**220**	**293**	**365**	**75.3**	**150**	**220**	**293**	**365**	**69.3**	**128**	**190**	**254**	**312**
Crude fibre	58.3	54.0	49.8	45.4	41.0	55.3	52.6	41.0	47.3	44.6	58.3	54.0	49.8	45.4	41.0	44.3	42.2	38.0	34.7	31.6
Calcium	9.40	9.40	9.40	9.40	9.40	9.40	9.40	9.40	9.40	9.40	9.40	9.40	9.40	9.40	9.40	9.40	9.40	9.40	9.40	9.40
Available phosphorus	4.38	4.38	4.38	4.38	4.38	4.40	4.40	4.40	4.40	4.40	4.40	4.40	4.40	4.40	4.40	4.37	4.37	4.37	4.37	4.37
Potassium	5.22	6.49	7.75	9.05	10.3	5.20	5.20	5.20	5.20	5.20	5.22	6.49	7.75	9.05	10.32	8.59	8.59	8.59	8.59	8.59
Sodium	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80
Lysine[c]	3.14	6.43	9.72	13.0	16.3	**3.63**	**7.37**	**11.1**	**14.7**	**18.3**	4.27	8.73	12.87	17.20	21.46	3.48	6.46	10.24	13.71	16.99
Methionine + cystiene	2.29	4.69	7.10	9.50	11.9	2.97	6.03	9.04	12.0	14.9	**2.58**	5.28	7.78	10.40	12.97	2.54	4.94	7.48	10.02	12.42
Methionine	1.54	3.16	4.78	6.39	8.01	1.87	3.80	5.71	7.58	9.42	1.49	**3.06**	**4.51**	**6.02**	**7.51**	1.74	3.38	5.12	6.86	8.50
Threonine	2.10	4.31	6.51	8.72	10.9	2.78	5.66	8.49	11.3	14.0	2.78	5.69	8.38	11.20	13.97	**1.91**	**3.72**	**5.63**	**7.54**	**9.35**
Tryptophan	2.10	4.31	6.51	8.72	10.9	0.77	1.55	2.33	3.10	3.85	0.76	1.56	2.30	3.08	3.84	0.63	1.23	1.87	2.50	3.10
Valine	2.54	5.21	7.87	10.5	13.2	4.60	6.87	10.3	13.7	17.0	3.36	6.88	10.13	13.54	16.89	2.68	5.20	7.87	10.55	13.07
Arginine	3.60	7.39	11.2	15.0	18.7	3.38	9.35	14.0	18.6	23.2	4.60	9.40	13.86	18.51	23.10	3.72	7.23	10.95	14.67	18.18
Leucine	5.58	11.4	17.3	23.1	29.0	7.34	14.9	22.4	29.7	36.9	7.24	14.81	21.82	29.16	36.38	6.88	13.35	20.23	27.11	33.59
Isoleucine	2.45	50.2	75.9	10.2	12.7	3.18	6.46	9.70	12.9	16.0	3.17	6.48	9.54	12.75	15.91	2.44	4.73	7.17	9.61	11.90

[a] Metabolizable energy, calculated according to WPSA.

[b,c] The values presented for the crude protein and amino acid contents were determined; the values for all of the other nutrients were calculated.

quality (e.g. L1, L2, L3, L4 and L5). In trial two (T2) Lys was the limiting amino acid in the diets; in trial three (T3) Met was limiting; and in trial four (T4) Thr was limiting (Table 20.1 and Table 20.2). Each trial included a control treatment in which a small amount of the amino acid under investigation was added to a diet with the same composition as the diet with the lowest content of the test amino acid to verify that the amino acid under test was first limiting in each trial.

Diets were formulated using the principles of the diet dilution technique (Fisher and Morris, 1970) according to the requirements of Rostagno *et al*. (2005). Table 20.2 presents the amino acid contents relative to crude protein and the ratio to the lysine content for each series of diets containing the various limiting amino acids. The treatments were the same in each study period.

Experimental procedures

Each experimental period was divided into an adaptation period (5 days) and a period with total excreta collection (10 days). For the first 2 days of the adaptation period, the feed was available *ad libitum* to determine the optimal feed intake under the metabolic cage conditions. Based on their *ad libitum* feed intake, the birds received a controlled quantity of feed for the next 3 days. This procedure was followed for the collection period. In the collection period, the excreta were collected once a day (in the afternoon) and immediately frozen at –20°C for later analysis. The amounts of feed intake (FI, g) and total excreta collected were quantified.

Excreta were freeze-dried for 72 h under controlled conditions (–80°C; –80 kPa; SuperModulyo; Thermo Fisher). Dry matter content was determined using a forced air oven at 105°C for 24 h, and the nitrogen content of the diets and excreta was quantified using the Kjeldahl method (AOAC, 1990: method 2001.11, Kjeltec 8400; Foss). To determine the amino acid composition of the diets the samples were hydrolysed with 6 M HCl under nitrogen for 24 h. The amino acids released by acid hydrolysis were separated using reversed-phase high performance liquid chromatography (HPLC) and detected in the UV range at 254 nm.

Nitrogen intake (*NI*, mg/$\mathrm{BW}_{\mathrm{kg}}^{0.67}$/day) and nitrogen excretion (*NEX*, mg/$\mathrm{BW}_{\mathrm{kg}}^{0.67}$/day) were determined. The nitrogen balance (*NB*, mg/$\mathrm{BW}_{\mathrm{kg}}^{0.67}$/day) was calculated from the difference between the *NI* and *NEX*, respectively.

Table 20.2. Amino acid content of dietary protein (g amino acid/100 g crude protein (CP)) and ratio to lysine (%) in the diets limiting in different amino acids.

	Lysine trial (T2)		Methionine trial (T3)		Threonine trial (T4)	
Amino acid[a]	L1 to L5 (g/100 g CP)	AA ratio to[b] Lys (%)	L1 to L5 (g/100 g CP)	AA ratio to[c] Lys (%)	L1 to L5 (g/100 g CP)	AA ratio to[d] Lys (%)
Lysine	**4.95**	**100**	5.82	100	5.37	100
Methionine + cysteine	4.05	82	3.52	60	3.92	73
Methionine	2.56	52	**2.04**	**35**	2.69	50
Threonine	3.80	77	3.79	65	**2.95**	**55**
Tryptophan	1.04	21	1.04	18	0.98	18
Arginine	6.28	127	6.26	108	5.74	107
Valine	4.62	93	4.58	79	4.13	77
Isoleucine	4.34	88	4.31	74	3.76	70
Leucine	10.0	202	9.86	170	10.6	198

[a] Amino acid content determined in the feed.

[b,c,d] Ratio of the amino acid relative to lysine (100%).

CP = Crude Protein

Nitrogen maintenance requirement (*NMR*) and maximum of theoretical potential for nitrogen deposition ($ND_{max}T$)

NMR (mg/$BW_{kg}^{0.67}$/day) was estimated by fitting an exponential function of *NI* and *NEX* ($NEX = NMR \cdot e^{b \cdot NI}$). *NMR* is the result of an extrapolation when the *NI* is equal to zero; e is the basic number of the natural logarithm; and *b* is the equation parameter that represents the slope of the exponential function. Nitrogen retention (*NR*, mg/$BW_{kg}^{0.67}$/day) is the sum of *ND* and *NMR*, and the theoretical maximum for daily nitrogen retention ($NR_{max}T$, mg/$BW_{kg}^{0.67}$/day) is the threshold value of the exponential function between *NI* and *ND*, i.e.:

$$NR = NR_{max}T \times (1 - e^{-b \times NI})$$

Or:

$$ND = NR_{max}T \times \ (1 - e^{-b \times NI}) - NMR$$

Data obtained from the four trials were used to determine *NMR*, $NR_{max}T$, and $ND_{max}T$, the latter being calculated as the difference between $NR_{max}T$ and *NMR*. $PD_{max}T$ was calculated as $ND_{max}T \times 6.25$.

Because these parameters express the theoretical potential for protein deposition of the genotype studied, data from the four trials were combined for further analysis.

Amino acid efficiency

The efficiencies of utilization of the test amino acids (bc^{-1}) were calculated using data from T2, T3 and T4, which involved individual limiting amino acids according to the following equation:

$$b = [\ln NR_{max}T - \ln (NR_{max}T - NR)]/NI$$

Where *b* is the slope of the exponential function resulting from graded amino acid or protein supply and indicates the dietary protein quality independent of *NI*.

The amino acid intake needed for a given *NR* is determined using the following equation, as derived by transformation of the basic function, with *NI* being replaced by intake of the *LAA*:

$$LAAI = [\ln NR_{max}T - \ln (NR_{max}T - NR)]/16 \cdot bc^{-1}$$

Where *LAAI* is the daily intake of the limiting amino acid (mg/$BW_{kg}^{0.67}$) needed for the intended response level (*NR*); and bc^{-1} is the linear slope resulting from the regression of the concentration of the *LAA* (*c* = g amino acid/100 g CP) in the feed protein on protein quality *b*. The bc^{-1} considered was in the linear range, where in each trial an amino acid was limiting. The conversion factor for *NI* based on the amino acid is given by the equation $NI = 16\ LAAI/c$.

Amino acid requirements

$NR_{max}T$ is the theoretical maximum or potential for nitrogen retention. In practice, it is impossible for the birds to achieve this theoretical threshold. Consequently, graded proportions of the potential (e.g. 40%, 50% and 60% of $ND_{max}T$) were used to calculate the Lys, Met and Thr requirements for pullets.

Statistical analysis

The Gauss method of the NLIN procedure in SAS software (version 9.2) was used to estimate the parameter values in the above equations. This method considers the sum of the least squares of the distances between the model and each point.

Results

Nitrogen balance

We studied chickens of the Dekalb White strain throughout the same growth periods in each of the trials. Therefore, the results for all of the nitrogen balance periods within equal age periods are summarized in Table 20.3. As the content of the limiting nutrient increased, the values for the *NI*, *NEX* and nitrogen balance (*ND*) also increased. Birds fed L1 had lower feed intake and body weight compared to those fed diets with higher protein contents, and the values of these variables were almost constant for the latter birds.

Table 20.3. Body weight (*BW*, g), feed intake (*FI*, g/day) nitrogen intake (*NI*, mg/$BW_{kg}^{0.67}$/day), nitrogen excretion (*NEX*, mg/$BW_{kg}^{0.67}$/day) and nitrogen balance (*ND*, mg/$BW_{kg}^{0.67}$/day) of the Dekalb White pullets as summarized for the individual age periods (I: 14 to 28 days, II: 56 to 70 days and III: 96 to 112 days).

Parameters	L1	L2	L3	L4	L5
			14 to 28 days		
BW	159	205	216	226	173
FI	18	24	25	23	17
NI	654	1221	1743	2176	2568
NEX	330	516	747	1029	1087
ND	324	705	996	1147	1481
			56 to 70 days		
BW	492	545	571	585	586
FI	32	34	34	35	34
NI	526	954	1315	1775	2357
NEX	295	431	642	971	1286
ND	231	524	673	803	1072
			96 to 112 days		
BW[a]	805	904	872	940	905
FI	43	51	44	43	40
NI	455	936	1385	1668	2066
NEX	289	477	689	997	1365
ND	166	459	696	671	701

[a] *BW* = average of the body weights at the beginning and end of each collection period.

NMR and $NR_{max}T$

NMR, $NR_{max}T$ and $ND_{max}T$ were calculated from data in Table 20.3. The nitrogen maintenance requirements increased with age until growth began to stabilize, and the retention and deposition of nitrogen decreased with increasing age.

In Fig. 20.1 the exponential function between *NI* and *NEX* from which *NMR* values are derived is illustrated. Because there are no observations in which *NI* is equal to zero, *NMR* values are extrapolations of the exponential function.

Values for $ND_{max}T$ obtained from the exponential function between *NI* and *ND* are illustrated in Fig. 20.2. This figure reveals that the *ND* data derived by approximation were higher than the observed values. This result was expected due to the theoretical basis of this methodology, which considers the maximum theoretical potential that characterizes the genotype, whereas in practice, the birds cannot achieve this daily deposition rate.

Table 20.4. Nitrogen maintenance requirements (*NMR*, mg/kg $BW^{0.67}$/day), theoretical maximum for daily nitrogen retention ($NR_{max}T$, mg/kg $BW^{0.67}$/day) and theoretical maximum for daily nitrogen deposition ($ND_{max}T$, mg/kg $BW^{0.67}$/day) during each growth period.

Period	*NMR*[a]	$ND_{max}T$[a]	$NR_{max}T$[b]
14 to 28 days	270	2938	3208
56 to 70 days	303	2050	2353
96 to 112 days	348	1391	1739

[a] $ND_{max}T$ – theoretical maximum for daily nitrogen deposition, calculated using the equation $NR_{max}T = ND_{max}T + NMR$.

[b] $ND = NR_{max}T\,(1 - e^{-b \cdot NI}) - NMR$.

Responses in nitrogen deposition of pullets fed different limiting amino acids (Lys, Met and Thr) during the periods studied are illustrated in Fig. 20.3, 20.4 and 20.5, respectively.

Amino acid efficiency and requirements

The daily protein deposition can be considered as a proportion of the theoretical

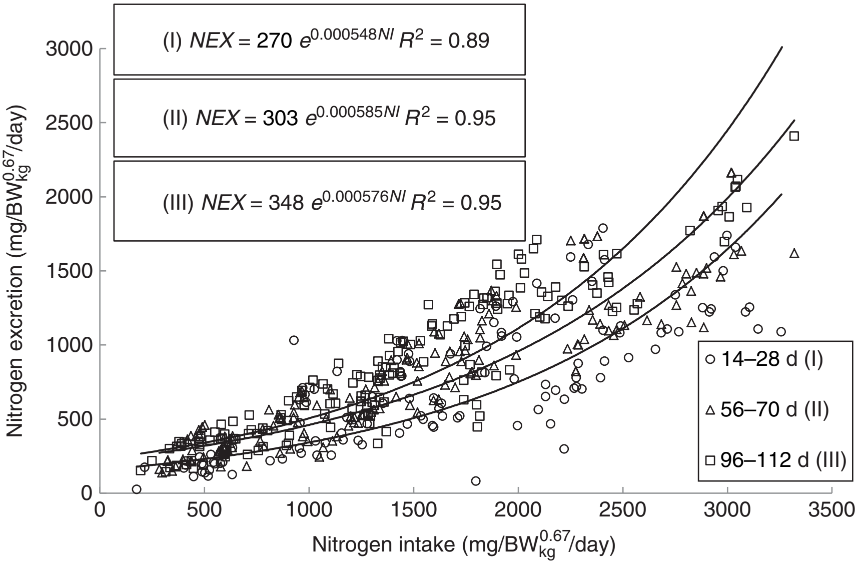


Fig. 20.1. Nitrogen maintenance requirements (*NMRs*) determined from the exponential function of nitrogen intake and nitrogen excretion values for the pullets in growth periods I (14 to 28 days), II (56 to 70 days) and III (96 to 112 days).

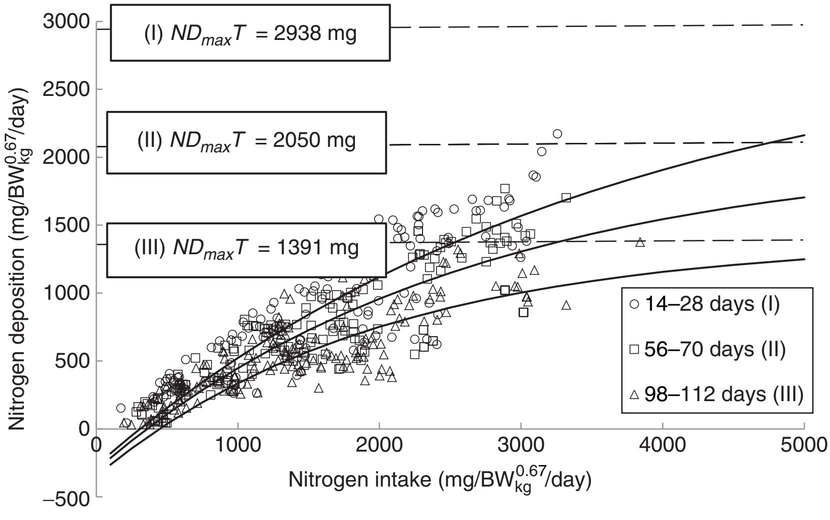


Fig. 20.2. Theoretical maximum daily nitrogen deposition (*ND*$_{max}$*T*) of pullets during periods I (14 to 28 days), II (56 to 70 days) and III (96 to 112 days) based on the relationship between their nitrogen intake and nitrogen deposition.

potential $ND_{max}T$. Subsequent calculations are based on 40%, 50% and 60% of the potential to reflect real performance by these birds. However, other proportions may be used depending on the situation.

Based on the efficiencies of amino acid utilization and protein deposition, the amino acid requirements were calculated from which the optimal amino acid contents in the diet were estimated by accounting for *FI* (Table 20.5, 20.6 and 20.7).

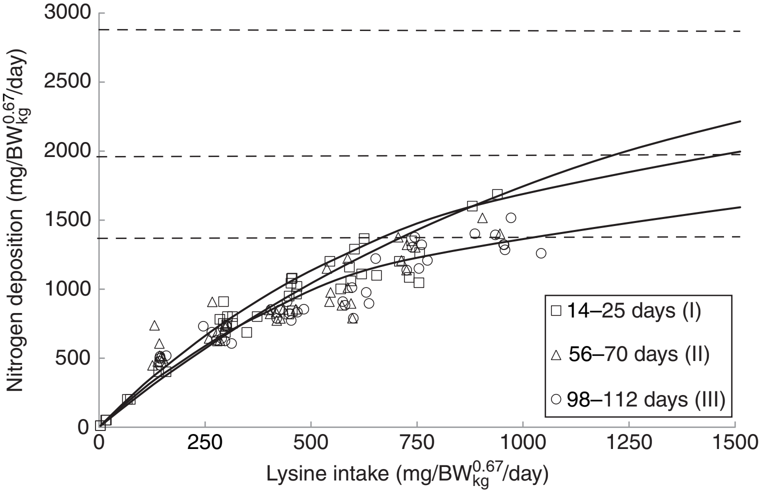


Fig. 20.3. Nitrogen deposition in pullets during periods I (14 to 28 days), II (56 to 70 days) and III (96 to 112 days) in response to lysine.

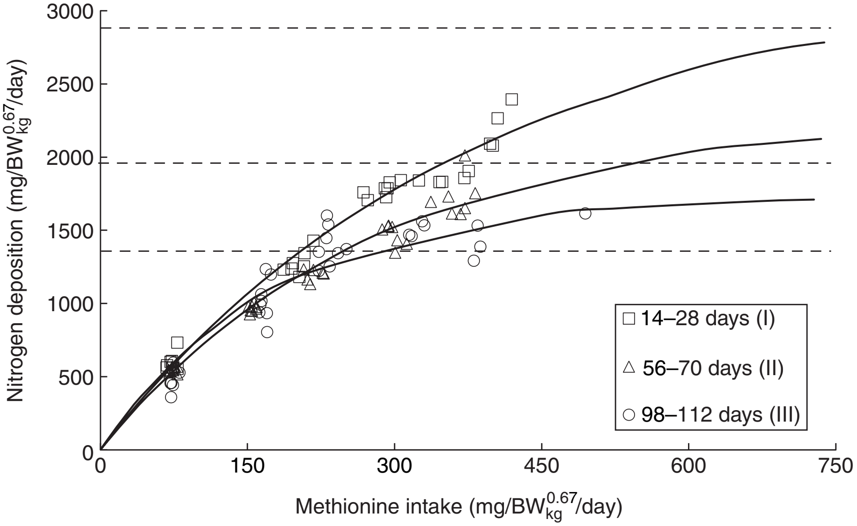


Fig. 20.4. Nitrogen deposition in pullets during periods I (14 to 28 days), II (56 to 70 days) and III (96 to 112 days) in response to methionine.

Discussion

The aims of this study were to model the amino acids, and to estimate the optimal amino acid contents in the diets of growing pullets according to their expected performance, based on the Goettingen approach. This approach considers *NMR*, $NR_{max}T$, *NR*, $ND_{max}T$ and the efficiency of amino acid utilization obtained from nitrogen balance trials.

This method calculates amino acid requirements needed to achieve a specific proportion of the theoretical genetic

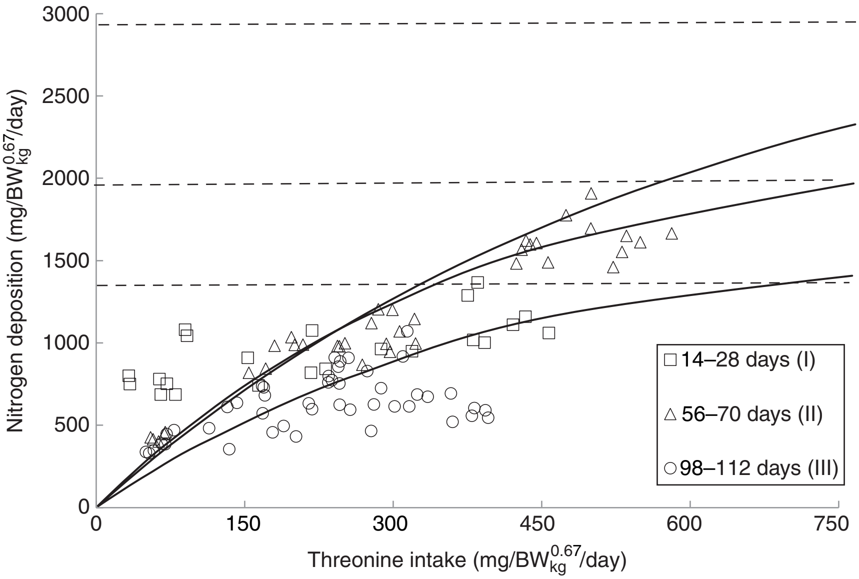


Fig. 20.5. Nitrogen deposition in pullets during periods I (14 to 28 days), II (56 to 70 days) and III (96 to 112 days) in response to threonine.

Table 20.5. Calculated amino acid requirements and optimal dietary contents of Lys, Met and Thr for pullets during growth period I (14 to 28 days, mean BW = 222 g) depending on protein deposition (PD) and observed amino acid efficiency.

	Lys			Met			Thr		
Efficiency of AA (bc^{-1})[a]		50			170			100	
PD (g/day)[b]	2.9	3.7	4.4	2.9	3.7	4.4	2.9	3.7	4.4
AA requirement[c]									
mg/BW$_{kg}^{0.67}$/day	651	884	1168	190	257	340	304	413	546
mg/day (at mean BW)	238	322	426	69	94	124	111	151	199
Optimal dietary content (g/kg)[d]	9.50	12.9	17.1	2.77	3.75	4.96	4.44	6.03	7.96

[a] Efficiency of amino acid utilization (bc^{-1}) considering that $b = [\ln NR_{max}T - \ln (NR_{max}T - NR)]/NI$ and c = protein content of the feed.

[b] Protein deposition values at 40%, 50% and 60% of the theoretical maximum for the daily nitrogen deposition ($ND_{max}T$).

[c] Amino acid requirements were calculated using the equation $LAAI = [\ln NR_{max}T - \ln (NR_{max}T - NR)]/16bc^{-1}$.

[d] For a daily feed intake of 25 g according to the pullet management guide.

potential for daily protein deposition. Therefore, a description of the potential nitrogen deposition of various strains is indispensable. As in other approaches for growth studies, the increased deposition of nitrogen or protein with age was considered here. Unlike other approaches, the description of nitrogen retention was separated into two parts, the first being the *NMR*, which is independent of nitrogen intake and appears to be specific for each genotype, and the second part is the physiological response boundary for given nitrogen deposition rates.

The average value for *NMR*, based on the three growth phases studied, was 307 mg/BW$_{kg}^{0.67}$/day, with *NMR* being extrapolated from *NI* = 0. The equivalent value for

Table 20.6. Calculated amino acid requirements and optimal dietary contents of Lys, Met and Thr for pullets during growth period II (56 to 70 days, mean BW = 582 g), depending on protein deposition (PD) and observed amino acid efficiency.

	Lys			Met			Thr		
Efficiency of AA (bc^{-1})[a]		90			230			160	
PD (g/day)[b]	4.1	5.1	6.1	4.1	5.1	6.1	4.1	5.1	6.1
AA requirement[c]									
mg/$BW_{kg}^{0.67}$/day	374	507	671	141	192	253	196	266	351
mg/day (at mean BW)	260	353	467	98	133	176	136	185	245
Optimal dietary content (g/kg)[d]	5.78	7.85	10.4	2.18	2.96	3.92	3.03	4.11	5.43

[a] Efficiency of amino acid utilization (bc^{-1}) considering that $b = [\ln NR_{max}T - \ln (NR_{max}T - NR)]/NI$ and c = protein content of the feed.

[b] Protein deposition values at 40%, 50% and 60% of the theoretical maximum for the daily nitrogen deposition ($ND_{max}T$).

[c] Amino acid requirements were calculated using the equation $LAAI = [\ln NR_{max}T - \ln (NR_{max}T - NR)]/16bc^{-1}$.

[d] For a daily feed intake of 45 g according to the pullet management guide.

Table 20.7. Calculated amino acid requirements and optimal dietary contents of Lys, Met and Thr for pullets during growth period III (96 to 112 days, mean BW = 920 g), depending on protein deposition (PD) and observed amino acid efficiency.

	Lys			Met			Thr		
Efficiency of amino acid (bc^{-1})[a]		100			350			180	
PD (g/day)[b]	4.1	5.1	6.2	4.1	5.1	6.2	4.1	5.1	6.2
Amino acid requirement[c]									
mg/$BW_{kg}^{0.67}$/day	309	419	554	91	123	162	177	240	318
mg/day (at mean BW)	292	397	524	86	116	154	167	227	300
Optimal dietary content (g/kg)[4=d]	4.00	5.43	7.18	1.51	2.05	2.71	2.10	2.85	3.76

[a] Efficiency of amino acid utilization (bc^{-1}) considering that $b = [\ln NR_{max}T - \ln (NR_{max}T - NR)]/NI$ and c = protein content of the feed.

[b] Protein deposition values at 40%, 50% and 60% of the theoretical maximum for the daily nitrogen deposition ($ND_{max}T$).

[c] Amino acid requirements were calculated using the equation $LAAI = [\ln NR_{max}T - \ln (NR_{max}T - NR)]/16bc^{-1}$.

[d] Daily feed intake at 65 g according to the pullet management guide.

laying hens determined by Filardi *et al.* (2000) was 178 mg/$BW_{kg}^{0.75}$/day. Our values were also higher than the 153 mg/$BW_{kg}^{0.75}$/day for Passeriformes (Allen and Hume, 2001) and 171 mg/$BW_{kg}^{0.67}$/day for slow-growing broilers (Samadi and Liebert, 2007b); however, they were 18% higher than the values determined for broilers (Samadi and Liebert, 2006a).

According to Reeds and Lobley (1980), when nitrogen is absent from the diet ($NI = 0$), catabolism or degradation of body protein occurs in order to maintain the pool of free amino acids for protein synthesis according to the metabolic priorities; the result of this degradation process is quantified in the *NMR*, so that differences found in *NMR* values can be associated with protein synthesis and degradation rates of different genotypes.

According to the traditional method described by Sakomura and Rostagno (2007) *NMR* is determined by positive and negative *NB* responses. The negative balance is limited by the rate of protein degradation, which tends to increase endogenous losses and hence *NMR*. Thus, with this approach, the positive *NB* is used to determine *NMR*, and hence, the result is closer to the observed value.

$NR_{max}T$ is dependent on the genotype and changes with age, as shown by our results. This value decreased from period I (14 to 28 days) to period III (96 to 112 days) and would tend to reach zero when growth of protein ceases in adult birds and only fat is deposited thereafter (Samadi and Liebert, 2006b, 2007a; Marcato *et al.*, 2010).

Traditionally, the potential for growth has been described by the Gompertz growth model, based on the body or body protein weight (*BP*) vs time (*t*). By dividing the first derivative of this equation by the metabolic weight of the bird ($dBP/dt \div BW_{kg}^{0.67}$) it is possible to determine the nitrogen deposition rate ($BP \div 6.25$) in mg/$BW_{kg}^{0.67}$/day. Considering the results of Martin *et al.* (1994) obtained on the same basis as in this study (mg/$BW_{kg}^{0.67}$/day), the $ND_{max}T$ values were 860 mg/$BW_{kg}^{0.67}$/day, 865 mg/$BW_{kg}^{0.67}$/day and 791 mg/$BW_{kg}^{0.67}$/day for the Hisex, Ross Brown and Amber-Link strains, respectively. The differences between their values and those of the present study are related to methodological aspects. Martin *et al.* (1994) used the comparative slaughter technique to determine protein deposition, and the dietary nitrogen intake levels were in agreement with practical conditions, in contrast with the conditions applied in this study.

Other differences between the above-mentioned approaches and the approach applied in this study are that values for $ND_{max}T$ were determined using non-destructive methods and the birds were subjected to high levels of nitrogen intake to characterize the nitrogen use limit of this modern strain, which provided knowledge that can be used to understand and explore their full deposition potential, thereby limiting dietary amino acid levels to minimize nitrogen excretion and avoid the use of excessive levels of nutrients.

The theoretical maximum rate of protein deposition ($PD_{max}T$) obtained from $ND_{max}T$ characterizes the genetic potential of the strain and it is not possible to attain this by improving the diet; therefore, different attainable threshold values can be expressed as a percentage of $PD_{max}T$ (Samadi and Liebert, 2006a).

The three amino acids under study produced different rates of deposition of nitrogen (Fig. 20.3, 20.4 and 20.5). This is due to the fact that each amino acid has a different composition in the protein being formed. However, as this method does not use the comparative slaughter technique, it is not possible to determine these concentrations. However, their importance may be observed in nitrogen deposition.

To estimate dietary amino acid requirements it is necessary to know the efficiency of utilization of each amino acid. In the approach taken in this study the efficiency is obtained from the relationship between *b* (protein quality of the feed) and *c* (concentration of the limiting amino acid in dietary protein). To compare the efficiencies of amino acid utilization found in this study with those in the literature, a calculation must be performed. Considering a protein deposition rate of 60% for each growth phase, based on the maximum potential for protein deposition and the Lys, Met and Thr contents of the body plus the feathers, according to Emmans (1989) and considering the estimated amino acid intake (Tables 20.5, 20.6 and 20.7), the calculated efficiencies for body protein deposition of the individual amino acids in the three growth phases are 86%, 73% and 75% for Lys, 75%, 73% and 65% for Met and 94%, 86% and 78% for Thr. The values obtained in this study are within the range of those reported in the literature (Hurwitz and Bornstein, 1973; Martin *et al.*, 1994; Edwards *et al.*, 1997, 1999; Edwards and Baker, 1999; Fatufe *et al.*, 2004). The great variation among the reported values is due to the use of different approaches and, moreover, these results are mostly for broilers because no studies using pullets were found in the literature. However, the efficiency of amino acid utilization is an important dietary parameter that must be thoroughly studied because it represents how the birds use an amino acid for growth.

All of the information regarding the Dekalb White pullets that was obtained in this study using the Goettingen approach was applied in the *LAAI* equations to provide the limiting amino acid intake as a percentage of $ND_{max}T$. The proportions chosen of the theoretical potential (40%, 50% and 60%) were within the range recommended by Samadi and Liebert (2006b) to be close to practical deposition values. These results were transformed to obtain the optimal content in the diet (g/kg) according to a given feed intake (g) and considering the recommendations for the strain, although accurate prediction of feed intake that may occur under practical housing conditions is as yet not possible (Samadi and Liebert, 2006b). However, this modelling methodology allows adjustment of the requirements according to the situation because it is possible to adapt the daily protein deposition and feed intake to that observed in the field.

The values found in this study based on 50% of the maximum protein deposition ($ND_{max}T$), which was the mean value assessed in this study, and the feed intake observed in growth period I, are higher than the predicted values presented in the literature, whereas the values for periods II and III are lower, except for the values for lysine, which were higher (NRC, 1994; Rostagno *et al.*, 2011). This result is due to the pullets depositing more protein in their bodies plus their feathers during the first period of growth (6 to 12 weeks), with protein deposition thereafter beginning to decrease. In general, the values are lower than recommended, which is due to the methodology applied in this study (factorial model type of approach), although the requirements are consistent for pullets.

While characterizing threshold protein deposition, Sakomura *et al.* (2012) obtained a standard deposition rate (protein deposition rate under normal conditions) and $PD_{max}T$, and found that pullets have a maximum relative potential of 11% from 1 to 63 days, meaning that they have a capacity for growth that could be exploited by nutritionists. According to Sakomura *et al.* (2012) another application of the knowledge of physiological limits is the identification of the more demanding individuals in the population, which can facilitate the decision about the ideal profile of amino acids to be included in dietary protein.

In conclusion, the Goettingen approach as applied in this study enables both the daily amino acid requirements and optimal in-feed contents to be estimated while considering the genetic growth potential of the birds, the desired rate of protein deposition and expected feed intake. Among the advantages of this method are the simplicity of the trials, the use of a small number of animals, the lack of the necessity to slaughter them so that they may be re-used, and its low cost. In addition, it is also possible to estimate with high accuracy the nitrogen requirement for maintenance and deposition, and the efficiency of utilization of amino acids using this method. However, further studies should be conducted to estimate the amino acid requirements of pullets during their growth period, due to the importance of this period in the development of hens.

Acknowledgements

We are grateful for the support of the Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP) and the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq).

References

Allen, L.R. and Hume, I.D. (2001) The maintenance nitrogen requirement of the Zebra Finch *Taeniopygia guttata*. *Physiological and Biochemical Zoology* 74, 366–375.

Association of Official Analytical Chemists (AOAC) (1990) *Official Methods of Analysis*, 15th edn. AOAC, Washington, DC, USA.

Baker, D.H., Batal, A.B., Parr, T.M., Augspurger, N.R. and Parsons, C.M. (2002) Ideal ratio (relative to lysine) of tryptophan, threonine, isoleucine and valine for chicks during the second and third weeks posthatch. *Poultry Science* 81, 485–494.

Edwards, H.M and Baker, D. (1999) Maintenance sulfur amino acid requirements of young chicks and efficiency of their use for accretion of whole-body sulfur amino acids and protein. *Poultry Science* 78, 1418–1423.

Edwards, H.M., Baker, D.H. Fernandez, S.R., Parsons, C.M. (1997) Maintenance threonine requirement and efficiency of its use for accretion of whole-body threonine and protein in young chicks. *British Journal of Nutrition* 78, 111–119.

Edwards, H.M., Fernandez, S.R., Baker, D.H. (1999) Maintenance lysine requirement and efficiency of using lysine for accretion of whole-body lysine and protein in young chicks. *Poultry Science* 78, 1412–1417.

Emmans, G.C. (1989) The growth of turkeys. In: Nixey, C.G. and Grey, T.C. (eds) *Recent Advances in Turkey Science*. Poultry Science Symposium, Butterworths, London, pp. 135–166.

EMBRAPA, Centro Nacional de Pesquisa de Suínos e Aves (2011) *Anuário Estatístico – Avicultura: Central de inteligência da Embrapa Suínos e Aves*, 1st edn. EMBRAPA-CNPSA, Documentos, 147.

Fatufe, A., Timmler, R. and Rodehutscord, M. (2004) Response to lysine intake in composition of body weight gain and efficiency of lysine utilization of growing male chickens from two genotypes. *Poultry Science* 83, 1314–1324.

Filardi, R.S., Sakomura, N.K., Basaglia, R., Resende, K.T. and Sanches, A. (2000) Equações de predição das exigências de proteína bruta para matrizes pesadas em crescimento. *Revista Brasileira de Zootecnia* 29, 2308–2315.

Fisher, C. and Morris, T.R. (1970) The determination of the methionine requirements of laying pullets by a diet dilution technique. *British Poultry Science* 11, 67–82.

Hurwitz, S. and Bornstein, S. (1973) The protein and amino acid requirements of laying hens: suggested models for calculation. *Poultry Science* 52, 1124–1134.

Liebert, F. (2008) Modelling of protein metabolism yields amino acid requirements dependent on dietary amino acid efficiency growth response, genotype and age of growing chicken. *Avian Biology Research* 1(3), 101–110.

Liebert, F. (2009) Amino acid requirement studies in *Oreochromis niloticus* by application of principles of the diet dilution technique. *Animal Physiology and Animal Nutrition* 93, 785–793.

Liebert, F. (2013) Basics and applications of an exponential N-utilization model ('Goettingen approach') for assessing amino acid requirements in growing pigs and meat type chicken depending on dietary amino acid efficiency. *Proceedings of the International Symposium: Modelling in Pig and Poultry Production*. Funep, Jaboticabal, São Paulo, Brazil.

Marcato, S.M., Sakomura, N.K., Fernandes, J.B.K., Siqueira, J.C., Dourado, L.R.B. and Freitas, E.R. (2010) Crescimento e deposição de nutrientes nos órgãos de frangos de corte de duas linhagens comerciais. *Revista Brasileira de Zootecnia* 39, 1082–1091.

Martin, P.A., Bradford, G.D. and Gous, R.M. (1994) A formal method of determining the dietary amino acid requirements of laying-type pullets during their growing period. *British Poultry Science* 35, 709–724.

National Research Council (NRC) (1994) *Nutrient Requirements of Poultry*, 9th edn. NRC, Washington, DC.

Reeds, P.J. and Lobley, G.E. (1980) Protein synthesis: are there real species differences? *Proceedings of the Nutrition Society* 39, 43–52.

Rostagno, H.S., Albino, L.F.T., Donzele, J.L., Gomes, P.C., Oliveira, R.F.M., Lopes, D.C., Ferreira, A.S. and Barreto, S.L.T. (2005) *Tabelas brasileiras para aves e suínos: composição de alimentos e exigências nutricionais*, 2nd edn. Universidade Federal de Viçosa, Viçosa, Minas Gerais, Brazil.

Rostagno, H.S., Albino, L.F.T., Donzele, J.L., Gomes, P.C., Oliveira, R.F.M., Lopes, D.C., Ferreira, A.S., Barreto, S.L.T. and Euclides, R.F. (2011) *Tabelas brasileiras para aves e suínos: composição de alimentos e exigências nutricionais*, 3rd edn. Universidade Federal de Viçosa, Viçosa, Minas Gerais, Brazil.

Sakomura, N.K. and Rostagno, H.S. (2007) *Métodos de pesquisa em nutrição de monogástricos*. Funep, Jaboticabal, São Paulo, Brazil.

Sakomura, N.K., Silva, E.P., Bonato, M.A. and Donato, D.C.Z. (2012) Níveis nutricionais de aminoácidos para aves de postura. *Proceedings of the IX Curso de Atualização em Avicultura para Postura Comercial*. Funep, Jaboticabal, São Paulo, Brazil, pp. 91–106.

Samadi and Liebert, F. (2006a) Estimation of nitrogen maintenance requirements and potential for nitrogen deposition in fast-growing chickens depending on age and sex. *Poultry Science* 85, 1421–1429.

Samadi and Liebert, F. (2006b) Modelling threonine requirement depending on age, protein deposition, dietary threonine efficiency and sex of fast growing chickens. *Poultry Science* 85, 1961–1968.

Samadi and Liebert, F. (2007a) Lysine requirement of fast growing chickens: effects of age, sex, level of protein deposition and dietary lysine efficiency. *The Journal of Poultry Science* 44, 63–72.

Samadi and Liebert, F. (2007b) Threonine requirement of slow growing male chickens depends on age and dietary efficiency of threonine utilization. *Poultry Science* 86, 1140–1148.

Samadi and Liebert, F. (2008) Modelling the optimal lysine to threonine ratio in growing chickens depending on age and efficiency of dietary amino acid utilization. *British Poultry Science* 49, 45–54.

Thong, H.T. and Liebert, F. (2004) Potential for protein deposition and threonine requirement of modern genotype barrows fed graded levels of protein with threonine as the limiting amino acid. *Journal of Animal Physiology and Animal Nutrition* 88, 196–203.

Wecke, C. and Liebert, F. (2009) Lysine requirement studies in modern genotype barrows dependent on age, protein deposition and dietary lysine efficiency. *Journal of Animal Physiology and Animal Nutrition* 93, 295–304.

Wecke, C. And Liebert, F. (2010) Optimal dietary lysine to threonine ratio in pigs (30–110kg BW) derived from observed dietary amino acid efficiency. *Journal of Animal Physiology and Animal Nutrition* 94, 277–285.

Wecke, C. and Liebert, F. (2013) Improving the reliability of optimal in-feed amino acid ratios based on individual amino acid efficiency data from N balance studies in growing chickens. *Animal* 3, 558–573.

21 A Comparison of Two Approaches for Determining the Optimum Dietary Amino Acid Ratios of Fast-growing Broilers

J.C.P. Dorigam,[1] N.K. Sakomura,[1]* A. Sünder[2] and C. Wecke[2]
[1] *Universidade Estadual Paulista, Jaboticabal, São Paulo, Brazil;*
[2] *Georg-August-University Goettingen, Goettingen, Germany*

Abstract

Two approaches using the amino acid (AA) dilution method, the comparative slaughter and nitrogen (N) balance methods, were used in the present study to re-evaluate the assumptions of ideal ratios between the essential amino acids (EAA): lysine (Lys), methionine + cystine (Met+Cys), threonine (Thr), tryptophan (Trp), arginine (Arg), valine (Val), isoleucine (Ile), leucine (Leu), phenylalanine + tyrosine (Phe+Tyr), glycine + serine (Gly+Ser) and histidine (His) for growing broilers of the Cobb 500 genotype over three periods (I: 6 to 21 days, II: 22 to 37 days, and III: 38 to 53 days). In each trial 120 male chickens were housed in metabolic cages for assessment of individual N balance and AA efficiency. An AA-balanced diet (BD) was formulated according to the recommendations of Brazilian tables for the ideal protein in growing broilers. The diets with different limiting AAs were created by dilution of the BD with maize starch to achieve 0.70 of the AA level in BD and supplemented with crystalline AAs, except for the AA under study. The AA-diluted diets led to significant impairment of protein utilization and indicated the valid limiting position of these AAs. Also, at the start and end of the trial a group of birds with the mean body weight of each replicate was killed with no blood loss to determine N deposition using the comparative slaughter technique. The mean values of the optimum ratios of the 11 tested EAAs determined by comparative slaughter in the three periods are: Lys 100, Met+Cys 65, Thr 66, Trp 17, Arg 108, Val 79, Ile 61, Leu 122, Phe+Tyr 128, Gly+Ser 155 and His 41. Based on observed AA efficiency data, the optimum ratios determined by N balance are: Lys 100, Met+Cys 72, Thr 65, Trp 17, Arg 106, Val 76, Ile 67, Leu 107, Phe+Tyr 115, Gly+Ser 137 and His 35. There are some differences among the results obtained by the two methods (the broken line model and the Goettingen approach) and they will be discussed in accordance with the key assumptions.

Introduction

In poultry feed formulation the quality of a dietary protein is associated with its amino acid (AA) composition and its bioavailability. In another words, the quality of a dietary protein can be considered to be the degree to which the composition of the absorbed AA mixture satisfies the AA balance required by the animal (Wang and Fuller, 1989). Consequently the estimation of the essential amino acids (EAAs) required by an animal can be

---

*E-mail: sakomura@fcav.unesp.br

Nutritional Modelling for Pigs and Poultry (eds N.K. Sakomura *et al.*)

used as an assessment of quality of any dietary protein based on the AA pattern of a reference protein considered to be 'ideal'. Thus, knowledge of the optimal dietary AA pattern in broiler diets is continuously being improved by the use of several procedures with different physiological bases and accuracy.

Conventionally EAA requirements have been assessed by dose–response studies using the graded supplementation technique (Baker and Han, 1994; Mack *et al.*, 1999; Baker *et al.*, 2002). However, this method is expensive and time-consuming (Rollin *et al.*, 2003) because multiple assays are needed. Therefore, another practical method was developed to measure the composition of the EAAs in the ideal protein required for swine (Fuller *et al.* 1989; Wang and Fuller, 1989) and this was later adapted for broilers (Gruber *et al.*, 2000; Roth *et al.*, 2001). The AA dilution method relies on a single experiment to determine optimum ratios of all EAAs. This method is based on the concept that the reduction of a non-limiting AA has no effect on nitrogen (N) deposition. Thus, the changes in N deposition measured on removal of a proportion of each EAA in turn are used to calculate a dietary AA pattern in which all EAAs were equally limiting. The advantage of this method is that all AA ratios are determined simultaneously using the same stock of animals and the same balanced diet (Green and Hardy, 2002). Consequently this allows better uniformity and consistency, facilitating the precision needed to determine the optimum AA ratios.

For practical use, Rollin *et al.* (2003) proposed an equation to determine the AA requirement that is described by a broken line regression. Although it was suggested that the utilization of a limiting EAA is well described by a non-linear model (Fatufe *et al.*, 2004; Samadi and Liebert 2008), the inflection point of a broken line model can predict minimal requirement values that are desirable for calculating EAA ratios (Baker, 2003). This method also assumes that the efficiencies of the EAAs are similar independent of their dietary concentration. Actually, it is known that the efficiency of utilization of the dietary AA is an important factor that affects amino acid requirements (Samadi and Liebert, 2006, 2007). Considering an equal protein deposition, the AA requirement is only dependent on the efficiency of its utilization (Samadi and Liebert, 2008). In this way, it is possible to compare the efficiency of utilization of individual AAs directly to evaluate the optimal AA ratio (Samadi and Liebert, 2008). This procedure to derive a scale of optimal AA ratios within one experiment is still under evaluation.

N deposition can be assessed when using the dilution method either by the N balance technique, where deposited N is obtained from the difference between N intake and N excretion, or by comparative slaughter, where deposited N corresponds to the difference in body N of broilers between the start and the end of the experimental period. However, the undetected and additive losses of feed and excreta can overestimate N deposition when using the N balance technique, and losses from the comparative slaughter technique can lead to errors in the opposite direction (Just *et al.*, 1982). Studies comparing both techniques indicate that the difference between these estimations of nitrogen deposition is variable (Just *et al.*, 1982), but the description of its influence on the determination of the EAA pattern has been examined in only a small number of studies (Zhengling, 2001).

In this context, the objective of the present study was to compare two approaches using the AA dilution method, comparative slaughter and the N balance technique, to re-evaluate the actual assumptions of an ideal ratio between the EAAs: lysine for male Cobb 500 broilers over three periods of growth (6 to 21 days, 22 to 37 days and 38 to 53 days).

Materials and Methods

One N balance trial was performed per age period (I: 6 to 21 days, II: 22 to 37 days and III: 38 to 53 days) using male Cobb 500 broilers. The experimental design consisted of 12 experimental diets and ten replicates per treatment. This study included two approaches for determining the optimum dietary amino acid ratio: for the N balance experiment a group of birds was utilized to study the effects of dilution of individual AAs on protein quality (Samadi and Liebert, 2008); simultaneously to this N balance trial a group of birds was slaughtered at the start and end of the experimental period to provide the data needed to calculate a dietary AA pattern, in which all the AAs were equally limited, by a proposed broken line model (Rollin *et al.*, 2003).

Animals and housing

The experiments were carried out in the Laboratory of Poultry Sciences of the Faculty of Agriculture and Veterinary Sciences, Universidade Estadual Paulista, Jaboticabal, São Paulo, Brazil. Within the age periods the birds were randomly allocated to treatments and individually housed in metabolism cages with wire floors, equipped with individual feeders and self-drinking systems. The temperature was controlled using a negative-pressure system, starting with 32°C (1-day-old chicks) and decreased continuously to 24°C by 53 days.

Experimental diets

A balanced diet (BD) was formulated according to the recommendations of the Brazilian tables for poultry and swine (Rostagno *et al.*, 2011) for the ideal amount of protein for growing broilers for each period. The N and AA content of the BD was supplied by maize, soy protein concentrate and a mixture of crystalline L-AAs. Experimental diets with different limiting AAs were created by dilution of the BD with maize starch to achieve 0.70 of the AA level in BD and supplemented with crystalline AAs, except for the AA under study. In all experimental diets the remaining nutrient and energy contents remained the same. The composition, AA and nutritional composition of the BD in each period is shown in Table 21.1.

Procedures

The N balance trials were divided into adaptation period (5 days) and two consecutive periods of excreta collection (5 days each). During this period the experimental diets were supplied until the end of excreta collection. At the beginning of the adaptation period diets were supplied *ad libitum* to predict the feed intake (according to metabolic body weight) for the collection period. The feed was supplied until the beginning of the third day of the adaptation period. Based on the measured consumption of the last 3 days of adaptation the feed supply was slightly adapted for the next 2 days. At the start of the collection period, feed intake was measured again and the feed supply for each individual was kept constant to the end of the collecting period. This procedure was suggested as an acceptable adaptation to increasing feed intake in fast-growing chickens (Samadi and Liebert, 2008). The excreta were collected directly from trays (free of feathers) and immediately stored in a freezer at –20°C until further analysis could be undertaken. Body N deposition was also determined using the comparative slaughter method. At the beginning of the trial two birds of each replicate with similar body weight were euthanized using CO_2 after a fasting period of 36 h in order to determine N content in the whole body (carcass plus feathers), and at the end of each assay all remaining birds were also slaughtered. The slaughtered birds were stored in a freezer at –20°C before further processing.

Chemical analysis

The excreta stored in the freezer were thawed, homogenized and weighed. The samples were then freeze-dried (Edwards 501, Thermo®, Crawley, West Sussex, UK) at –90°C for 72 h. The dried samples were ground in a micromill (A11 Basic, IKA®, Staufen, Germany) and then stored in a freezer (–20°C) until analysis. The initial and final groups of slaughtered birds stored

Table 21.1. Composition of the experimental diets (g/kg in dry matter) to determinate the optimum ratio between the amino acids for male broilers (Cobb 500).

Composition of the balanced diets (g/kg in dry matter)			
	Period I (6 to 21 days)	Period II (22 to 37 days)	Period III (38 to 53 days)
Maize	740	779	804
Soy protein concentrate (60)	136	97.7	62.2
Soybean oil	12.7	15.4	21.9
Dicalcium phosphate	17.2	14.9	12.8
L-Alanine (990 g/kg)	40.7	41.6	46.8
Limestone	8.95	8.42	7.51
L-Lysine HCl (780 g/kg)	7.16	7.05	7.01
DL-Methionine (990 g/kg)	4.40	3.99	3.54
Choline chloride (600 g/kg)	2.82	2.76	2.73
L-Glycine (960 g/kg)	6.19	4.47	4.51
Salt	4.80	4.58	4.49
Potassium chloride	1.41	2.69	4.03
L-Threonine (960 g/kg)	2.91	2.74	2.62
Vitaminic\mineral premix[a]	1.00	1.00	1.00
L-Arginine (990 g/kg)	3.84	4.07	4.34
L-Isoleucine (990 g/kg)	2.67	2.76	2.78
L-Valine (980 g/kg)	3.11	3.07	2.96
L-Phenylalanine (990 g/kg)	2.55	2.68	2.88
L-Histidine (990 g/kg)	0.76	0.77	0.80
L-Tryptophan (980 g/kg)	0.62	0.77	0.81
Nutritional composition[b] of the balanced diets (g/kg in dry matter)			
Calcium	8.20	7.30	6.40
Metabolizable enegy (MJ/kg)	13.0	13.2	13.4
Crude fibre	16.6	16.2	15.6
Available phosphorus	3.90	3.40	3.00
Potassium	5.90	5.80	5.80
Crude protein	210	190	175
Sodium	2.10	2.00	2.00
Content of amino acids[c] (g/kg in dry matter) and EAA:lysine ratio in the balanced diets			
Arginine	13.2 (108)	11.6 (108)	10.2 (109)
Phenylalanine	9.3 (76)	8.3 (78)	7.5 (80)
Phenylalanine + tyrosine	14.0 (115)	12.3 (115)	10.8 (115)
Glycine + serine	17.9 (147)	14.4 (135)	12.6 (134)
Histidine	4.5 (37)	4.0 (37)	3.5 (37)
Isoleucine	8.2 (67)	7.3 (68)	6.4 (68)
Leucine	13.0 (107)	11.6 (108)	10.2 (109)
Lysine	12.2 (100)	10.7 (100)	9.4 (100)
Methionine + cystine	8.8 (72)	7.8 (73)	6.9 (73)
Methionine	6.6 (54)	6.0 (56)	5.2 (55)
Threonine	7.9 (65)	7.0 (65)	6.1 (65)
Tryptophan	2.1 (17)	1.9 (18)	1.7 (18)
Valine	9.4 (77)	8.4 (79)	7.3 (78)

[a] Content/kg – vitamin A = 15,000,000 UI; vitamin D3 = 1,500,000 UI; vitamin E = 15,000 UI; vitamin B1 = 2.0 g; vitamin B2 = 4.0 g; vitamin B6 = 3.0 g; vitamin B12 = 0.015 g; nicotinic acid = 25 g; pantotenic acid = 10 g; vitamin K3 = 3.0 g; folic acid = 1.0 g; zinc bacitracine = 10 g; selenium = 250 mg; antioxidant butylated hydroxytoluene = 10 g; manganese = 80g; iron = 80 g; zinc = 50g; copper = 10 g; cobalt = 2 g; iodine = 1 g; e vehicle quantity sufficient to 1000 g.

[b] Calculated.

[c] Analysed content of diets and calculated based on true digestibility of the amino acids in the diets (analysis performed by Ajinomoto LTDA).

in the freezer were autoclaved for 6 h once the temperature reached 127°C at a pressure of 1 atm. The birds were then homogenized in an industrial blender and the samples weighed before being placed in a forced draught oven at 55°C for 72 h. The dried samples were milled in a ball mill and kept in a freezer (–20°C) until analysis. The diets were analysed for dry matter, crude protein and AA. The excreta and whole-body composition were analysed for dry matter and crude protein. Samples were analysed using the following conventional procedures (AOAC, 2002): dry matter by drying at 105°C for 16 h, crude protein (N × 6.25) by using the Kjeldahl method (method no. 2001.11) after acid digestion. Daily N gain was calculated on the basis of whole-body composition analysis. The AA composition of diets was measured by hydrolysis with 6 N hydrochloric acid for 24 h. AAs released in the acid hydrolysis were separated by reverse phase high-performance liquid chromatography (HPLC) and detected using UV at 254 nm. Additionally, the apparent metabolizable energy content of BD was calculated according to the method of Rostagno *et al*. (2011).

Data analysis

All statistics were performed using a SAS statistical package (version 9.1). Data were submitted to variance analysis, and average AA ratios were compared using the *F* test with a probability of 0.05. Significant differences between deficient treatments and the BD treatment responses were tested using Dunnett's test, and values of $P < 0.05$ were deemed statistically significant.

In the N balance study the dietary protein quality (b) in each treatment was estimated according to the equation of Samadi and Liebert (2008):

$$b = \frac{\ln NR_{max}T - \ln(NR_{max}T - NR)}{NI}$$

Where $NR_{max}T$ is the theoretical maximum N retention (mg N/$BW_{kg}^{0.67}$/day), NI is N intake (mg N/$BW_{kg}^{0.67}$/day) and NR is N retention (mg N/$BW_{kg}^{0.67}$/day). The $NR_{max}T$ value is considered to be 'theoretical' because this value is not the same as for practical performance data, but estimates genetic potential (Samadi and Liebert, 2006). The $NR_{max}T$ value for the Cobb 500 genotype was estimated in a previous study (Dorigam, 2012) according to the procedure of Samadi and Liebert (2007). The $NR_{max}T$ values used in the equation were 3966 mg N/$BW_{kg}^{0.67}$/day (6 to 21 days); 3401 mg N/$BW_{kg}^{0.67}$/day (22 to 37 days); and 2480 mg N/$BW_{kg}^{0.67}$/day (38 to 53 days). The slope of the linear function between dietary L-AA concentration 'c' (g AA/100 g crude protein (CP)) and feed protein quality 'b' was directly utilized as model parameter (bc^{-1}) indicating the efficiency of L-AA utilization (Samadi and Liebert, 2006) and it is only valid when the AA is in a limiting position. Consequently, it is possible to compare the model parameters (bc^{-1}) of an individual AA directly. Using this procedure for evaluating the optimal AA ratio, comparisons are only allowed within equal age periods because $NR_{max}T$ varies with body weight and affects the established value of (bc^{-1}). The relationship between lysine efficiency (reference) and the efficiency of the AA under study is utilized to derive ideal AA ratios (IAAR):

$$IAAR = \frac{bc_{Lys}^{-1}}{bc_{LAA}^{-1}}$$

In the comparative slaughter study the analysed N content of the whole-body composition was used to determine the N deposition using the following equation proposed by Rollin *et al*. (2003):

$$\text{N deposition} = \frac{(W_f \times N_f) - W_i \times N_i)}{\frac{1}{2}\left(\left(\frac{W_f}{1000}\right)^{0.67} + \left(\frac{W_i}{1000}\right)^{0.67}\right) \times \Delta t}$$

Where W_f and W_i are the mean final and initial live body weights (g), Δt is the duration of the feeding period (days) and N_f and N_i are the mean N contents of the whole body of the broiler at the end and at the beginning of the experimental period (g/g), respectively. The coefficient for metabolic body weight used in the equation is 0.75, but for data comparison the coefficient 0.67 was used. From the relationship of N deposition obtained in the amino acid dilution experiment it was possible to determine an optimum dietary amino acid pattern. In practice, Rollin *et al*. (2003) proposed to calculate the EAA requirement values (g/kg dry matter) for a given EAA as follows:

$$\text{Requirement} = (EAA)_{BD} \times \left(2 - DEL - \left(\frac{ND_{EAA}}{ND_{BD}}\right)\right)$$

Where $(EAA)_{BD}$ is the concentration of the considered EAA in the BD (g/kg DM (dry matter)), *DEL* is the dilution rate of the EAA in the deficient diet compared with the BD, ND_{EAA} is the N deposition (mg N/$BW_{kg}^{0.67}$/day) corresponding to the EAA diet and ND_{BD} is the N deposition observed on the BD (mg N/$BW_{kg}^{0.67}$/day). This method is based on the assumption that N retention is a linear function of dietary EAA content when a particular amino acid is limiting. An optimal balance between the EAAs was derived by dividing the estimated requirement for each EAA by the estimated requirements for lysine (base lysine = 100).

Results

All experimental diets were well accepted by the broilers. No mortality was observed during the trial but feather abnormalities were observed in broilers on the treatments in which valine and leucine were deficient. As the individual feed supply was controlled and kept constant during the experimental period, N intake was similar between dietary treatments (Tables 21.2 and 21.3). The results of the single dietary EAA dilution for the N deposition and protein efficiency ratio (PER) obtained in the comparative slaughter study are presented in Table 21.2 and the results of the N balance studies for each age period (relative effects on protein quality) are summarized in Table 21.3.

High N deposition and protein efficiency ratios ($P < 0.05$) were observed in the BD treatment during the trial. Dilution of individual EAAs significantly reduced N deposition, but the extent of reduction depended on the EAA removed. For each EAA, a 0.30 reduction was sufficient to set it in limiting position. The protein efficiency ratio was also significantly reduced by EAA dilution. The dilution of valine promoted the greatest reduction in N deposition ($P < 0.05$) in period I (6 to 21 days), followed by leucine in periods II and III (22 to 37 days and 38 to 53 days). Based on the data obtained from the comparative slaughter technique and assuming a linear response between N deposition and EAA intake when a given AA is limiting, the quantity of each EAA that can be removed from the BD without affecting N deposition was determined. From these data, and assuming that each EAA is equally limiting, the ideal dietary EAA profile relative to lysine (=100) is presented in Fig. 21.1. Expressed as g/kg of dry matter, the optimal balance was estimated and these are presented in Table 21.2.

The effects of dilution of individual EAAs on protein quality in the experimental diets are also of fundamental importance for evaluation of the applied procedure. N deposition and protein quality were higher in BD ($P < 0.05$) than in reduced EAA treatments during the trial. However, when comparing the N deposition obtained with the two techniques, the N deposition determined by the comparative slaughter technique was lower than that obtained using N balance. The observed protein quality in this study declined following dilution of the crystalline EAA under study. The dilution of histidine caused a lower protein quality in period I (6 to 21 days), followed by lysine and threonine in periods II and III (22 to 37 days and 38 to 53 days), respectively. In each treatment bc^{-1}, the efficiency of the utilization of dietary AAs was calculated. The ideal ratio between EAAs was derived by dividing efficiency of utilization of lysine by the efficiency of utilization of the

Table 21.2. Effect of deleting single amino acids from the diet on nitrogen deposition (ND) and protein efficiency ratio (PER) of fast-growing broilers (Cobb 500) using the comparative slaughter technique.

	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12
Diets	BD	Lys	Met+Cys	Trp	Thr	Arg	Val	Ile	Leu	Phe+Tyr	Gly+Ser	His
Period I (6 to 21 days)												
Initial BW^{a} (g)	123 ± 3.5	123 ± 3.6	123 ± 3.7	123 ± 3.7	123 ± 3.3	123 ± 3.3	123 ± 3.6	123 ± 3.8	123 ± 3.9	123 ± 3.9	123 ± 4.6	123 ± 4.9
Final BW (g)	913 ± 57	686 ± 47	798 ± 87	731 ± 75	646 ± 42	739 ± 41	723 ± 64	778 ± 73	671 ± 56	669 ± 54	835 ± 71	695 ± 33
ND (mg N/kg BW$^{0.67}$/day)	2427 ± 23	2022 ± 28	2135 ± 30	2059 ± 19	1958 ± 16	1988 ± 10	1956 ± 42	2054 ± 43	1969 ± 28	1979 ± 27	2096 ± 33	2076 ± 66
NI (mg N/kg BW$^{0.67}$/day)^{b}	4200 ± 85	4214 ± 87	4389 ± 69	4306 ± 102	4041 ± 52	4201 ± 170	4038 ± 8.8	4121 ± 155	4102 ± 41	4206 ± 24	4052 ± 52	4146 ± 46
PER (g/g)^{c}	3.38 ± 0.19	2.78 ± 0.12	2.95 ± 0.18	2.84 ± 0.24	2.77 ± 0.16	2.94 ± 0.11	3.00 ± 0.19	3.09 ± 0.09	2.80 ± 0.14	2.73 ± 0.17	3.30 ± 0.20	2.85 ± 0.12
ND (% NI)	58.2 ± 1.1	48.5* ± 0.9	47.3* ± 0.7	50.2* ± 1.0	48.2* ± 0.5	44.0* ± 2.1	48.6* ± 0.2	46.5* ± 1.2	48.4* ± 0.4	47.0* ± 0.2	52.3* ± 0.8	51.1* ± 0.6
Requirement (g/kg dry matter)	–	10.6 ± 0.04	7.20 ± 0.05	1.76 ± 0.01	7.41 ± 0.04	11.6 ± 0.03	9.15 ± 0.02	5.08 ± 0.06	12.6 ± 0.04	14.8 ± 0.16	16.6 ± 0.10	4.27 ± 0.12
Period II (22 to 37 days)												
Initial BW (g)	975.6 ± 14	975.6 ± 12	975.6 ± 13	975.2 ± 12	975.2 ± 10	975.6 ± 11	975.8 ± 11	975.8 ± 10	975.6 ± 10	975.6 ± 10	975.8 ± 10	975.0 ± 12
Final BW (g)	2139 ± 106	1939 ± 91	2045 ± 65	1863 ± 189	1872 ± 108	1903 ± 88	1889 ± 91	1958 ± 86	1773 ± 76	2032 ± 104	2074 ± 108	2080 ± 82
ND (mg N/kg BW$^{0.67}$/day)	1982 ± 15	1674 ± 28	1752 ± 30	1603 ± 28	1715 ± 20	1647 ± 33	1591 ± 38	1714 ± 19	1279 ± 28	1680 ± 9	1644 ± 24	1722 ± 9
NI (mg N/kg BW$^{0.67}$/day)	3105 ± 9	3537 ± 83	3615 ± 34	3152 ± 80	3444 ± 138	3340 ± 243	3294 ± 189	3464 ± 165	2923 ± 21	3503 ± 124	3395 ± 161	3427 ± 107
PER (g/g)	3.01 ± 0.22	2.28 ± 0.15	2.43 ± 0.13	2.36 ± 0.35	2.22 ± 0.25	2.38 ± 0.31	2.35 ± 0.15	2.38 ± 0.21	2.37 ± 0.20	2.48 ± 0.18	2.63 ± 0.08	2.63 ± 0.15
ND (% NI)	63.8 ± 0.2	47.3* ± 0.9	48.5* ± 0.3	50.9* ± 1.0	49.8* ± 1.5	49.3 ± 3.0	48.3* ± 2.4	49.5* ± 2.0	43.8* ± 0.3	48.0* ± 1.4	48.4* ± 2.0	50.2* ± 1.3
Requirement (g/kg dry matter)	–	9.41 ± 0.04	6.50 ± 0.12	1.72 ± 0.03	6.40 ± 0.05	10.92 ± 0.09	8.04 ± 0.07	6.50 ± 0.08	12.2 ± 0.20	12.0 ± 0.04	14.8 ± 0.23	4.05 ± 0.01
Period III (38 to 53 days)												
Initial BW (g)	2591.2 ± 41	2591.4 ± 40	2591.0 ± 38	2591.2 ± 38	2591.2 ± 38	2591.4 ± 38	2591.0 ± 38	2591.2 ± 38	2591.4 ± 38	2591.4 ± 38	2591.2 ± 38	2591.4 ± 38
Final BW (g)	3747 ± 103	3419 ± 145	3448 ± 90	2883 ± 375	3026 ± 385	3326 ± 164	3390 ± 101	3157 ± 70	3045 ± 50	3435 ± 194	3286 ± 29	3453 ± 164
ND (mg N/kg BW$^{0.67}$/day)	1321 ± 19	812 ± 19	1018 ± 16	943 ± 15	947 ± 14	805 ± 30	962 ± 14	889 ± 15	694 ± 11	814 ± 7	849 ± 12	1012 ± 19

Continued

Table 21.2. Continued

	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12
Diets	BD	Lys	Met+Cys	Trp	Thr	Arg	Val	Ile	Leu	Phe+Tyr	Gly+Ser	His
NI (mg N/kg $BW^{0.67}$/day)	2210 ± 22	2011 ± 39	2205 ± 100	1988 ± 55	2210 ± 64	1897 ± 8	2072 ± 13	2082 ± 29	1982 ± 33	2034 ± 5	2083 ± 27	2167 ± 26
PER (g/g)	2.58 ± 0.20	2.09 ± 0.29	1.99 ± 0.22	1.65 ± 0.31	1.78 ± 0.06	1.99 ± 0.42	1.97 ± 0.22	1.43 ± 0.15	1.22 ± 0.11	2.10 ± 0.45	1.73 ± 0.04	2.01 ± 0.32
ND (% NI)	59.7 ± 0.5	40.4* ± 0.8	46.2* ± 1.6	47.4* ± 1.4	42.8* ± 1.0	42.4* ± 0.3	46.4* ± 0.2	42.7* ± 0.4	35.0* ± 0.5	40.0* ± 0.1	40.7* ± 0.6	46.7* ± 0.3
Requirement (g/kg dry matter)	–	11.6 ± 0.13	6.70 ± 0.08	1.80 ± 0.02	7.08 ± 0.11	11.4 ± 0.11	7.54 ± 0.06	7.70 ± 0.05	13.7 ± 0.02	13.9 ± 0.06	17.4 ± 0.17	4.47 ± 0.04

*Significantly different from balanced diet (BD) treatment ($P < 0.05$) according to Dunnett's test.

[a] Mean body weight (BW) +/– standard error of mean (SEM).

[b] Nitrogen intake (NI).

[c] PER = (weight gain/crude protein intake).

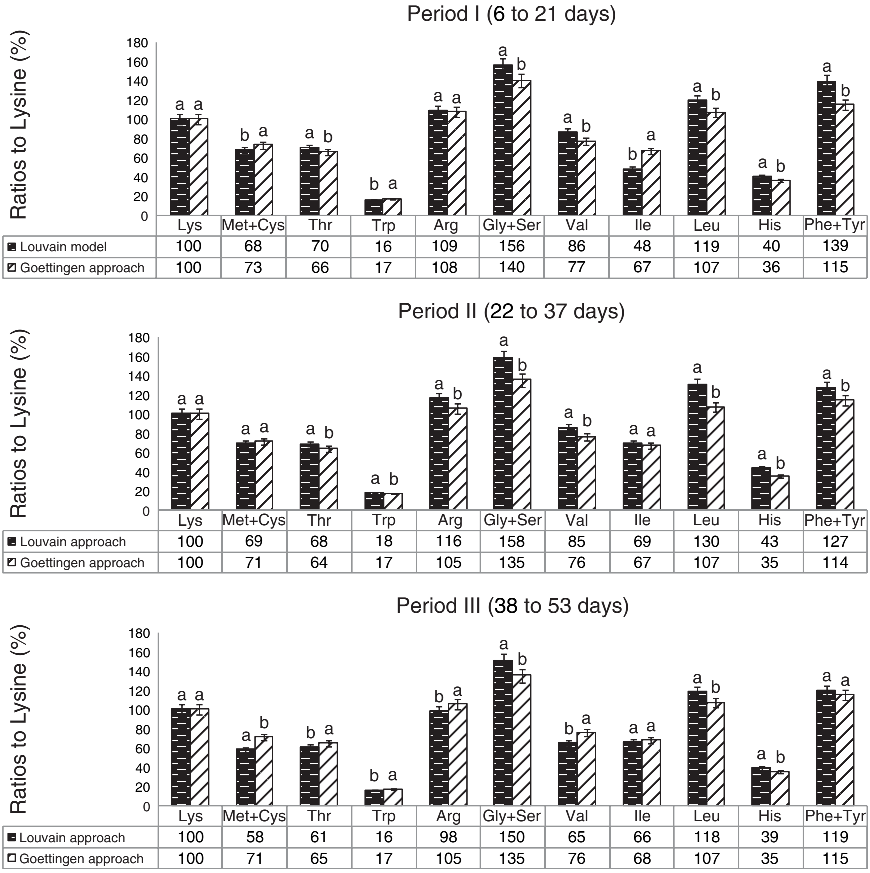
Table 21.3. Effect of deleting a single amino acid from the diet on protein quality (*b*) and nitrogen deposition (ND) of fast-growing broilers (Cobb 500) in N balance trials.

	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12
Diets	BD	Lys	Met+Cys	Trp	Thr	Arg	Val	Ile	Leu	Phe+Tyr	Gly+Ser	His
Period I (6 to 21 days)												
Mean BW (g)[a]	534 ± 85	434 ± 61	507 ± 70	443 ± 75	394 ± 70	472 ± 68	446 ± 73	483 ± 74	427 ± 66	444 ± 64	515 ± 74	449 ± 60
Dry matter intake (g/day)[b]	72 ± 6	57 ± 4	71 ± 5	61 ± 6	51 ± 6	59 ± 6	55 ± 6	62 ± 6	53 ± 4	56 ± 4	65 ± 5	58 ± 3
N intake (mg N/BW$_{kg}^{0.67}$/day)	4430 ± 121	4238 ± 117	4545 ± 143	4364 ± 95	4004 ± 41	4078 ± 32	3850 ± 138	4203 ± 152	4002 ± 101	3904 ± 136	3993 ± 153	4192 ± 252
N deposition (mg N/BW$_{kg}^{0.67}$/day)	2960 ± 28	2466 ± 34	2604 ± 36	2510 ± 23	2387 ± 19	2424 ± 12	2386 ± 52	2505 ± 52	2402 ± 35	2414 ± 33	2556 ± 41	2532 ± 80
Protein quality ($b \times 10^{-6}$)	366 ± 1.8	267* ± 1.8	275* ± 3.0	268* ± 2.5	268* ± 1.7	269* ± 0.7	279* ± 1.9	277* ± 0.8	271* ± 2.2	280* ± 4.5	303* ± 4.5	208* ± 1.7
Efficiency (bc^{-1})	–	82 ± 0.6	112 ± 1.2	468 ± 4.4	125 ± 0.8	75 ± 0.2	107 ± 0.7	123 ± 0.3	77 ± 0.6	71 ± 1.1	58 ± 0.9	229 ± 1.3
Period II (22 to 37 days)												
Mean BW (g)	1603 ± 136	1512 ± 106	1514 ± 158	1469 ± 115	1437 ± 130	1506 ± 121	1490 ± 112	1526 ± 114	1392 ± 121	1593 ± 110	1580 ± 127	1566 ± 131
Dry matter intake (g/day)	131 ± 6	117 ± 4	123 ± 7	102 ± 5	114 ± 5	110 ± 4	104 ± 3	120 ± 4	75 ± 4	121 ± 6	118 ± 5	117 ± 8
N intake (mg N/BW$_{kg}^{0.67}$/day)	3448 ± 54	3557 ± 118	3625 ± 115	2943 ± 72	3441 ± 88	3291 ± 130	3211 ± 120	3469 ± 93	2381 ± 69	3436 ± 37	3371 ± 79	3232 ± 58
N deposition (mg N/BW$_{kg}^{0.67}$/day)	2417 ± 18	2042 ± 34	2137 ± 36	1955 ± 35	2092 ± 25	2009 ± 40	1940 ± 47	2091 ± 23	1559 ± 34	2049 ± 11	2005 ± 29	2100 ± 11
Protein quality ($b \times 10^{-6}$)	451 ± 0.5	320* ± 2.1	339* ± 2.0	360* ± 0.9	344* ± 2.7	337* ± 2.5	326* ± 1.2	341* ± 3.4	323* ± 2.4	332* ± 2.3	327* ± 2.7	368* ± 4.8
Efficiency (bc^{-1})	–	104 ± 0.7	146 ± 0.8	620 ± 1.5	164 ± 1.3	99 ± 0.7	137 ± 0.5	156 ± 1.6	97 ± 0.7	92 ± 0.6	77 ± 0.6	301 ± 3.9
Period III (38 to 53 days)												
Mean BW (g)	3205 ± 163	3042 ± 117	3028 ± 112	2993 ± 146	3027 ± 92	2989 ± 119	2998 ± 123	2807 ± 120	2811 ± 97	3014 ± 147	2910 ± 126	3032 ± 121
Dry matter intake (g/day)	153 ± 4	109 ± 4	140 ± 1	121 ± 2	131 ± 2	105 ± 4	129 ± 2	114 ± 4	86 ± 1	108 ± 2	112 ± 3	132 ± 3
N intake (mg N/BW$_{kg}^{0.67}$/day)	2346 ± 64	1824 ± 58	2203 ± 40	1936 ± 39	2213 ± 44	1752 ± 69	2065 ± 36	1983 ± 46	1429 ± 25	1725 ± 29	1893 ± 46	2088 ± 60
N deposition (mg N/BW$_{kg}^{0.67}$/day)	1610 ± 23	990 ± 23	1241 ± 19	1150 ± 18	1155 ± 18	982 ± 37	1173 ± 18	1084 ± 18	847 ± 14	992 ± 9	1035 ± 15	1234 ± 24
Protein quality ($b \times 10^{-6}$)	611 ± 0.9	393* ± 2.9	430* ± 1.7	442* ± 1.1	389* ± 2.4	405* ± 1.3	425* ± 1.8	402* ± 1.9	422* ± 3.6	416* ± 5.5	398* ± 5.8	451* ± 3.0
Efficiency (bc^{-1})	–	125 ± 0.9	176 ± 0.7	721 ± 1.8	191 ± 1.2	119 ± 0.4	164 ± 0.7	185 ± 0.9	117 ± 1.0	108 ± 1.4	93 ± 1.3	362 ± 2.4

*Significantly different from balanced diet (BD) treatment ($P < 0.05$) according to Dunnett's test.

[a] Mean ± standard error of mean (SEM).

[b] Average of two collecting periods.



Period I (6 to 21 days)

	Lys	Met+Cys	Thr	Trp	Arg	Gly+Ser	Val	Ile	Leu	His	Phe+Tyr
■ Louvain model	100	68	70	16	109	156	86	48	119	40	139
▨ Goettingen approach	100	73	66	17	108	140	77	67	107	36	115

Period II (22 to 37 days)

	Lys	Met+Cys	Thr	Trp	Arg	Gly+Ser	Val	Ile	Leu	His	Phe+Tyr
■ Louvain approach	100	69	68	18	116	158	85	69	130	43	127
▨ Goettingen approach	100	71	64	17	105	135	76	67	107	35	114

Period III (38 to 53 days)

	Lys	Met+Cys	Thr	Trp	Arg	Gly+Ser	Val	Ile	Leu	His	Phe+Tyr
■ Louvain approach	100	58	61	16	98	150	65	66	118	39	119
□ Goettingen approach	100	71	65	17	105	135	76	68	107	35	115

Fig. 21.1. The ideal dietary EAA profiles relative to lysine in each age period for fast-growing broilers (Cobb 500) determined using a broken line model with comparative slaughter technique and the Goettingen approach with a N balance study. Different letters in the graph indicate significant ($P < 0.05$) differences.

other EAA. The ratio between the EAAs in each period using this procedure is presented in Fig. 21.1.

In the present study significant differences ($P < 0.05$) were observed in amino acid profiles between the two methods in periods I and II, but in period III they did not differ significantly ($P = 0.649$). Over the whole growth period the ideal ratios were significantly different ($P < 0.05$) when using the broken line model, but with the Goettingen approach the amino acid ratios in periods II and III were similar ($P = 0.287$). In this way we can consider the ratios between period II and III as comparable to the Goettingen approach.

Discussion

Amino acids surplus to the animal's requirement are degraded and their N is excreted, and when dietary energy is limiting, amino acids are oxidized and used as an energy source. In the present study non-protein energy was supplied according to the broiler requirement for age and maintained constantly in diets to prevent energy being a limiting factor for protein accretion. Also, in all treatments, apart from those with amino acid dilutions, all other dietary conditions (e.g. dietary energy and fibre) were the same. Another point is that the diets in the dilution method use crystalline AAs to precisely modify the EAA composition of the experimental diets. However, the lower utilization efficiency of crystalline AAs compared to protein-bound AAs suggested by many authors (Dabrowski and Guderley, 2002) may influence the estimation of the EAA pattern. In this study, all the essential amino acids were supplemented in each experimental diet to ensure a balanced mixture and instead of feeding the animals once daily, the animals were fed several times a day *ad libitum*.

The observed changes in N deposition when dietary amino acids were reduced from the BD were used to calculate the optimum balance between the EAAs in the N balance trial. In both methods, the dilution of valine promoted the greatest reduction in N deposition in period I (6 to 21 days), followed by leucine in periods II and III (22 to 37 days and 38 to 53 days). This indicates that valine and leucine were the first limiting AAs in the BD given in periods I, II and III, respectively. This would lead to the feather abnormalities observed in the valine and leucine treatments, similar to those observed by Gruber *et al.* (2000). As dietary valine and leucine levels decreased, a similar progressive feather abnormality became apparent and gave the feathers a ragged appearance (Robel, 1977), and was responsible for a decrease in body weight and feed conversion (Farran and Thomas, 1992).

As protein is essential for both growth and maintenance, nitrogen deposition is affected by the level of protein intake and by the quality of the dietary protein (Wang and Fuller, 1989). As the individual feed supply was controlled and kept constant during the experimental period, N intake was similar between dietary treatments. The decrease in protein efficiency ratio observed during the experimental period may be explained largely by the fact that as body weight gain increased with age, protein requirements for maintenance also increased (Brody, 1945) while feed or protein intake did not increase proportionately (Scott *et al.*, 1969), hence the quantity of protein available for growth (weight gain) decreased. However, the protein efficiency ratio is not a good indicator of protein quality because this method does not consider the quantity of protein used for maintenance, and values of protein efficiency ratio vary with levels of protein intake. Additionally, body weight gain does not necessarily correspond to body protein gain. However, protein quality (b) calculated using the Goettingen approach is a parameter that plots the slope of the exponential function. Thus, the dietary protein quality (b) is independent of NI but is linearly dependent on the concentration of the limiting AA in the feed protein (c). The observed protein quality (b) declined following dilution of the crystalline AA under study. Due to EAA dilution protein quality was significantly affected. According to Samadi and Liebert (2008) the daily AA requirement for equal daily protein deposition is dependent only on the efficiency of utilization of the individual dietary AA under study, and this was established by the model parameter (bc^{-1}). Consequently, it is possible to compare the model parameters (bc^{-1}) of individual AAs directly. Using this procedure for evaluating the optimal AA ratio, comparisons are only allowed within equal age periods because varying $NR_{max}T$ depending on age affected the established value of bc^{-1}. Thus, the optimal lysine to EAA ratio was derived by dividing the efficiency of utilization of lysine by the efficiency of utilization of the EAA.

The dilution method is generally accepted as an efficient and rapid tool to estimate the ideal EAA profile (Baker, 2003). This method was initially outlined by Wang and Fuller (1989) in pigs and is based on the concept that each EAA is equally limiting for protein accretion. In broiler chickens, estimation of the ideal dietary EAA profile has already been applied using the dilution method (Gruber *et al.*, 2000; Roth *et al.*, 2001) but only from 7 to 28 days post-hatching. Roth *et al.* (2001) estimated the EAA profile for broiler chicks using the dilution method, and values obtained (Table 21.4) are very similar to those estimated in the present study using the broken line model and the Goettingen approach. The data are also consistent with the recommendations of Brazilian tables (Rostagno *et al.*, 2011) for periods I and II and the Illinois ideal protein pattern (Baker and Han, 1994; Baker *et al.*, 2002) in period I.

Table 21.4. Ideal protein patterns based on literature.

	Baker and Han (1994)	Baker *et al.* (2002)	Roth *et al.* (2001)	Rostagno *et al.* (2011)		Mack *et al.* (1999)
Amino acids	8 to 21 days	8 to 21 days	8 to 28 days	1 to 21 days	22 to 56 days	21 to 42 days
Lysine	100	100	100	100	100	100
Met+Cys	72–75[a]	nd	70	72	73	75
Tryptophan	16–17	17–19	14	17	18	19
Threonine	67–70	56–62	66	68	68	63
Arginine	105–108	nd	108	105	105	112
Valine	77–80	77–87	81	79	80	81
Isoleucine	67	60–72	63	67	68	71
Leucine	109	nd	108	107	108	nd
Phe+Tyr	105	nd	121	115	115	nd
Gly+Ser	nd[b]	nd	nd	150	137	nd
Histidine	32–35	nd	38	37	37	nd

[a] Ranges are due to differences in the criterion optimized and in the model fitted data.

[b] nd = not determined.

Additionally, in the whole grower period the ideal ratios differed with the broken line model, but using the Goettingen approach the amino acid ratios in periods II and III were similar ($P = 0.287$). Studies indicate that the ideal dietary amino acid profile for birds scarcely undergoes change in the whole grower period (Baker and Han, 1994) but the differences between periods I to II and III (22 to 53 days) indicate the opposite. This difference is due to the total requirement pattern depending on the relative contribution of maintenance and growth requirements (Zhen and Li, 1999) in which the maintenance contribution is smaller in young birds and increases with age.

In the present study, the N deposition measured by the N balance technique was overestimated compared to nitrogen deposition estimated by the comparative slaughter technique. This explains in part the small difference in EAA profiles determined by the two techniques, since the variation between the two estimates can represent approximately 0.16 (Just *et al.*, 1982). Compared with N balance technique, the differential of N in carcass analysis by the comparative slaughter technique has an additional advantage of not overestimating the N gain due to potential unrecorded N losses (Heger and Frydrych, 1985) but the N balance technique is mostly preferable because of the association with animal welfare.

The model proposed by Rollin *et al.* (2003) relies on two key assumptions. First, the equation assumes that the response to EAAs is well described by the 'broken line' regression approach. However, some authors (Gahl *et al.*, 1991, 1994) have shown a continuously diminishing approach to a maximum, whereas other researchers (Campbell *et al.*, 1984, 1985; Dunkin *et al.*, 1986) describe the responses of their animals as linear models. In broilers most of the reported requirements have been estimated according to the broken line model (Baker *et al.*, 2002). Curvilinear models have also been proposed (Robbins *et al.*, 1979; Rodehutscord *et al.*, 1997), but the broken line approach does not generally give a worse fit than the non-linear models with regard to the standard deviation of the residuals (Rodehutscord and Pack, 1999). In addition, inflection points of best fit broken lines are objectively established and predict minimal requirement values, and this is viewed as desirable for calculating EAA ratios (Baker, 2003). Second, the equation assumes that EAAs are utilized with similar efficiencies. According to Fuller (1994), the results of some authors (Gahl *et al.*, 1991; Fuller, 1994) suggest that most EAAs are used with a similar efficiency in pig and rat. In the Goettingen approach, the slope (bc^{-1}) calculated assumes that the dietary protein quality (b) is linearly dependent on the concentration of the limiting AA in the feed protein (c) (Samadi and Liebert, 2008). However, in this approach the calculated efficiencies (bc^{-1}) for each EAA are different and would be responsible for the differences in the estimation of the EAA ratio by the two methods. Clearly, research is still needed in these fields in order to clarify the potential limitations of these methodologies.

Results of this study support the premise that the dilution method can be used to estimate the optimum EAA pattern. Although this methodology relies on some assumptions that need to be further clarified, fast growth of animals and rigorous dietary formulation are expected to improve the consistency of the results. Comparing the two methods, the estimation of optimum amino acid ratio by the Goettingen approach gave values closer to those in the literature and also exhibited lower variation.

Acknowledgements

The authors gratefully acknowledge the financial support of Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP) and the crystalline amino acids donated by Ajinomoto LTDA.

References

AOAC (2002) *Official Methods of Analysis*, 17th edn. AOAC, Washington DC.

Baker, D.H. (2003) Ideal amino acid patterns for broiler chicks. In: D'Mello, J.P.F. (ed.) *Amino Acids in Animal Nutrition*. CAB International, Wallingford, UK, pp. 223–235.

Baker, D.H. and Han, Y. (1994) Ideal amino acid profile for chicks during the first three weeks posthatching. *Poultry Science* 73, 1441–1447.

Baker, D.H., Batal, A., Parr, T., Augspurger, N. and Parsons, C. (2002) Ideal ratio (relative to lysine) of tryptophan, threonine, isoleucine, and valine for chicks during the second and third weeks posthatch. *Poultry Science* 81, 485–494.

Brody, S. (1945) *Bioenergetics and Growth: With Special Reference to the Efficiency Complex in Domestic Animals*. Reinhold Publishing Corporation, New York.

Campbell, R.G., Taverner, M.R. and Curic, D.M. (1984) Effect of feeding level and dietary protein content on the growth, body composition and rate of protein deposition in pigs growing from 45 to 90 kg. *Animal Science* 38, 233–240.

Campbell, R.G., Taverner, M.R. and Curic, D.M. (1985) The influence of feeding level on the protein requirement of pigs between 20 and 45 kg live weight. *Animal Science* 40, 489–496.

Dabrowski, K. and Guderley, H. (2002) Intermediary metabolism. In: Halver, J.E. (ed.) *Fish Nutrition*. Academic Press, San Diego, California, USA, pp. 309–365.

Dorigam, J.C.P. (2012) Modeling of responses of broiler to different lysine intakes. MSc Thesis, University of Agrarian and Veterinary Sciences of Jaboticabal, São Paulo, Brazil.

Dunkin, A.C., Black, J.L. and James, K.J. (1986) Nitrogen balance in relation to energy intake in entire male pigs weighing 75 kg. *British Journal of Nutrition* 55, 201–207.

Farran, M.T. and Thomas, O.P. (1992) Valine deficiency. 1. The effect of feeding a valine-deficient diet during the starter period on performance and feather structure of male broiler chicks. *Poultry Science* 71, 1879–1884.

Fatufe, A., Timmler, R. and Rodehutscord, M. (2004) Response to lysine intake in composition of body weight gain and efficiency of lysine utilization of growing male chickens from two genotypes. *Poultry Science* 83, 1314–1324.

Fuller, M.F. (1994) Amino acid requirements for maintenance, body protein accretion and reproduction. In: D'Mello, J.P.F. (ed.) *Amino Acids in Animal Nutrition*. CAB International, Wallingford, UK, pp. 155–184.

Fuller, M.F., McWilliam, R., Wang, T.C. and Giles, L.R. (1989) The optimum dietary amino acid pattern for growing pigs. 2. Requirements for maintenance and for tissue protein accretion. *British Journal of Nutrition* 62, 255–267.

Gahl, M.J., Finke, M.D., Crenshaw, T.D. and Benevenga, N.J. (1991) Use of a four-parameter logistic equation to evaluate the response of growing rats to ten levels of each indispensable amino acid. *The Journal of Nutrition* 121, 1720–1729.

Gahl, M.J., Crenshaw, T.D. and Benevenga, N.J. (1994) Diminishing returns in weight, nitrogen, and lysine gain of pigs fed six levels of lysine from three supplemental sources. *Journal of Animal Science* 72, 3177–3187.

Green, J.A. and Hardy, R.W. (2002) The optimum dietary essential amino acid pattern for rainbow trout (*Oncorhynchus mykiss*) to maximize nitrogen retention and minimize nitrogen excretion. *Fish Physiology and Biochemistry* 27, 97–108.

Gruber, K., Roth, F.X. and Kirchgessner, M. (2000) Effect of partial dietary amino acid deductions on growth rate and nitrogen balance in growing chicks. *Archiv für Geflügelkunde* 64, 244–250.

Heger, J. and Frydrych, Z. (1985) Efficiency of utilization of essential amino acids in growing rats at different levels of intake. *British Journal of Nutrition* 54, 499–508.

Just, A., Fernandez, J.A. and Jorgensen, H. (1982) Nitrogen balance studies and nitrogen retention. In: Laplace, J.P., Corring, T. and Rerat, A. (eds) *Digestive Physiology of Pigs*. INRA, Paris, pp. 111–122.

Mack, S., Bercovici, D., DeGroate, G., Leclercq, B., Lippens, M., Pack, M., Schutte, J.B. and Van Cauwenberghe, S. (1999) Ideal amino acid profile and dietary lysine specification for broiler chickens of 20 to 40 days of age. *British Poultry Science* 40, 257–265.

Robbins, K.R., Norton, H.W. and Baker, D.H. (1979) Estimation of nutrient requirements from growth data. *The Journal of Nutrition* 109, 1710–1714.

Robel, E.J. (1977) A feather abnormality in chicks fed diets deficient in certain amino acids. *Poultry Science* 56, 1968–1971.

Rodehutscord, M. and Pack, M. (1999) Estimates of essential amino acids requirements from dose-response studies with rainbow trout and broiler chicken: effect of mathematical model. *Archives of Animal Nutrition* 52, 223–244.

Rodehutscord, M., Becker, A., Pack, M. and Pfeffer, E. (1997) Response of rainbow trout (*Oncorhynchus mykiss*) to supplements of individual essential amino acids in a semipurified diet, including an estimate of the maintenance requirement for essential amino acids. *The Journal of Nutrition* 127, 1166–1175.

Rollin, X., Mambrini, M., Abboudi, T., Larondelle, Y. and Kaushik, S.J. (2003) The optimum dietary indispensable amino acid pattern for growing Atlantic salmon (*Salmo salar L.*) fry. *British Journal of Nutrition* 90, 865–876.

Rostagno, H.S., Albino, L.F.T., Donzele, J.L., Gomes, P.C., Oliveira, R.F., Lopes, D.C., Ferreira, A.S., Barreto, S.L.T. and Euclides, R.F. (2011) *Tabelas Brasileiras para Aves e Suínos – Composição de alimentos e exigências nutricionais*. 3rd edn. UFV, Viçosa, Minas Gerais, Brazil.

Roth, F.X., Gruber., K. and Kirchgessner, M. (2001) The ideal dietary amino acid pattern for broiler-chicks of age 7 to 28 days. *Archiv für Geflügelkunde* 65, 199–206.

Samadi and Liebert, F. (2006) Estimation of nitrogen maintenance requirements and potential for nitrogen deposition in fast-growing chickens depending on age and sex. *Poultry Science* 85, 1421–1429.

Samadi and Liebert, F. (2007) Lysine requirement of fast growing chickens: effects of age, sex, level of protein deposition and dietary lysine efficiency. *The Journal of Poultry Science* 44, 63–72.

Samadi and Liebert, F. (2008) Modelling the optimal lysine to threonine ratio in growing chickens depending on age and efficiency of dietary amino acid utilisation. *British Poultry Science* 49, 45–54.

Scott, M.L., Nesheim, M.C. and Young R.J. (1969) *Nutrition of the Chicken*. M.L. Scott, Ithaca, New York, USA.

Wang, T.C. and Fuller, M.F. (1989) The optimum dietary amino acid pattern for growing pigs. 1. Experiments by amino acid deletion. *British Journal of Nutrition* 62, 77–89.

Zhen, C.T. and Li, D.F. (1999) The amino acid requirements of chicks and pigs and their ideal amino acid patterns. *China Feed* 22, 20–22.

Zhengling, C. (2001) Comparative study of meat-type duck's ideal protein amino acids pattern by different methods. PhD Thesis, Sichuan Agricultural University, Sichuan, China.

Index