A MODELLING STUDY OF BROILER CHICKEN GROWTH AND BODY COMPOSITION, ESPECIALLY BREAST MEAT YIELD, IN RESPONSE TO NUTRIENT INPUTS

BY

DAVID R. HICKLING

A Thesis
Submitted to the Faculty of Graduate Studies
in Partial Fulfillment of the Requirements
for the Degree of

DOCTOR OF PHILOSOPHY

Department of Animal Science
University of Manitoba
Winnipeg, Manitoba

ISBN 0-315-71865-X

A MODELLING STUDY OF BROILER CHICKEN GROWTH AND BODY COMPOSITION, ESPECIALLY BREAST MEAT YIELD, IN RESPONSE TO NUTRIENT INPUTS

BY

DAVID R. HICKLING

A thesis submitted to the Faculty of Graduate Studies
of the University of Manitoba in partial fulfillment of the
requirements of the degree of

DOCTOR OF PHILOSOPHY

ABSTRACT

A mechanistic model was constructed which predicts broiler growth and body composition in response to changes in nutrient intake from day-old up to 10 weeks of age. The model partitions nutrient intake into body processes of maintenance and tissue growth. The various forms of heat loss from the body such as fasting heat production, activity heat, thermoregulation heat and a detailed accounting of heat increment are accounted for before energy retention by the bird in the form of body protein and fat is considered. The model has a priority system of allocating nutrients to the various metabolic activities of the bird. Daily growth is computed as the sum of the gain of feathers, body protein, fat, ash and water. The model also predicts the content of breast meat, leg meat and abdominal fat in the broiler. The model was validated using a number of data sets from the published literature.

In addition three experiments were conducted to investigate the effects of dietary lysine and methionine on breast meat yield. These data sets were also used to validate the model. The results of the experiments demonstrated that increasing dietary lysine and methionine concentration will increase breast meat yield. Body weight was found to be an excellent linear predictor of breast meat content up to at least 3.5 kg BW (9 weeks of age).

ACKNOWLEDGEMENTS

I would like to thank my advisor, Professor W. Guenter, for his guidance, which allowed me free reign to develop my own ideas while also providing me with a solid base. I would like to thank my committee members; Professors L.D. Campbell, G.H. Crow and A.N. Arnason. They each made unique contributions. I especially thank Dr. Crow for the considerable time he spent teaching me. There were many instances in which he anticipated my needs before I was aware of them. I would also like to thank my external examiner, Dr. G.M. Pesti of the University of Georgia. His previous work inspired this thesis.

I gratefully acknowledge the financial assistance of Cargill (Canada) Ltd. and Heartland Lysine Inc.

I would to thank my parents, Ben and Eileen, for their steadfast support over the years. I thank most of all my wife Karen for her moral support and love. I dedicate this thesis to her and our daughter Susannah.

TABLE OF CONTENTS

TABLE OF CONTENTS

TABLE OF CONTENTS

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF TABLES

LIST OF TABLES

LIST OF TABLES

LIST OF ABBREVIATIONS

A	body ash gain, g/day
AF	abdominal fat
AH	activity heat, kcal
AMEn	apparent metabolizable energy corrected for N, kcal
B	rate of decline of relative growth
BM	breast meat
BW	body weight, g
BWg	body weight gain, g/day
CHO	carbohydrate
DH	digestion heat, kcal
EAAi	the ith essential amino acid
EAAbi	essential amino acids used for carcass protein, g
EAAe	extra essential amino acids, g
EAAfi	essential amino acids used for feather growth, g
EAAmi	essential amino acids used for maintenance, g
Eb	energy used for body protein accretion, kcal
Ef	energy used for feather growth, kcal
EH	excretion heat, kcal
Els	energy of lipid synthesis, kcal
Emt	energy required for maintenance, kcal/day
Eps	energy of protein synthesis, kcal
ER	energy retention, kcal
ERl	energy retained as lipid, kcal
ERp	energy retained as protein, kcal
Exp	energy from extra protein deamination, kcal
F	feather weight, g
FHP	fasting heat production, kcal
FI	feed intake, g
FOM	fecal organic matter, g/day
FSR	protein fractional synthetic rate, %
HI	heat increment, kcal
HP	heat production, kcal
L	body lipid gain, g
Ld	direct body lipid gain (from diet fat), g
LH	light hours, % of 24
Li	indirect body lipid gain (from lipogenesis), g
LM	leg meat
ME	metabolizable energy corrected for N retention, kcal
MEI	ME intake, kcal/day
P	digestible protein intake, g
Pb	protein in body, g
Pbg	body protein gain, g/day
Pbm	protein in mature body, g
Pbmax	genetic potential for protein accretion, g
Pe	extra protein, g
Pf	protein in feathers, g
Pmt	protein used for maintenance (FHP + TH + AH + HI), g
Ps	protein synthesis, g
t	age, days
T	temperature, deg C
TH	thermoregulation heat, kcal
W	body water gain, g

1. INTRODUCTION

Broiler chicken production is subject to diminishing returns - both biologically and economically. Increasing inputs of feed, medication, management, environmental control and time result in a plateauing response output of market birds (with a specific composition) and an optimum in profits. The challenge for the quantitative nutritionist is to characterize the appropriate nutrient response curves so that broiler production can be biologically and/or economically optimized.

The initial step in the process is deciding appropriate inputs and outputs. The important nutritional inputs should also have economic significance; if not they should be supplied at levels that support maximum biological performance. For example, the input of dietary protein is important because it is relatively expensive. Therefore the response to protein is of major interest. On the other hand, dietary calcium is an inexpensive nutrient and it should be supplied at levels that allow the response to economically important nutrients to optimize. The economically important nutritional inputs are dietary energy and protein (amino acids). Outputs should be economically important and sensitive to inputs. The important outputs are the body weight of the bird and its meat content.

Due to the complex nature of animals, the inputs and outputs are best analyzed with the use of computer models. The main objective of this thesis is to construct a model which accounts for energy and protein (amino acid) inputs. Current models will be reviewed and a new model will be developed and tested. Experiments will be conducted to improve both our general knowledge and the model prediction accuracy in the area of breast meat yield.

2. REVIEW OF THE LITERATURE

2.0 QUANTITATIVE NUTRITION

Animal growth responses to inputs of nutrients are not linear. There is a nonlinear response to intake of nutrients up to the point where further inputs will result in no response ie. a plateau. The plateau may have several causes, two of these are: either the genetic potential of the animal for maximum growth may be reached, or there may be a primary limitation of some other dietary nutrient. It is the latter - the interaction between nutrients that makes nutrition such a complex field of study. This is why many experiments and growth studies are difficult to interpret - there may be unaccounted for nutrient limitations and interactions.

The job of the quantitative nutritionist is to describe the animal's response to nutrients. The need for such work is evident for both scientific and practical reasons. The scientist is interested in obtaining the clearest possible description of animal response. The animal industry is interested in the economic production of meat.

The nutrients of primary economic interest to practical quantitative nutritionists are protein (amino acids) and energy. These nutrients are expensive. It is important to know how the animal responds to incremental changes in the dietary concentrations of these nutrients so that production can be economically optimized.

2.0.0 RESPONSE TO DIETARY PROTEIN AND AMINO ACIDS

Almquist (1953) demonstrated a linear relationship between amino acid concentration (log 10) and broiler growth. This relationship could be used to predict response to dietary amino acids, but was valid only for specific amino acids and to the experimental conditions used in the study; nutrient interactions were ignored. Combs (1964) developed a set of multiple regression equations which predicted amino acid response under a wider set of conditions. This added to the empirical knowledge base, but the predictive value was still limited.

An alternative approach was to do body amino acid composition studies in order to determine what balance of dietary amino acids were optimum for tissue growth. A series of studies was done (Marks et al. 1945, Holmes et al. 1963) which determined that the amino acid composition of broilers is relatively constant for different sexes and breeds. There is however, an age effect which can be accounted for by differing feather and meat proportions (Fisher and Scougall, 1982). These amino acid composition studies represented a major change in thinking to more of a mechanistic and less of an empirical approach to quantitative nutrition. Amino acid utilization efficiency, which includes digestive losses and inefficiencies due to amino acid imbalance, was not accounted for in these early studies. Saunders et al. (1977) determined that lysine had a 75.6% utilization efficiency. Leclercq (1983) determined that protein utilization efficiency was greater with lean strains of birds than fat strains.

Generally, little specific information is available on the efficiencies of and the factors that affect amino acid utilization.

2.0.1 RESPONSE TO DIETARY ENERGY

Energy metabolism is difficult to quantify because of difficulties in accurate measurement of energy value of diets and the complex reactions of energy conversion in the body. Basically increases in energy allow an increased amount of growth to take place. Fisher and Wilson (1974) determined that, generally, increases in energy concentration result in increases in body weight gain and improvements in feed efficiency. The nature of this growth is dependent on the supply of other nutrients eg. sufficient amino acids to permit continued muscle growth. It was long ago demonstrated (Fraps, 1943) that widening the energy to protein ratio will result in a fatter carcass.

It is commonly thought that animals will adjust their feed intake to meet a constant energy intake - their requirement. This may be true for some animals, but it is apparently not true for modern-day broilers. The standard test of this hypothesis is to dilute a diet with an inert substance (sand) and see if the birds increase feed consumption to maintain a constant energy intake. Most recent studies show that feed consumption does not fully adjust to maintain energy intake (Hsieh and Rowland, 1983; Onwudike, 1986) although a study by Farjo et al. (1986) supported the constant energy intake hypothesis. In most practical situations, broilers are energy intake limited by gut fill capacity, as influenced by environmental temperature and access time to feed (Barbato et al. 1984; Forbes, 1988).

The appropriate approach to understanding broiler response to energy intake is to understand how the animal uses energy ie. what body functions does it need energy for and what are the priorities. Energy intake also needs to be partitioned according to its form in the diet. Metabolizable energy, corrected for nitrogen retention, is based on the assumption that all protein in the feed is catabolized for energy. In the practical feeding situation, most of the dietary amino acids are deposited directly in the tissues and are therefore not catabolized. Also, body lipid gain may occur via direct deposition of dietary fat or through lipogenesis. Since these processes have different efficiencies, the proportion of fat in the diet and the amount of fat deposited in the body can affect the energy value of the diet.

2.1 BROILER MODELS

The advantage of computer models for predicting broiler performance is their ability to perform the multitude of calculations necessary to account for the many nutrient interactions. There are two types of computer models: empirical models and mechanistic models. Empirical models are based on a mathematical description of experimental data. They are typically derived by picking an output(s) of interest (dependent variable) and statistically describing that output response to inputs (independent variables). The resulting model is the one that mathematically best describes the data. By definition, it is confined to the data from which it was derived. Mechanistic models on the other hand attempt to explain the underlying mechanisms of the response, and usually involve a model construction of the animal "from the ground up". In the case of growing animals, there is an attempt to describe the various components of the animal, eg. muscle, bone, organs, fat etc.. The whole animal is the sum of the components. Mechanistic models can be extrapolated to novel situations.

It should be noted that there is usually an empirical aspect to mechanistic models in that growth in a portion or all of a body component is described empirically; eg. feather weight is often described as an empirical function of age. To be exclusively mechanistic, a model would have to rely solely on basic biological mechanisms ie. cellular biochemistry. Such a comprehensive description of a whole animal is not currently possible. Therefore the term mechanistic will be used in this thesis to refer to any model which attempts to partition the animal into components and create a description of the animal by summing the components.

2.1.0 EMPIRICAL MODELS - QUADRATIC PROGRAMMING

There is one empirical model for broilers which for two reasons merits discussion. It is more comprehensive than most empirical models in that it addresses response to several inputs, rather than the single input of most empirical models. It also addresses the problem of economic application by optimizing output to inputs. This model is commonly known as the Broiler Quadratic Programming model and was described by Pesti et al. (1986) and Miller et al. (1986). The model empirically describes the response of male broiler chickens in the growing phase (3-7 weeks) to intakes of dietary energy and protein. The ouputs of interest are body weight and feed efficiency. A quadratic equation was used to describe response. The prediction equation for body weight is:

$$BW = .042 + 1.458 \times P + .026 \times E - 1.759 \times P^{2} - .0004 \times E^{2} + .039 \times P \times E$$

where BW = body weight (kg), P = protein intake (kg) and E = metabolizable energy intake (MJ)

The prediction equation is integrated with a feed ingredient matrix which has specified protein and energy contents and costs. The output is optimized (usually a fixed BW at least input cost) with the use of quadratic programming.

The animal data from which the model was derived was generated in 1982. It would be expected that changing genetics (broilers are 20% heavier at 6 weeks of age today, in 1990, than they were in 1982) would invalidate the model. However, the model still accurately predicts the body weight response of current strains to protein and energy intake. The genetic changes in the bird since 1982 appear to be in the ability to eat more feed (Forbes, 1988). There are apparently no changes in how the bird metabolizes that feed (Leeson, 1989); the birds are 20% bigger because they eat almost 20% more feed (the relative proportion of dietary nutrients needed for maintenance decreases with increasing feed intake). The broiler appears to be limited in its growth potential by its ability to consume feed so that the genetic potential for growth may never be expressed.

2.1.1 MECHANISTIC MODELS

Mechanistic models are more interesting than empirical models because they are theoretically based. They attempt to answer the fundamental questions: 'how' and 'why'. They also offer greater long term potential than empirical models, because they can be extrapolated. They demand a greater construction effort in the early stages than empirical models but are ultimately more useful. Three different deductive models for broilers will be discussed: 1. the Israeli model, 2. the Edinburgh model and 3. the Japanese model. Symbols used in describing these models are explained in the List of Abbreviations.

2.1.1.0 ISRAELI (HURWITZ) MODEL

The Israeli model was first described by Hurwitz et al. (1978) and was subsequently improved (Hurwitz et al. 1980b, Hurwitz 1988). Of the three deductive models, it is probably the least useful because it is not driven by changes in nutrient input. Instead, it starts with an assumption of what the bird will weigh at specific ages and then assumes a 'typical' body composition. For example; a body weight is chosen; the maintenance, feather, body protein, and lipid components of the bird are then assumed. Next, the amino acid composition of the components is ascertained. Finally, the model describes what nutrient levels are needed in the diet to meet the requirements of those components of 'typical' magnitude, and by summation, the animal itself. For example, the lysine requirement would be:

$EAAlys = EAAmlys + EAAflys + EAAblys$

The model is efficient in determining the optimum balance of nutrients for a specific level of production but has difficulty predicting the requirements for changing levels of production. Since the model is driven from 'top down' it cannot predict how various nutrients will interact and how the animal will adjust its growth (relative priorities for tissue component growth) in restricted nutrient situations. Feed intake is calculated as a function of ME requirements.

The energy requirement per day is broken into a requirement for maintenance and a requirement for gain:

$Emt = 1.91 \times BW^{.667} + 2.15 \times BWg$

The energy requirement for maintenance is influenced by environmental temperature and has been adjusted for 6 week old male broilers (Hurwitz et al. 1980a) using a multiplicative correction factor which minimizes at 27.5 degrees Celcius:

$TH\ adjustment = 3.9098 - .1429 \times T + .0026 \times T^2$

In the gain portion, the 2.15 coefficient is adjusted for the proportion of gain that is fat:

$Gain\ coeff = .6 + 9.2 \times Fat$

The protein requirement for maintenance is given by:

$Pmt = .023 \times BW^{.667}$

Dietary protein is assumed to have a utilization efficiency of 85%.

The model has been tested and adjusted by Fisher (1981) and Jackson (1987). The model has not received widespread commercial use because of the lack of detail and because it is not sensitive to changes in nutrient input.

2.1.1.1 EDINBURGH MODEL

This second of the mechanistic models is the most comprehensive model. It was first described by Emmans (1981) and portions of it were subsequently described by Emmans (1987), Emmans and Fisher (1986) and Fisher (1988). It is an input driven model. It predicts performance of the bird by determining nutrients consumed, and then by apportioning those nutrients to various body functions, eg. maintenance, body protein accretion, feather growth, body ash gain, body water gain and fat gain.

The model relies heavily on the genetic growth potential of the bird. Several of its parameters such as fasting heat production, maximum potential protein accretion, maximum feather growth, are calculated with reference to the weight and composition of the mature bird and the degree of maturity it has attained at the age of interest. The growth rate of the bird is determined by summing the growth components. It is an iterative model which computes gain on a daily basis.

The potential body weight gain is driven by potential carcass protein gain which is hypothesized to be the primary genetic driving force of growth in the model. The maximum possible protein gain is described (Emmans and Fisher, 1986) as:

$$Pbg = B \times Pb \times \ln(Pbm/Pb)$$

The model also specifies a minimum fat to body protein ratio in the animal to allow for essential fat synthesis - for the mature animal of "average" genetics this is .7 for the male and 1.1 for the female (Fisher 1988).

Feather growth is also determined by relative maturity using the data of Hakansen et al. (1978). Amino acids are apportioned in a similar manner to the Israeli model. Fasting heat production is considered to be a function of carcass protein content:

$$FHP = .39 \times Pbm^{.73} \times Pb/Pbm.$$

Feed intake is predicted from dietary energy concentration and the bird's energy requirements for maximum growth (Emmans 1987, Fisher 1988) and is limited by gut fill capacity. The 'energy requirement' of the bird is defined (Fisher 1988) as the maintenance energy requirement plus the energy required for protein and lipid gains, including both synthesis and retention energies. The 'effective' energy in the diet is defined as Metabolizable Energy minus work done in protein and fecal excretion plus a bonus for the amount of fat that can be deposited directly in the tissues. These equations represent the most detailed attempt to partition broiler metabolizable energy to date.

The model can be criticized on a number of points:

1. The data does not support an 'energy requirement' driver for feed intake, which means that the energy partitioning equations have a questionable theoretical base.
2. Some important energy components are oversimplified in the model. For example, the energy cost of protein synthesis is assumed to be a constant; irregardless of protein accretion rate. The amount of dietary fat deposited directly in the body is not related to the total dietary energy content.
3. The Gompertz equation to predict potential growth rate is not accurate for the first 6 weeks of age (Rogers et al. 1987).
4. The theoretical validity of determining growth rate by a relative maturity driver as proposed by Taylor (1980) has not been proven - especially at early stages of growth.

Despite these deficiencies, the Edinburgh broiler model remains the most complete theoretically and the most comprehensive model in current use.

2.1.1.2 JAPANESE (ISARIYODOM) MODEL

A model was developed recently by Isariyodom et al. (1988). It is similar to the Edinburgh model in that it is input driven. It is simpler than the Edinburgh model in that it accounts for only dietary energy and protein - there is no separate calculation of amino acid utilization, only reference to the biological value of the protein and a utilization efficiency of 80%. It is based on the Edinburgh model for growing pigs (Whittemore and Fawcett, 1974, 1976). It differs from the Edinburgh broiler model in that it does not express the growth of the animal in terms of its relative maturity. Instead it relies on the empirical responses observed at various ages. In many respects, this simplifies model construction. Although body protein and feather protein are not considered separately, the Japanese model does have a detailed accounting of protein retention and energy utilization. It accounts for energetic efficiencies of both protein synthesis and degradation. The energy value of protein in the diet is subtracted from total energy before it is partitioned, and the energy released from excess protein is added back.

The model also includes an adjustment for changing protein turnover rate with age (Muramatsu and Okumura, 1985) which is a partial recognition of the effect of increasing growth rate on increasing the energy costs of protein synthesis:

$$FSR = .9 \times (36.0 - .3857 \times t) \text{ if } t <= 30$$

$$FSR = .9 \times (24.93 - .0107 \times t) \text{ if } t > 30$$

The Japanese model treats feed intake prediction somewhat differently than the Edinburgh model. It empirically treats intake as a function of required energy intake, which in turn is a function of body weight, environmental temperature and lighting period.

The model has not been tested by other workers. The major drawbacks to the model are:

1. There is no consideration of amino acid balance.
2. Feed intake is driven by energy 'requirement'.

2.2 BREAST MEAT YIELD

The breast meat is the most economically important component of the broiler. It makes up almost 50% of the total meat yield of the bird and its retail value per unit weight is usually more than twice that of the next most expensive meat component. There is a limited amount of data with respect to the effects of dietary protein and energy on breast meat yield (Salmon et al. 1983, Summers et al. 1988). Generally, increasing protein while maintaining energy levels constant results in a greater relative proportion of breast meat as a percent of body weight.

In addition to the need to incorporate breast meat yield into a mechanistic model, there is a need to empirically characterize the breast meat content of the broiler over the commercial life of the bird and to quantify its response to different nutrient (especially protein and essential amino acid) intakes. The study by Prescott et al. (1985) supplies useful data for generating allometric relationships between breast meat and age and body weight. They found that breast meat is very closely related to body weight by the equation:

$$BM = .045 \times BW^{1.148}$$

Also, the study of Howlider and Rose (1989) contributes useful data on the gain of different carcass meat components with increasing body weight and age.

2.3 SUMMARY

The mechanistic broiler models discussed so far have some deficiencies and limitations. The Israeli model is driven by assumptions about the final bird composition which makes it inappropriate for economic analysis. As well, there is a lack of detail. Likewise, the Japanese model lacks detail but has the advantage of being 'response to input' driven which makes it useful in economic analysis. The Edinburgh model has both an input - output structure and has considerable detail which makes it the most acceptable model of the three. The limitations of the Edinburgh model are; the questionable theoretical treatment of feed intake based on energy requirement, the bird requirement basis of calculating available energy and the reliance on error prone growth curves to predict maximum growth rate.

In addition, none of the models adequately address meat yield, especially breast meat, as influenced by growth and dietary parameters. This is due to a lack of basic research information on the subject.

3. DEVELOPMENT OF MODEL

A mechanistic rather than an empirical approach was chosen with the view that the model would have more generalized application. There is an abundance of empirical studies in the literature but relatively few attempts to explain nutritional effects and interactions in terms of a unified theory.

3.0 MODEL STRUCTURE

The model has an input - output structure in which a specified or predicted intake of nutrients results in a mechanistic partitioning of nutrients to body maintenance and growth processes. Of the three mechanistic models already discussed, the model most closely resembles the Edinburgh model. Several of the predictive equations in the Edinburgh model are used directly. A subtle but significant difference in approach between this model and the Edinburgh model should be noted. The Edinburgh model starts with the premise that the bird at specific ages and stages of development is driven by its genetic potential for growth and that this stimulates the bird to consume needed nutrients. While this is a logical theory, the evidence is that broiler chickens, like most animals, do not actively choose between different diets or nutrients and do not fully adjust feed intake with changes in diet nutrient density in order to maintain constant nutrient intake (Forbes, 1988).

Instead, the premise of this model is that the bird eats what it is given, ie. the level of consumption is not determined precisely by its 'need' for nutrients. Rather, the bird can alter its nutrient utilization to adjust to changes in nutrient intake in order to maximize metabolic efficiency. In other words, the mechanism of the model has little to do with nutrient "requirements" but has a lot to do with changing nutrient partitioning in the body as influenced by nutrient intake.

Some other key differences between this model and the Edinburgh model are:

1. Less reliance is placed on exponential growth curves in this model.

2. Energy partitioning is more detailed than in the Edinburgh model. Energy partitioning is strictly determined by intake.

3. Feed intake in this model is predicted from gut capacity (BW), temperature, dietary energy concentration and photoperiod rather than from energy requirement as in the Edinburgh model.

As with the previously discussed mechanistic models, the animal is the sum of its parts. Weight gain, calculated on a daily basis, is the sum of body lipid, feather and body protein, bone and water gains. The two major inputs to the model are digestible dietary protein (digestible amino acids) and energy.

A simple impact diagram of the model is given in Figure 1. The model was programmed in Turbo C (Borland version 2.0) on a microcomputer running in MS DOS. The pseudocode is listed in Figure 2.

3.1 ENERGY PARTITION

Energy intake (MEI), which is apparent metabolizable energy corrected for N retention (AMEn), is either lost as heat production (HP) or retained in the body (ER).

$$MEI = HP + ER$$

HP is comprised of energy used for fasting heat production (FHP), thermoregulation (TH), activity (AH) and heat increment (HI). HI can in turn be partitioned into heats of protein and lipid synthesis (Eps and Els), heat of digestion and defecation (DH) and heat cost of nitrogen excretion (EH). Fermentation heat is ignored in the broiler. ER consists of energy retained as protein (ERp) and energy retained as lipid (ERl).

AMEn is calculated on the basis that all protein in the diet is catabolized for energy. In fact most of it is retained in the tissues with a higher energy retention efficiency than if it was catabolized. Therefore, the first step is to correct MEI by subtracting the catabolic energy value of protein (4.32 kcal/g) from the total. The energy value of excess protein is added back later (before fat deposition).

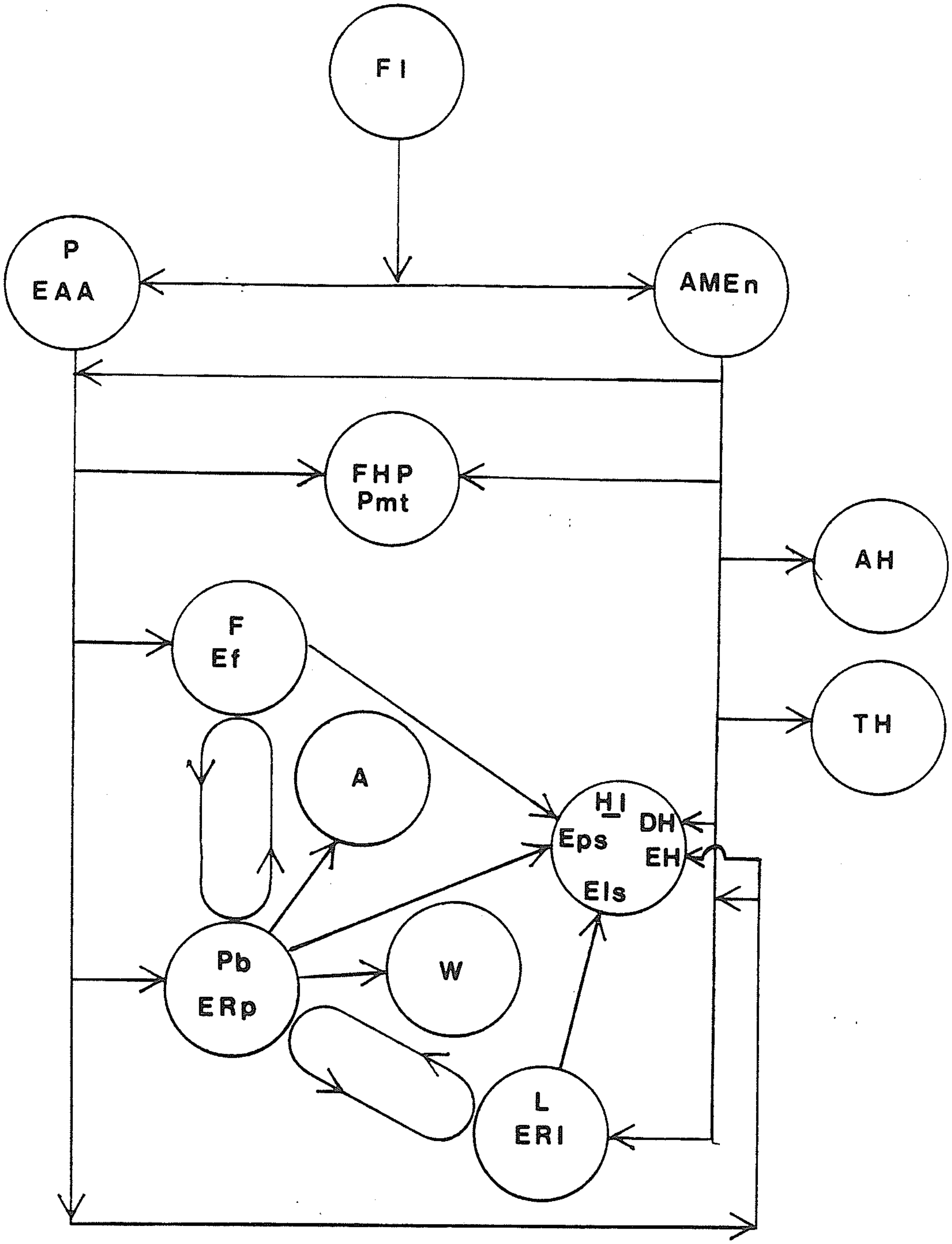

Figure 1. Impact diagram of broiler model structure. See list of abbreviations for explanation of symbols.

```
Input (initial age, final age, initial body weight, initial
body composition (protein, feather, fat, ash and water),
sex, temperature, light hours, genetic adjustment for feed
intake, dietary AMEn, fat, digestible protein, digestible
amino acids (arg, his, lys, trp, phe+tyr, phe, tsaa, met,
thr, leu, ile, val))

Start loop of daily body weight gain
 Calculate daily feed intake
  If feed intake unknown use equations in section 3.6
  If feed intake known use equation in section 4.1
 Calculate maintenance req. for protein and amino acids
 (section 3.2.0)
 Calculate feather req. for protein and amino acids (section
 3.2.1)
  Calculate amino acids left over for body protein gain
  ie. first limiting amino acid (section 3.2.2)
  Calculate maximum genetic potential body protein gain
  (section 3.2.2)
  Compare amino acid limited body protein gain with genetic
  potential and take lower
  Start loop of minimum feather protein/body protein
  (Section 3.2.2)
   Start loop for minimum body fat/body protein gain
   (section 3.1.1.1)
    Calculate lipid gain  (section 3.1.1.1).
     Calculate energy intake (section 3.1)
      Subtract fasting heat production (section 3.1.0.0)
      Subtract thermoregulation heat (section 3.1.0.1)
      Subtract activity heat (section 3.1.0.2)
      Subtract heat increment (section 3.1.0.3)
       Add heat of defecation, heat of nitrogen excretion,
       heat of feather synthesis and heat of body protein
       synthesis
      Subtract energy value of directly deposited fat
      (section 3.1.1.1)
     Calculate fat deposition from lipogenesis (section
     3.1.1.1)
    Compare ratio of lipid gain to protein gain and adjust
    protein gain down by 5% increments if below minimim
    ratio until minimum reached
   End loop for minimum body fat/body protein gain
  End loop for feather protein/body protein
 Calculate body ash gain (section 3.3)
 Calculate body water gain (section 3.4)
 Calculate breast meat, leg meat and abdominal fat (section
 3.5)
 Sum body components to get body weight (section 3.0)
End loop of daily body weight gain
Start next day calculation
Do for each day of age interval
```

Figure 2. Broiler model pseudo code.

$$MEI\ (CHO, fat) = FI \times (AMEn - 4.32 \times prot) + 4.32 \times Pe$$

3.1.0 HEAT PRODUCTION

3.1.0.0 FASTING HEAT PRODUCTION

There are a number of published predictive equations for maintenance energy and fasting heat production (FHP) (Emmans and Fisher, 1986; Hurwitz et al., 1978; Isariyodom et al., 1988; Keller, 1980; Kirkwood and Webster, 1984; Robbins and Ballew, 1984; Rogers and Pesti, 1988). It is remarkable how much they vary. No doubt this is in part due to some estimates also including activity, thermoregulatory and feeding effects. For this model, the equation of Kirkwood and Webster (1984) will be used. It is a general equation for all animals which relates FHP to body weight:

$$FHP = 95.6 \times BW\ (kg)\ \hat{}\ .75$$

The equation may be criticized because it does not account for carcass composition as does the equation of Emmans and Fisher (1986) and the exponent may not be the most appropriate one for poultry (Rogers and Pesti, 1988). Nevertheless it is the preferable equation to use because its universality gives it credibility.

3.1.0.1 THERMOREGULATION HEAT

A cold environmental temperature will cause an increase in heat production in order to keep warm. A warm environment will cause an increase in heat production through operation of heat loss mechanisms such as panting, vasodilation and perspiration. The data of Hurwitz et al., (1980a) was used to generate a predictive equation for both males and females relative to BW^.75.

$$Emt = (4.4570 - .1566xT + .0026xT^2) \times BW^{.75}$$

This equation is used to calculate the number of extra kcal per day by subtracting the value at thermoneutrality (30.1 degrees C) from the value at the actual environmental temperature. The limitation of this equation is that it was developed from data on 6 week old birds. There is insufficient data to account for age effects on TH.

3.1.0.2 ACTIVITY HEAT

There are no studies of activity heat in broilers. Van Kampen (1976 a, b) has shown that the energy costs of locomotion, standing and eating raise FHP by 50%, 40% and 50% in laying hens. Damme et al. (1987) showed that FHP in laying hens is 37% higher in the light than in the dark. Accordingly, AH is given a value of 50% of FHP with the recognition that this is a rough and variable estimate.

3.1.0.3 HEAT INCREMENT

The model uses the Edinburgh value of .91 kcal/g of fecal organic matter (FOM) for digestion heat (DH). DH is approximated from feed digestibility estimated from the following equations which use dietary energy values to assess carbohydrate digestibility. Dietary protein and fat were given arbitrary digestibility values of 85% and 90% respectively. The coefficients 40 and 80 are used to convert the energy yield of % dietary protein and fat respectively to kcal/kg. Diet dry matter is assumed to be 95%.

actual CHO energy = AMEn - digestible diet prot x 40 + diet fat x .9 x 80

possible CHO energy = (95 - diet prot/.85 - diet fat/.9) x .9 x 40

FOM = 1 - (actual CHO energy/possible CHO energy) + (diet prot/.85)x.0015 + diet fat x .001

The value for excretion heat (EH, energy cost of nitrogen excretion) is 1.12 kcal/g of protein excreted as determined by the amount of excess protein (Fisher, 1988).

The energy requirement for protein synthesis (Eps) is .85 kcal/g. This corresponds to the cost in ATP of 5 steps of protein synthesis (Waterlow et al., 1978). Increased growth rate will increase heat production (Keller, 1980). This effect is accounted for by increasing protein fractional synthetic rate (FSR). FSR is influenced by a number of factors, especially age (Jones et al., 1986; Kang et al., 1985). Normally the energy cost of FSR is measured as part of FHP. However, studies have shown that growth rate as influenced by nutritional status can influence FSR (Kino and Okumura, 1986, 1987; Kita et al., 1989). The data of Kita et al. (1989) indicates that FSR increases by 1.5 for each unit increase in % protein gain (% BW) growth rate. This increase in energy cost of carcass protein synthesis with protein synthesis rate is in good agreement with empirical data (Fisher, 1988). There is no accounting for amino acid conversions so that this value may underestimate total energy costs of protein synthesis. The cost of feather protein accretion is not corrected for FSR. The energy costs of fat synthesis (Efs) are not added in at this stage because calculation of fat synthesis is done last, ie. the model gives it lowest priority.

3.1.1 ENERGY RETENTION

The energy intake by the animal that is not lost as heat production is retained, according to the first law of thermodynamics. For modelling purposes, the retained energy is in the form of protein or lipid - other reserves being negligible.

3.1.1.0 PROTEIN ENERGY RETENTION

The actual cost of energy retained as protein is not costed in the model because it was subtracted from initial energy intake. The energy value of retained protein is 5.64 kcal/g (Whittmore and Fawcett, 1974). The actual amount of usable energy from body protein catabolism is 4.32 kcal/g (NRC, 1981) due to the loss of the energy in uric acid.

3.1.1.1 FAT ENERGY RETENTION

It is assumed in the model that body lipid gain is due to the conversion of energy left over after all other energy requirements are met. As well, the energy value of excess protein is made available for lipogenesis at this stage. At low energy intakes, the model could decide that there was insufficient energy for any fat synthesis after other requirements were met. There is an essential fat synthesis and accordingly the model maintains a minimum lipid to protein accretion ratio. This minimum ratio starts at .4 at a day of age and then increases with age up to 1.0 for males and 1.4 for females (equations developed from the data of Leeson and Summers, 1980):

$$\text{Male min } L/Pbg = .4 + .0137 \times t \quad \text{until} = 1.0$$

$$\text{Female min } L/Pbg = .4 + .0204 \times t \quad \text{until} = 1.4$$

These ratios will, in fact, be different for different strains and the model should be adjusted for these genetic differences in practice.

The conversion of excess energy to body lipid is complicated by the amount of dietary fat. Where the extra energy is in a nonfat form, there is a lipogenic energy cost of 3.92 kcal/g fat deposited. Where dietary fat is deposited directly in the tissues then the energy cost is 1.05 kcal/g. Both these values are used as in the Edinburgh model along with a retained energy value of 9.46 kcal/g of fat (Emmans and Fisher, 1986; Fisher, 1988). The model calculates fat utilization on the basis that no dietary fat is used for any other purpose than fat deposition unless there is insufficient energy from other sources for higher priority processes. This is obviously an oversimplification as all three energy sources would be used simultaneously. The model will therefore underestimate the true costs of fat deposition.

There is a theoretical situation where maximum fat deposition capability may be reached at very high energy intakes. There is no mechanism in the model to account for this other than to continue increasing fat storage. This situation is probably not a practical concern.

3.2 PROTEIN PARTITION

There is a primary protein requirement for maintenance. After this need is met, protein may be deposited in the body. Body protein gain can be separated into feather protein gain and the remainder (muscles, skin, organs). These two components are best treated separately in the chicken because they grow mostly independently and because they have very different amino acid compositions. Dietary amino acids will be used for body protein gain up to the genetic potential for growth or up to the first limiting essential amino acid. Any excess dietary protein will be catabolized for energy.

Dietary amino acids have a utilization efficiency which is poorly quantified. It is most likely that different amino acids have different utilization efficiencies. As well, utilization efficiency will likely be affected by such factors as growth rate and proportion of growth of various tissues. The Edinburgh model uses a value of 75% utilization efficiency (Fisher, 1988). The Hurwitz model uses 85% and the Japan model uses 80%. This model uses a high value of 85%, since amino acid input to the model is already on a digestible basis.

3.2.0 PROTEIN AND AMINO ACIDS USED FOR MAINTENANCE

The protein requirement for maintenance is measured as the endogenous protein loss. It is primarily a function of body weight. The equation of Hurwitz et al. (1978) is used.

Pmt = .023 x BW^.667

The amino acid profile for the maintenance requirement (Table 1) was taken from Hurwitz et al. (1978) which was adapted from Leveille and Fisher (1958), and from Fisher (1988).

3.2.1 PROTEIN AND AMINO ACIDS USED FOR FEATHER GROWTH

Feather growth is considered to be second in priority after maintenance. Feather growth is primarily a function of age rather than body weight. Although differences in feather percentage of body weight between sexes and breeds have been reported (Block and Weiss, 1956; Edwards et al,

Table 1. Essential amino acid profile (% of protein), for broiler maintenance, feather and body protein.

Amino acid	Maintenance	Feathers	Body
Arg	6.8	7.2	6.9
His	2.4	.7	3.0
Lys	6.8	1.9	8.0
Trp	1.1	.7	1.0
Phe + Tyr	5.0	9.5	7.1
Phe	3.0	5.1	4.0
Met + Cys	4.8	7.6	3.6
Met	2.4	.6	2.5
Thr	4.2	4.6	4.2
Leu	4.8	8.1	7.1
Ile	3.6	5.0	4.0
Val	3.5	7.7	5.4

Hurwitz et al. (1978), Fisher (1988), Block & Weiss (1956)

1973; Fisher et al., 1981; Fisher, 1988; Plavnik and Hurwitz, 1983), when actual feather weights at specific ages are compared, the breed and sex differences disappear.

The Plavnik and Hurwitz (1983) data was subjected to regression analysis. Feather weight gain demonstrated a quadratic relationship to age ($R^2 = .92$):

$$F = .103 \times t - .0009 \times t^2$$

$$Pf = F \times .93$$

The function maximum of 57 days may be premature and so feather weights of birds older than 8 weeks may be underestimated. The reported amino acid composition data of feathers varies between researchers. The data used in this model (Table 1) is derived, by averaging, from Hurwitz et al. (1983), Block and Weiss (1956) and Fisher (1988).

3.2.2 PROTEIN AND AMINO ACIDS USED FOR BODY PROTEIN

The body will gain protein up to a maximum deposition allowed by genetic potential or up to the supply of the first limiting amino acid. The maximum genetic potential for lean tissue accretion may be calculated in a number of ways. The Edinburgh model uses a growth predicting Gompertz equation and a relative maturity value to determine maximum potential protein gain. This model follows the Edinburgh model approach. The procedure of estimating parameters for mature body protein contents and rates of potential body protein gain as outlined by Emmans and Fisher (1986) are used. Due to a lack of suitable data for different breeds, average values are used in this model (Fisher, 1988):

$$Pbmax = .044 \times Pb \times \ln(1.3/Pb) \quad \text{(males)}$$

$$Pbmax = .044 \times Pb \times \ln(.85/Pb) \quad \text{(females)}$$

The .044 value for B was derived from inserting the growth data reported by Rogers et al. (1987) into the equation of Kirkwood and Webster (1984).

It is recognized that there is a potential for model error in carcass protein prediction. The Gompertz equation (along with other exponential equations) does not accurately predict body weights at the young ages which are important in commercial broiler production (Rogers et al., 1987). The Gompertz equation overestimates weight and the Logistic equation underestimates weight by about 50% for the first four weeks of age. And since commercial broilers are typically only grown to 10 weeks of age maximum, there is questionable benefit in describing the growth curve to maturity. As well, the confidence in empirically derived maximum protein accretion estimates is low because it is often uncertain whether an adequate dietary regime was used to test it. For these reasons, an alternative empirical measure of maximum protein accretion based on the data of Leeson and Summers (1980) is also incorporated into the model and compared with the Edinburgh model calculation:

$$Pbmax = BW \times (30 - 6.957 \times BW + .951 \times BW^2) \quad \text{(males)}$$

$$Pbmax = BW \times (30 - 12.07 \times BW + 2.727 \times BW^2) \quad \text{(females)}$$

Where there are differences between the empirical and relative maturity value equations, the lower value prevails.

The amino acid composition of body protein (Table 1) was taken from Plavnik and Hurwitz (1983) and Fisher (1988). The level of the first limiting amino acid for carcass protein accretion was determined by first supplying amino acids to maintenance requirements, then to feather growth requirements and finally to body protein requirements. It is clear that maintenance needs have highest priority, but that there will be both feather and lean body synthesis simultaneously. It is recognized that at moderate protein intakes there may be insufficient sulfur amino acids for maximum feather synthesis, and the animal will simply produce less feathers while continuing to grow. If the model calculated body protein gain is less than 30% of its potential then feather growth is reduced by 25%. This is an arbitrary correction factor. There is no available data to test it.

3.3 BODY ASH GAIN

The skeleton is a major portion of the total bird. The Edinburgh model estimates body ash content from total feather-free body protein with which it is highly correlated. This model uses the same predictive equation (Emmans, 1981):

$$A = .16 \times Pb$$

3.4 BODY WATER GAIN

The amount of water in the body is also strongly correlated with feather-free body protein content. The data of Hakanssen et al. (1978) as described by Emmans and Fisher (1986) is used to calculate body water contents:

$$W = 5.35 \times Pb^{.9062}$$

3.5 BODY PART YIELD

The weight yield of commercially important body components is of interest. The objective is to maximize meat yield; therefore breast meat yield and leg meat yield would be useful components of a model. Conversely, the objective is to minimize fat content, therefore a prediction of abdominal fat would be useful.

The data of Prescott et al. (1985) was used to develop allometric relationships between breast meat yield and leg meat yield to carcass protein content and abdominal fat yield to carcass fat. The data of Leeson and Summers (1980) was used to relate carcass protein and fat to whole body protein and fat at different ages. The breast meat data of Prescott et al. (1985) was derived from sampling only the left side of the breast and therefore was adjusted to correct a 3% heavier left breast muscle than right breast muscle (Appendix). The resulting prediction equations are:

$$BM = .3156 \times Pb^{1.162} \qquad R^2=.99$$

$$LM = .1782 \times Pb^{1.251} \qquad R^2=.99$$

$AF = .1875 \times L^{.911}$ $R^2=.93$

One question of interest is how much these components behave independently of their dependent variable. Although the coefficients of determination are uniformly high, the equations were derived from bird growth data on a uniform plane of nutrition. Excess levels of dietary amino acids and energy may be stored in body protein and fat.

3.6 FEED INTAKE

Feed intake is a very critical and inadequately predicted aspect of broiler models. The Israeli, Edinburgh and Japanese models all rely primarily on the birds "requirement" for energy to dictate feed intake. As mentioned previously, today's strains of broilers clearly do not adjust their feed intake to fully account for energy differences in the diets (Forbes, 1988). Gut fill seems to be the primary determinant of feed intake (Barbato et al., 1984) and feed intake is significantly influenced by temperature and hours of light (Forbes, 1988).

An allometric relationship between body weight and feed consumption was derived from NRC (1984) data:

$FI = .2 \times BW^{.9}$

An alternative equation relating feed intake to age was developed from NRC (1984):

$FI = 3.57 \times t$

The age equation recognizes that body weight may lag seriously behind genetic potential and there needs to be a mechanism whereby the bird will attempt to catch up through increasing its feed consumption. Therefore the model compares the results of both the BW and age prediction equations and uses the greater value.

The multiplicative lighting period adjustment of the Japanese model was used with modifications:

$$\text{Correction factor} = .6 + .004 \times LH$$

The equation of Howlider and Rose (1987) was used to multiplicatively correct feed intake for temperature:

$$\text{Correction factor} = .973 + .015 \times T - .00064 \times T^2$$

As well, the bird will adjust feed intake to make a partial adjustment for differences in dietary energy concentration. The following multiplicative correction factor was developed from the data of Fisher and Wilson (1974).

$$FI = FI + ((3000 - AMEn) \times .00015 \times FI)$$

The influence that erroneous feed intake prediction could have on total model performance is recognized. Since the primary rationale of the model is that the performance of the bird is predictable once feed has been consumed, the bulk of validation work will involve testing of the model from the point after nutrients are in the bird. The prediction of feed intake and its validation are entirely separate from the partitioning mechanics of the model and are treated as a secondary issue in this thesis.

4. MODEL VALIDATION

Since there are many critical assumptions and independant features in the model, it is not feasible to conduct sufficient original biological experiments in order to fully test the model. Instead, existing data from the scientific literature will be used.

An additional problem in validating this type of model is that it is difficult to test the sensitivity of specific equation coefficients in the model. For any nutrient effect of interest, there is no one equation in the model which will account for total response to that nutrient. Rather several equations are used to predict each nutrient effect. As such, the model functions as a whole and is therefore best evaluated at a "macro" level where a broad data set is used to point out areas of model weakness.

4.0 CRITICAL ASSUMPTIONS

There are several critical assumptions in the model that can be tested:

1. Assumption: The bird is input driven, ie. the bird will respond to differences in feed intake.

Test: Evaluate data where feed intake of a specific diet is restricted by varying degrees.

2. Assumption: The bird will partition energy intake between heat production and energy retention in a manner which varies with energy intake.

Test: Evaluate data where energy retention is measured over different energy intakes.

3. Assumption: Increasing levels of dietary fat have an extra-caloric effect. The model accounts for this by giving body lipid deposition from dietary fat a higher efficiency than body lipid deposition from lipogenesis.

Test: Evaluate data where response to variable fat levels in the diet is measured at constant dietary energy concentration and feed intake.

4. Assumption: Changes in the protein to energy ratio will change growth rate and carcass composition.

Test: Evaluate data where protein and energy proportions in the diet are varied.

5. Assumption: Changes in the essential amino acid levels in the diet from limiting to non-limiting concentrations will have effects on growth rate and carcass composition.

Test: Evaluate data where lysine and methionine are fed at different concentrations from a limiting to non-limiting state.

6. Assumption: Environmental temperature will have an effect on thermoregulation heat.

Test: Evaluate data where environmental temperature is varied.

7. Assumption: Males and females will have different

growth rates and carcass composition.

Test: Evaluate sex output differences under changing nutrient intakes.

8. Assumption: Feed intake is primarily a function of body weight, environmental temperature, photoperiod and dietary energy concentration.

Test: Evaluate data where environmental temperature, photoperiod and dietary energy concentration are varied.

4.1 LITERATURE DATA CRITERIA AND HANDLING

The data was derived from the scientific literature, and was limited to published papers in Poultry Science, British Poultry Science and the Canadian Journal of Animal Science from 1980 to the present. The following information was required in order for the data to be acceptable:

1. Sex
2. Diet composition - practical diets only
3. Age period of test
4. Weight of bird at start of test - actual or estimate
5. Feed consumption over test period
6. Weight gain over test period
7. Environmental conditions - temperature and lighting
8. Multiple treatment levels

The nutrient composition of the diets was calculated from NRC (1982) unless analyzed. ME values for fat were taken from NRC (1984). Digestible amino acid levels were calculated from coefficients published by Heartland Lysine (1990). An equation to distribute specified total feed intake over the experimental period was derived from NRC (1984) feed intake curves as a function of age:

Percent feed intake increase over previous day

$$= (93.27 \times age^{-.969} + 100)/100$$

This equation was tested on the feed intake pattern of current genetic strains of broilers (Arbor Acres 1987) and was found to be valid. It is recognized that daily changes in feed intake do not follow a smooth curve (Forbes 1988), and that use of the above equation will probably overestimate the efficiency of nutrient utilization.

4.2 ASSUMPTION TESTS

The difficulty in testing the model is in holding all other factors, including feed intake, constant while the factor of interest is tested. Where it is not possible to hold feed intake constant, the test data should incorporate enough treatments to allow feed intake differences to be treated as a covariate.

4.2.0 RESPONSE TO CHANGING FEED INTAKE

The data of Proudfoot and Hulan (1982) was used to test the effect of varying intakes of a starter (0-28 days) and a finisher (29-49 days) diet on growth rate. Variable intake was accomplished by restricting light to male and female

Cobb broilers to as little as 8 hours per day. The composition of the diets is shown in Table 2. The actual feed consumption and the actual and model predicted weight gains are given in Table 3. The results show that the model predicts lower growth rate than actual in both the starter and finisher period. The increase in growth rate with increasing feed intake is the same for both actual and predicted in the starter phase. The rate of actual growth increase with increasing feed intake in the finisher phase is lower than predicted. The actual growth rate increase with increasing feed intake was linear in both the starter and finisher phases but had a higher coefficient of determination in the starter phase ($R^2 = .88$ vs $R^2 = .68$).

4.2.1 ENERGY PARTITIONING

A central mechanism of the model is that energy is available for tissue growth (retention) only after heat production is accounted for. The experiment of Brue and Latshaw (1985) was used to examine energy retention and heat production under conditions of changing energy intake. In this experiment three different dietary fat types and two different fat levels (plus a low fat control) were used to examine growth rate, carcass fat content and energy retention in mixed sex Cobb broilers from 6 to 28 days of age. The composition of the diets is shown in Table 4. The diets were iso-nitrogenous although essential amino acid

Table 2. Calculated nutrient composition of diets (Proudfoot and Hulan, 1982) used to test ability of broiler model to predict response to changing feed intake.

Nutrient	Starter	Finisher
AMEn, kcal/kg	3022	3229
Crude fat, %	4.7	6.0
Dig. protein, %	21.6	14.4
Dig. arg, %	1.43	.86
Dig. his, %	.55	.35
Dig. lys, %	1.17	.64
Dig. trp, %	.25	.15
Dig. phe + tyr, %	1.80	1.19
Dig. phe, %	1.07	.68
Dig. met + cys, %	.70	.52
Dig. met, %	.39	.31
Dig. thr, %	.84	.53
Dig. leu, %	1.84	1.27
Dig. ile, %	1.02	.62
Dig. val, %	1.08	.70

Table 3. Actual and model predicted broiler growth performance in response to changing feed intake from 0-28 and 29-49 days old using the data of Proudfoot and Hulan (1982).

Starter Period (0-28 days) Parameter	Treatment 1	 2	 3	 4	 5	 6
0-28 Feed int. (g)	1277	1306	1331	1377	1397	1443
Actual BW, 28 days	810	808	857	883	893	898
Pred. BW, 28 days	767	789	808	838	854	889
Act/Pred BW	1.056	1.024	1.061	1.054	1.046	1.010

Sulfur amino acids predicted limiting in all diets

Act/Pred BW: mean = 1.042, SD = .020

Regression analysis: Act/Pred dependent on Feed intake.

Parameter	Estimate	SE	PR>T	R^2 = .24
Intercept	1.2588	.1951	.0030	
Feed int.	-.0002	.0001	.3281	

Finisher Period (29-49 days) Parameter	Treatment 1	 2	 3	 4	 5	 6
29-49 Feed int. (g)	2514	2574	2661	2797	2791	2856
Actual BW gain (g)	1132	1216	1207	1149	1177	1228
Pred. BW gain (g)	969	1001	1033	1095	1089	1121
Act/Pred BW gain	1.168	1.215	1.168	1.049	1.081	1.095

Sulfur amino acids predicted limiting in all diets

Act/Pred BW gain: mean = 1.129, SD = .064

Regression analysis: Act/Pred dependent on Feed intake.

Parameter	Estimate	SE	PR>T	R^2 = .72
Intercept	2.1927	.3327	.0027	
Feed int.	-.0004	.0001	.0329	

Table 4. Calculated nutrient composition of diets (Brue and Latshaw, 1985) used to test ability of broiler model to predict response to and partition changing energy intake.

Nutrient	Diet 1	Diets 2-4	Diets 5-7
Diet 1 AMEn, kcal/kg	2909		
Diet 2 AMEn, kcal/kg		3036	
Diet 3 AMEn, kcal/kg		3021	
Diet 4 AMEn, kcal/kg		3024	
Diet 5 AMEn, kcal/kg			3299
Diet 6 AMEn, kcal/kg			3254
Diet 7 AMEn, kcal/kg			3261
Crude fat, %	2.8	5.2	10.0
Dig. protein, %	20.7	20.6	20.7
Dig. arg, %	1.42	1.42	1.43
Dig. his, %	.56	.56	.56
Dig. lys, %	1.12	1.13	1.16
Dig. trp, %	.24	.24	.24
Dig. phe + tyr, %	1.83	1.82	1.82
Dig. phe, %	1.10	1.10	1.10
Dig. met + cys, %	.77	.76	.77
Dig. met, %	.47	.47	.48
Dig. thr, %	.83	.83	.84
Dig. leu, %	1.87	1.86	1.85
Dig. ile, %	1.03	1.03	1.04
Dig. val, %	1.06	1.06	1.07

composition varied slightly between different fat level diets. Dietary AMEn varied with fat level and fat type. The actual and predicted outputs are shown in Table 5.

The results show that both actual and predicted growth rate increased with increasing fat but that predicted growth was numerically but not significantly (P=.24) closer to actual at the highest fat (ME) levels. Within each fat level there was no effect of fat type on the pattern of residuals. Actual carcass fat increased with increasing dietary fat level in the same manner that whole body predicted fat content increased. There was no variance pattern of actual/predicted residuals with increasing fat level (P=.62). Percentage heat production decreased with increasing fat level as would be expected from the higher growth rate and the lower level of heat increment from dietary fat. Again, there was no pattern of residual variance (P=.19). The close agreement of actual and predicted percentage energy retention and growth rates suggest that the model operates well under these test conditions.

4.2.2 EXTRA-CALORIC VALUE OF FAT

The addition of fat to the diet while maintaining total energy constant often results in an unexpected improvement in performance. The model incorporates a mechanism for this in that body lipid deposition from dietary fat is more

Table 5. Actual and model predicted broiler growth, body fat and energy retention in response to changing energy intake from 6-28 days of age using the data of Brue and Latshaw (1985).

Parameter	Diet						
	1	2	3	4	5	6	7
6-28 Feed int. (g)	1023	964	986	1008	955	1016	1014
Act. BW gain (g)	592	607	605	623	647	664	640
Act. Carcfat (% DM)	32.7	34.0	36.1	37.3	39.6	38.9	39.9
Energy int. (kcal)	2976	2927	2979	3048	3151	3306	3307
Act. ER (kcal)	1124	1195	1225	1278	1390	1452	1384
Act ER % MEI	37.8	40.8	41.1	41.9	44.1	43.9	41.9
Pred. BW gain (g)	535	535	550	565	586	629	630
Pred. Carcfat	32.2	34.5	34.1	34.3	39.5	38.2	38.4
Pred. ER (kcal)	1003	1060	1073	1084	1284	1290	1328
Pred. ER % MEI	33.7	36.2	36.0	35.6	40.7	39.0	40.2
Sulfur amino acids predicted limiting in all diets							
Act/Pred BW gain	1.107	1.135	1.100	1.103	1.104	1.056	1.016
Mean = 1.089 SD = .040							
ANOVA: A/P = Fat% PR>F = .24							
Act/Pred Carcfat	1.016	.986	1.059	1.087	1.003	1.018	1.039
Mean = 1.030 SD = .035							
ANOVA: A/P = Fat% PR>F = .62							
Act/Pred ER % MEI	1.122	1.127	1.142	1.177	1.084	1.126	1.043
Mean = 1.117 SD = .043							
ANOVA: A/P = Fat% PR>F = .19							

efficient than fat derived from lipogenesis. The study of Bartov (1987) was used to quantify this mechanism. In this study, male White Rock broiler chicks were tested from 8 to 27 days of age on iso-caloric diets containing either .5% or 3.5% supplemental fat (soybean oil or tallow at each level). The composition of the diets is shown in Table 6. Feed intakes were equal (1130 g) for each of the two fat levels. The actual and predicted weight gains along with actual/predicted ratio are shown in Table 7.

The results show that the model accurately predicted weight gain within 3% for all dietary treatments and ages except the 8 to 14 day period. The short time period of this interval may have contributed to the experimental error. There was an actual and predicted increase in weight gain with increasing fat. The actual weight gain was greater than the predicted weight gain to the extent that 85% of the total extra-caloric effect was not accounted for by the model. Mateos and Sell (1981) have suggested that increasing fat levels slows down feed passage rate in the digestive tract which may allow for increased nutrient breakdown and utilization. This effect is not accounted for in the model.

4.2.3 ENERGY - PROTEIN EFFECTS

It is important that the model account for changing proportions of dietary energy and protein. These nutrients

Table 6. Calculated nutrient composition of diets (Bartov, 1987) used to test ability of broiler model to predict extra-caloric effect of dietary fat.

Nutrient	Diet 1	Diet 2	Diet 3
AMEn, kcal/kg	3034	3029	3030
Crude fat, %	3.2	3.2	6.2
Dig. protein, %	16.8	16.8	16.8
Dig. arg, %	1.13	1.13	1.13
Dig. his, %	.45	.45	.45
Dig. lys, %	.89	.89	.89
Dig. trp, %	.19	.19	.19
Dig. phe + tyr, %	1.51	1.51	1.51
Dig. phe, %	.90	.90	.90
Dig. met + cys, %	.66	.66	.66
Dig. met, %	.42	.42	.42
Dig. thr, %	.68	.68	.68
Dig. leu, %	1.56	1.56	1.56
Dig. ile, %	.83	.83	.83
Dig. val, %	.87	.87	.87

Table 7. Actual and model predicted broiler growth from 8 to 27 days of age in response to increased dietary fat concentration when feed intake and energy concentration are equalized, using the data of Bartov (1987).

Parameter	Diet			
	1	2	Avg 1+2	3
8-14 Feed int.	242	244	243	243
8-21 Feed int.	670	656	663	666
8-27 Feed int.	1140	1120	1130	1130
Act. BW gain (g)				
8-14	153	148	151	158
8-21	378	367	373	393
8-27	600	582	591	620
Pred. BW gain (g)				
8-14	132	134	133	134
8-21	367	358	363	366
8-27	612	599	606	609
Act/Pred BW gain				
8-14	1.159	1.104	1.135	1.179
8-21	1.030	1.025	1.028	1.074
8-27	.980	.972	.975	1.018

are expensive and small changes can result in large profitability differences. Two studies were used to validate the model in this area (Pesti and Fletcher, 1983; Pesti et al. 1986). These studies were chosen from the many available studies on protein - energy combinations because the central composite design of the experiments make them especially useful in determining quantitative protein, energy and protein - energy interaction effects and in equalizing possible feed intake differences. The composition of the Pesti and Fletcher (1983) diets is shown in Table 8. The actual and predicted body weight gain responses are shown in Table 9. The results show that the model estimated average weight gain within 4% of actual in the first trial and within 1% in the second trial. There was no effect of energy on the pattern of residuals but the model did overestimate weight gain at high protein concentrations. Some possible reasons for this are:

1. The assumption of 85% amino acid utilization efficiency may be wrong and therefore the model may incorrectly estimate body protein gain.

2. The estimate of amino acid content of body protein may be low.

3. The estimate of energy release from excess protein may be high.

Given the uncertainty of estimates of amino acid utilization efficiency, that is likely the main reason that

Table 8. Calculated nutrient composition of diets (Pesti and Fletcher, 1983) used to test ability of broiler model to predict effects of energy and protein on broiler BW gain from 22 to 49 days of age.

Nutrient	Diet 1	Diet 2	Diet 3	Diet 4	Diet 5
AMEn, kcal/kg	3144	3080	3269	3016	3178
Crude fat, %	6.1	5.6	8.3	5.0	6.7
Dig. protein, %	19.2	18.1	18.3	17.0	17.2
Dig. arg, %	1.31	1.22	1.24	1.13	1.15
Dig. his, %	.49	.46	.47	.42	.43
Dig. lys, %	.99	.91	.93	.83	.86
Dig. trp, %	.21	.20	.20	.18	.19
Dig. phe + tyr, %	1.62	1.50	1.54	1.38	1.43
Dig. phe, %	.97	.90	.92	.83	.86
Dig. met + cys, %	.66	.62	.63	.58	.59
Dig. met, %	.39	.37	.38	.34	.35
Dig. thr, %	.76	.70	.72	.64	.67
Dig. leu, %	1.74	1.63	1.66	1.51	1.57
Dig. ile, %	.93	.86	.88	.79	.81
Dig. val, %	.99	.93	.94	.86	.88

Nutrient	Diet 6	Diet 7	Diet 8	Diet 9
AMEn, kcal/kg	3394	3087	3276	3158
Crude fat, %	10.4	5.1	7.8	5.2
Dig. protein, %	17.3	16.2	16.3	15.3
Dig. arg, %	1.17	1.07	1.09	1.00
Dig. his, %	.44	.40	.41	.37
Dig. lys, %	.87	.78	.80	.73
Dig. trp, %	.19	.17	.18	.16
Dig. phe + tyr, %	1.45	1.33	1.37	1.28
Dig. phe, %	.87	.79	.81	.75
Dig. met + cys, %	.60	.56	.57	.53
Dig. met, %	.36	.33	.34	.31
Dig. thr, %	.68	.62	.64	.59
Dig. leu, %	1.58	1.48	1.51	1.44
Dig. ile, %	.82	.75	.76	.70
Dig. val, %	.89	.82	.84	.78

Table 9. Actual and model predicted broiler BW gain from 22 to 49 days of age as a function of varying dietary protein and energy concentration, using the data of Pesti and Fletcher (1983).

Diet	Trial 1			Trial 2		
	FI	Act	Pred	FI	Act	Pred
1	2864	1270	1420	2914	1310	1458
2	2874	1230	1337	2914	1270	1366
3	2844	1290	1391	2864	1340	1406
4	2964	1230	1277	2854	1220	1201
5	2914	1250	1316	2864	1350	1318
6	2864	1280	1364	2804	1350	1318
7	2834	1170	1151	2834	1220	1151
8	2814	1220	1215	2894	1350	1272
9	2894	1180	1131	2874	1230	1118

Lysine and sulfur amino acids predicted equally limiting in all diets

Actual/Predicted (A/P):

Crude				AMEn		
Protein		2900	3030	3150	3280	3400
22	Diet A/P Trial 1 A/P Trial 2			1 .894 .898		
20.9			2 .926 .930		3 .927 .953	
19.8		4 .963 1.016		5 .950 1.016		6 .938 1.024
18.6			7 1.017 1.060		8 1.004 1.061	
17.5				9 1.043 1.100		

Combined trial stepwise regression analysis: A/P dependent on protein and energy (full quadratic model with interaction).

Parameter	Estimate	SE	PR>T	R^2 = .80
Intercept	1.7944	.1009	.0001	
Protein	-.0471	.0059	.0001	

growth rate is overestimated at high protein intakes.

The second study of Pesti et al. (1986) which was basically a replication of the previous study (additional diets shown in Table 10) gave similar results (Table 11). Here the model overestimated weight gain from 22 to 42 days by 6%. Again, the overestimation was greatest at high protein concentrations. In order to test whether the 85% coefficient for amino acid utilization efficiency contributed to the overestimation at high protein levels, a sensitivity analysis was performed where amino acid utilization efficiency coefficients of 80% and 90% were used to test the Pesti et al. (1986) data. The results are shown in Table 11. In both cases, predicted weight gain was still overestimated at the highest protein levels, but the protein effect was less at the 90% efficiency level. On the other hand, total model accuracy was best at the 80% level (less than 1% difference between average predicted and actual).

4.2.4 RESPONSE TO AMINO ACIDS

Since amino acid partitioning is a central mechanism in the model, it is appropriate to examine data where essential amino acids are fed in varying amounts from a limiting to a non-limiting state. Two studies were chosen; the study of Gous and Morris (1985) which investigated response to lysine, and the study of Mendonca and Jensen (1989) which investigated response to sulfur amino acids.

Table 10. Calculated nutrient composition of diets (Pesti et al., 1986) used to test ability of broiler model to predict effects of energy and protein on broiler BW gain from 22 to 42 days of age.

Nutrient	Diet 1	Diet 11
AMEn, kcal/kg	2996	3394
Crude fat, %	4.9	9.4
Dig. protein, %	19.0	15.3
Dig. arg, %	1.28	1.01
Dig. his, %	.48	.38
Dig. lys, %	.97	.76
Dig. trp, %	.21	.16
Dig. phe + tyr, %	1.56	1.28
Dig. phe, %	.94	.75
Dig. met + cys, %	.75	.61
Dig. met, %	.49	.40
Dig. thr, %	.73	.59
Dig. leu, %	1.67	1.43
Dig. ile, %	.90	.71
Dig. val, %	.96	.78

Diets 2 - 10 are the same as diets 1 - 9 in Table 8 (Pesti and Fletcher, 1983).

Table 11. Actual and model predicted broiler BW gain from 22 to 42 days of age as a function of varying dietary protein and energy concentration, using the data of Pesti et al. (1986). Model tested at 80% and 90% amino acid utilization efficiency in addition to standard 85%.

Diet	FI	Act	Pred	80% Pred	90% Pred	Limit AA
1	2414	1152	1242	1215	1246	Lys
2	2416	1155	1334	1263	1384	M+C, Lys
3	2500	1170	1284	1217	1345	M+C, Lys
4	2446	1255	1319	1245	1382	M+C, Lys
5	2527	1107	1193	1128	1250	M+C, Lys
6	2510	1173	1270	1208	1330	M+C, Lys
7	2509	1195	1308	1230	1373	M+C, Lys
8	2514	1105	1144	1079	1201	M+C, Lys
9	2462	1144	1173	1099	1235	M+C, Lys
10	2488	1079	1073	998	1135	M+C, Lys
11	2532	1156	1171	1098	1238	Lys

Actual/Predicted (A/P)

Crude				AMEn		
Protein		2900	3030	3150	3280	3400
22.0	Diet	1		2		
	A/P 85	.927		.866		
	A/P 80	.948		.914		
	A/P 90	.925		.835		
20.9			3		4	
			.911		.951	
			.961		1.008	
			.870		.908	
19.8		5		6		7
		.928		.924		.914
		.981		.971		.972
		.886		.882		.870
18.6			8		9	
			.966		.975	
			1.024		1.041	
			.920		.926	
17.5				10		11
				1.001		.987
				1.081		1.053
				.951		.934

Table 11. continued

Statistics:

A/P (85%): mean = .941 S.D. = .039
A/P (80%): mean = .996 S.D. = .050
A/P (90%): mean = .901 S.D. = .035

Stepwise regression analysis: A/P dependent on protein and energy (full quadratic model with interaction).

85 % Amino acid utilization efficiency

Parameter	Estimate	SE	PR>T	R^2 = .71
Intercept	1.3613	.0905	.0001	
Protein	-.0244	.0052	.0012	

80 % Amino acid utilization efficiency

Parameter	Estimate	SE	PR>T	R^2 = .80
Intercept	1.5645	.0955	.0001	
Protein	-.0331	.0055	.0002	

90 % Amino acid utilization efficiency

Parameter	Estimate	SE	PR>T	R^2 = .43
Intercept	1.1898	.1114	.0001	
Protein	-.0168	.0065	.0286	

The composition of the diets in the lysine study is given in Table 12. The actual and predicted performance results are given in Table 13. The results show that the actual performance is greater than the predicted performance by a wide margin (35% on average). Feed intakes were very low in this study. The animal may compensate for low feed intakes by making changes in metabolism that the model does not account for. The pattern of actual/predicted growth rate change with changing lysine concentrations shows a quadratic relationship which minimizes at 1.17% digestible lysine.

The sulfur amino acid study diets are summarized in Table 14. The performance results are given in Table 15. The results show that actual and predicted performance are in close agreement. Again, actual and predicted BW gains are closest to each other at intermediate sulfur amino acid levels.

4.2.5 ENVIRONMENTAL TEMPERATURE EFFECT

The study of Charles et al. (1981) was used to investigate the effects of environmental temperature ranging from 18 to 27 degrees Celcius on broiler performance. The composition of the diets is given in Table 16. The performance results are given in Table 17. The results show that the model underestimated growth and that the underestimation was greatest at the lowest temperatures. At

Table 12. Calculated nutrient composition of diets (Gous and Morris, 1985) used to test ability of broiler model to predict response to different levels of dietary lysine.

Nutrient	Diet 1	Diet 2	Diet 3	Diet 4
AMEn, kcal/kg	3196	3196	3195	3195
Crude fat, %	8.6	8.0	7.4	6.8
Dig. protein, %	31.0	27.9	24.8	21.7
Dig. arg, %	1.97	1.77	1.58	1.04
Dig. his, %	.81	.73	.65	.57
Dig. lys, %	1.49	1.34	1.19	1.04
Dig. trp, %	.32	.29	.26	.22
Dig. phe + tyr, %	2.95	2.66	2.36	2.07
Dig. phe, %	1.76	1.58	1.41	1.23
Dig. met + cys, %	1.39	1.25	1.11	.97
Dig. met, %	.91	.82	.73	.64
Dig. thr, %	1.21	1.09	.97	.85
Dig. leu, %	3.27	2.94	2.62	2.29
Dig. ile, %	1.52	1.37	1.22	1.06
Dig. val, %	1.60	1.44	1.28	1.12

Nutrient	Diet 5	Diet 6	Diet 7	Diet 14
AMEn, kcal/kg	3194	3194	3194	3193
Crude fat, %	6.2	5.6	4.9	4.3
Dig. protein, %	18.6	15.5	12.4	9.3
Dig. arg, %	1.18	.99	.79	.59
Dig. his, %	.49	.41	.32	.24
Dig. lys, %	.89	.75	.60	.61
Dig. trp, %	.19	.16	.13	.10
Dig. phe + tyr, %	1.77	1.48	1.18	.89
Dig. phe, %	1.06	.88	.70	.53
Dig. met + cys, %	.83	.70	.56	.42
Dig. met, %	.55	.46	.36	.27
Dig. thr, %	.73	.61	.48	.36
Dig. leu, %	1.96	1.64	1.31	.98
Dig. ile, %	.91	.76	.61	.46
Dig. val, %	.96	.80	.64	.48

Diets 8 - 13 are the same as diets 2 - 7 except that digestible lysine levels are 1.51, 1.36, 1.21, 1.06, .92 and .77% respectively.

Table 13. Actual and model predicted broiler BW gain response from 8 to 21 days of age, to different levels of dietary lysine, using the data of Gous and Morris (1985).

Diet	FI	Act.	Pred	Act/Pred	Limit AA
1	464	356	270	1.319	-
2	476	375	289	1.298	-
3	490	364	314	1.159	-
4	495	350	302	1.159	Lys
5	494	335	266	1.259	Lys
6	460	281	211	1.332	M+C,Lys
7	439	216	135	1.600	M+C
8	467	362	281	1.288	-
9	462	364	287	1.268	-
10	489	349	322	1.051	-
11	491	336	303	1.109	multi
12	493	315	250	1.260	multi
13	466	250	157	1.592	M+C
14	440	186	84	2.214	M+C

Act/Pred: mean = 1.351 SD = .293

Stepwise regression analysis of Act/Pred dependent on lysine (quadratic model).

Parameter	Estimate	SE	PR>T	R^2 = .74
Intercept	4.2818	.6004	.0001	
Lysine	-5.3970	1.2022	.0009	
Lysine^2	2.2984	.5663	.0019	

Table 14. Calculated nutrient composition of diets (Mendonca and Jensen, 1989) used to test ability of broiler model to predict response to different levels of dietary methionine.

Expt. 1 Nutrient	Diet 1	Diet 5	Diet 9
AMEn, kcal/kg	3126	3129	3119
Crude fat, %	5.0	6.6	8.2
Dig. protein, %	17.3	20.8	24.3
Dig. arg, %	1.16	1.43	1.71
Dig. his, %	.44	.54	.63
Dig. lys, %	.85	1.12	1.38
Dig. trp, %	.18	.23	.28
Dig. phe + tyr, %	1.46	1.76	2.05
Dig. phe, %	.87	1.06	1.26
Dig. met + cys, %	.53	.61	.69
Dig. met, %	.28	.32	.36
Dig. thr, %	.68	.83	.97
Dig. leu, %	1.60	1.86	2.11
Dig. ile, %	.82	1.02	1.22
Dig. val, %	.89	1.07	1.26

Diets 2-4, 6-8 and 10-12 differ from 1, 5 and 9 in the levels of met + cys / met: .58/.33, .63/.38, .68/.43, .66/.37, .71/.42, .76/.47, .74/.41, .79/.46, .84/.51.

Expt. 2 Nutrient	Diet 1	Diet 5	Diet 9
AMEn, kcal/kg	3184	3181	3183
Crude fat, %	5.1	6.0	6.8
Dig. protein, %	14.3	16.0	17.7
Dig. arg, %	.92	1.07	1.21
Dig. his, %	.37	.43	.48
Dig. lys, %	.87	.85	.93
Dig. trp, %	.15	.18	.20
Dig. phe + tyr, %	1.27	1.43	1.58
Dig. phe, %	.74	.84	.94
Dig. met + cys, %	.46	.48	.53
Dig. met, %	.25	.25	.27
Dig. thr, %	.56	.64	.72
Dig. leu, %	1.38	1.52	1.65
Dig. ile, %	.66	.77	.87
Dig. val, %	.72	.82	.92

Diets 2 - 4, 6 - 8 and 10 - 12 differ from 1, 5 and 9 in the levels of met + cys / met: .52/.31, .58/.37, .63/.43, .54/.31, .60/.39, .66/.43, .59/.33, .65/.39, .71/.45.

Table 15. Actual and model predicted broiler BW gain response from 22 to 42 days of age, to different levels of dietary sulfur amino acids, using the data of Mendonca and Jensen (1989).

Expt. 1 Diet	FI	Act.	Pred.	Act/Pred	Limit AA
1	2776	1327	1316	1.008	M+C
2	2785	1337	1394	.959	Lys, M+C
3	2809	1396	1408	.991	Lys
4	2733	1383	1364	1.014	Lys
5	2699	1352	1466	.922	M+C
6	2699	1352	1569	.862	M+C
7	2743	1421	1628	.873	Lys
8	2661	1389	1563	.889	Lys
9	2640	1357	1470	.923	-
10	2597	1335	1438	.928	-
11	2656	1336	1494	.894	-
12	2735	1422	1546	.920	-

Act/Pred: mean = .932 SD = .051

Expt. 2 Diet	FI	Act.	Pred.	Act/Pred	Limit AA
1	2700	1196	1098	1.089	M+C
2	2679	1219	1244	.980	M+C
3	2630	1252	1344	.931	M+C, Lys
4	2611	1235	1338	.923	Lys
5	2899	1348	1282	1.051	M+C
6	2759	1316	1351	.974	M+C
7	2653	1324	1337	.990	Lys
8	2603	1291	1308	.987	Lys
9	2570	1290	1187	1.087	M+C
10	2644	1346	1394	.966	M+C
11	2516	1341	1346	.996	Lys
12	2472	1283	1319	.973	Lys

Act/Pred: mean = .996 SD = .054

Combined experiments stepwise regression analysis: A/P dependent on meth + cys (quadratic model).

Parameter	Estimate	SE	PR>T	R^2 = .48
Intercept	1.2353	.0613	.0001	
Meth + cys	-.4296	.0959	.0002	

Table 16. Calculated nutrient composition of diets (Charles et al., 1981) used to test ability of broiler model to predict temperature and sex effects on broiler BW gain response from 43 to 49 days of age.

Nutrient	Diet 1	Diet 2
AMEn, kcal/kg	3142	3063
Crude fat, %	9.3	7.6
Dig. protein, %	19.9	19.7
Dig. arg, %	1.21	1.19
Dig. his, %	.49	.48
Dig. lys, %	1.01	.98
Dig. trp, %	.23	.22
Dig. phe + tyr, %	1.58	1.56
Dig. phe, %	.97	.96
Dig. met + cys, %	.62	.62
Dig. met, %	.32	.32
Dig. thr, %	.72	.70
Dig. leu, %	1.52	1.49
Dig. ile, %	.89	.88
Dig. val, %	.95	.93

Table 17. Actual and model predicted male and female broiler BW gain response from 43 to 49 days of age in response to different environmental temperatures, using the data of Charles et al. (1981).

	Temperature			
Parameter	18	21	24	27
Males, Diet 1:				
Feed int. (g)	1030	990	950	850
Act BW gain (g)	420	400	300	400
Pred BW gain (g)	377	379	371	308
Act/Pred	1.110	1.056	.810	1.298
Males, Diet 2:				
Feed int. (g)	1040	1060	1010	900
Act BW gain (g)	500	430	370	340
Pred BW gain (g)	378	445	427	354
Act/Pred	1.320	.966	.867	.960
Females, Diet 1:				
Feed int. (g)	870	840	820	740
Act BW gain (g)	330	310	310	260
Pred BW gain (g)	231	261	274	240
Act/Pred	1.429	1.188	1.131	1.083
Females, Diet 2:				
Feed int. (g)	920	870	840	790
Act BW gain (g)	330	310	310	260
Pred BW gain (g)	231	261	274	240
Act/Pred	1.183	1.099	1.060	1.016

Temp	Act/Pred	SD
18	1.26	.14
21	1.08	.09
24	.97	.15
27	1.09	.15

ANOVA PR>F = .06

Total df = 15

Temp df = 3

Sex	Act/Pred	SD
Male	1.05	.17
Female	1.15	.13

ANOVA PR>F = .23

Total df = 15

Sex df = 1

Diet	Act/Pred	SD
1	1.14	.18
2	1.06	.14

ANOVA PR>F = .35

Total df = 15

Diet df = 2

21 degrees and above there was no significant effect of temperature on the actual/predicted BW gain.

4.2.6 SEX EFFECT

The data of Charles et al. (1981) was also used to look at sex differences. The performance data is shown in Table 17. The results indicate that model predicts male performance better than female performance but that the differences were not significant (P=.23).

4.2.7 FEED INTAKE PREDICTION

The data of Proudfoot and Hulan (1982) was used to investigate the effect of photoperiod on feed intake. The results are shown in Table 18. The model predicted a greater depression in feed intake from decreasing light hours than was actually observed. In the finisher period, the nature of the decrease was curvilinear whereas the model predicted a linear decrease.

The effect of dietary energy concentration and sex on feed intake was investigated using the data of Charles et al. (1981). The results are shown in Table 19. The results show no difference in the model's ability to predict feed intake as influenced by either variable.

4.3 DISCUSSION

The model generally does a good job of predicting

Table 18. Actual and model predicted broiler feed intake in response to changing photoperiod from 0-28 and 29-49 days old using the data of Proudfoot and Hulan (1982).

Starter Period (0-28 days)	Light hrs					
Parameter	8	10	12	14	16	24
Act. Feed int. (g)	1277	1306	1331	1377	1397	1443
Pred. Feed int. (g)	1011	1059	1107	1154	1199	1385
Act/Pred Feed	1.263	1.233	1.202	1.193	1.166	1.042

Act/Pred Feed: mean = 1.183, SD = .077
Stepwise regression analysis: Act/Pred dependent on light (quadratic model).

Parameter	Estimate	SE	PR>T	R^2 = .99
Intercept	1.3723	.0105	.0001	
Light	-.0135	.0007	.0001	

Finisher Period (29-49 days)	Light hrs					
Parameter	8	10	12	14	16	24
Act. Feed int. (g)	2514	2574	2661	2797	2791	2856
Pred. Feed int. (g)	2022	2117	2215	2304	2398	2769
Act/Pred Feed	1.243	1.216	1.201	1.214	1.164	1.031

Act/Pred Feed: mean = 1.178, SD = .077
Stepwise regression analysis: Act/Pred dependent on light (quadratic model).

Parameter	Estimate	SE	PR>T	R^2 = .97
Intercept	1.2684	.0099	.0001	
Light^2	-.0004	.0000	.0003	

Table 19. Actual and model predicted male and female broiler feed intake from 43 to 49 days of age in response to different dietary energy concentrations, using the data of Charles et al. (1981) (Temperature = 27 degrees C).

	Diet AMEn (kcal/kg)			
Parameter	3142	3063	2957	2767
Males:				
Act Feed int. (g)	850	900	890	900
Pred Feed int. (g)	1121	1107	1124	1155
Act/Pred	.758	.813	.792	.779
Females:				
Act Feed int. (g)	740	790	790	800
Pred Feed int. (g)	1013	1028	1046	1076
Act/Pred	.731	.768	.755	.743

Statistics:

Sex	Act/Pred	SD	ANOVA PR>F = .04	Total df = 7
Male	.786	.02		Sex df = 1
Female	.749	.02		

Diet	Act/Pred	SD	ANOVA PR>F = .44	Total df = 7
3142	.745	.02		Diet df = 3
3063	.791	.03		
2957	.774	.03		
2767	.761	.03		

performance. When the eleven data sets used in the validation study are averaged, actual BW gain was greater than predicted BW gain by only 4.8%.

The model does overpredict growth rate at high protein levels which may be due to the amino acid utilization efficiency of 85% being too low. Testing of a 90% coefficient slightly reduced the variability of model accuracy over a protein range. It is unclear what the proper coefficient for amino acid utilization efficiency should be. Perhaps the coefficient should vary with protein intake and possibly with age.

It is interesting to note that the model does a better job of predicting performance under "average practical" conditions than it does at extremes, eg. extreme lysine, sulfur amino acid, protein and temperature levels. This is not surprising because the data used to derive the predictive equations in the model was mainly derived from experiments conducted in average conditions. These results suggest that the bird, when faced with extremes in input can vary its intermediary metabolism to adjust its priorities of partitioning nutrients.

Overall, the model appears to work well. Some adjustments in the areas of amino acid utilization efficiency and feed intake adjustment for differences in photoperiod are warranted.

An important area of the model that needs validation is the prediction of meat yield, especially breast meat. There are no suitable studies in the scientific literature. Consequently, the next step was to conduct biological experiments in order to validate and enhance the ability of the model to predict breast meat yield.

5. EXPERIMENT 1. THE EFFECTS OF DIETARY METHIONINE AND LYSINE ON BROILER CHICKEN PERFORMANCE AND BREAST MEAT YIELD.

5.0 INTRODUCTION

The carcass composition of broiler chickens is receiving considerable attention as a result of "further processing" by the industry. There is an emphasis on increasing the meat yield, especially breast meat, and decreasing the fat content of the broiler carcass. It has been well demonstrated that decreasing the energy to protein ratio in the feed will accomplish these objectives (Salmon et al., 1983). However, it remains to be determined whether increasing the level of essential amino acids rather than total protein will produce the same effects and do so more economically.

Increasing the essential to nonessential amino acid ratio in the diet will increase carcass protein and decrease carcass fat (Bedford and Summers, 1985). Similarly, increasing dietary lysine content causes an increase in broiler carcass protein retention and a decrease in fat retention (Sibbald and Wolynetz, 1986). Since lysine is present in high levels in poultry muscle (Scott et al., 1969), it would be useful to know the effects of dietary lysine on meat yield - especially breast meat. The extent to which dietary lysine will increase breast meat yield may, in part, depend on the level of other amino acids; ie. there may be an interaction between amino acids.

The main objective of this study was, therefore, to test and quantify the hypothesized breast meat yield response to increasing dietary lysine, at two methionine levels. Dietary amino acid levels in excess of NRC (1984) were used to allow the genetic potential for body protein accretion to be approached. For the same reason, a relatively high energy diet (corn based) was used to allow sufficient energy for protein accretion. The second objective of the study was to provide data for validation of the broiler model.

5.1 MATERIALS AND METHODS

Feather sexed male, day old commercial broiler chicks (Ross x Arbor Acres) were used. The birds were grown in floor pens measuring 1.54 x 4.31 meters in a windowless environmentally controlled house which was divided into two rooms containing 32 pens each. Fresh water was available ad libitum.

The experimental design was a completely randomized design with a 2 x 2 x 4 factorial arrangement of treatments: two rooms (one continuous lighting and the other a 16 hour light, 8 hour dark regime), two levels of dietary methionine (NRC and 112% NRC) and four levels of dietary lysine (NRC, 106% NRC, 112% NRC and 118% NRC). The diets were available ad libitum in both the starter (0-3 weeks) and finisher (3-6 weeks) phases. The methionine and lysine contents of the diets were as follows: starter/finisher methionine; .50%/.38% and .56%/.43%, starter/finisher lysine; 1.20%/1.00%, 1.27%/1.06%, 1.34%/1.12% and 1.42%/1.18%. There were 4 pen replications per treatment and 60 birds per pen for a total of 64 pens and 3840 birds.

The composition of the diets is given in Table 20. Prior to the experiment, the ingredients corn, wheat and soybean meal were analyzed for crude protein and amino acids and the experimental diets were formulated on that basis. The mixed diets were also analyzed and the results were in close agreement with calculated values except that lysine in the starter diet was higher ($P<0.01$) than expected. The starter diet was fed crumbled and the finisher diet was fed as a short pellet (.5 cm maximum length and diameter).

The birds were weighed, after fasting 12 hours, on days 1, 21 and 42. Feed consumption was measured for the periods 1 to 21 and 22 to 42 days. At 42 days, 8 randomly selected birds from each pen were individually weighed, double wing-banded and commercially processed. Carcasses were retrieved from the processor and weighed. The breast meat (pectoralis major and minor muscles) was excised and weighed. Unfortunately, there was only 55% bird retrieval from the processor because of missing wing bands, incomplete carcasses and bird condemnations. However, the bird numbers

Table 20. Composition of diets used in Experiment 1.

Ingredient	Basal Starter (%)	Basal Finisher (%)
Corn	40.6	62.4
Wheat	14.4	----
Soybean meal (46.5)	36.4	29.2
Sunflower oil	4.6	5.0
DL-methionine	.18	.08
Limestone	1.5	1.3
Monocal Phosphate	1.4	1.4
Salt	.3	.3
Other *	.62	.32

Nutrient	Calculated		Analyzed ± SD	
	Str	Fin	Str	Fin
Crude Protein, %	22.0	19.0	23.6±0.20	20.3±0.16
Dig. Protein, %	20.7	17.5		
Crude Fat, %	6.9	7.8		
ME, kcal/kg	3075	3225		
Calcium, %	1.00	.90		
Phosphorus, %	.75	.72		
Lysine, %	1.20	1.00	1.28±0.03	1.02±0.04
Met + Cys, %	.93	.74	.90±0.05	.75±0.05
Met, %	.50	.38	.52±0.02	.39±0.04
Dig. arg, %	1.39	1.19		
Dig. his, %	.55	.47		
Dig. lys, %	1.11	.91		
Dig. trp, %	.24	.20		
Dig. phe + tyr, %	1.79	1.56		
Dig. phe, %	1.09	.93		
Dig. met + cys, %	.78	.60		
Dig. met, %	.46	.34		
Dig. thr, %	.81	.70		
Dig. leu, %	1.79	1.63		
Dig. ile, %	1.01	.86		
Dig. val, %	1.04	.90		

* To supply/kg feed: Vitamin A, 8000 IU; vitamin D3, 2000 IU; vitamin E, 15 IU; vitamin B12, 10 ug; vitamin K, 1.5 mg; riboflavin, 5 mg; pantothenate, 10 mg, niacin, 50 mg; folacin, .75 mg; biotin, .25 mg; choline, 425 mg; manganese, 60 mg; ferrous Fe, 80 mg; iodine, .4 mg; copper, 10 mg; zinc, 60 mg; selenium, .1 mg; ethoxyquin, 1.17 g; pen strep, .1 g; amprol Hi E, .5 g.

Synthetic L-lysine HCl and DL-methionine were added to the basal diets to make the various treatment diets.

were well distributed across treatments and sufficient for analysis.

Full statistical models, containing room, methionine and lysine independent variables and their interactions were fit to the data. The models were analyzed using the General Linear Models procedure of SAS (1987). The effects of graded lysine levels on the dependent variables were investigated with orthogonal polynomials. Multiple regression analysis was performed on breast meat yield response to methionine and lysine intake per bird. The experimental unit was a pen of birds and the analysis was weighted for differences in the number of bird observations per pen. The full model, containing linear, interaction, quadratic and cubic terms was analyzed with Forward, Backward and Stepwise procedures of SAS. The simplest model with the most improved coefficient of determination was chosen.

The data was also used to validation-test the broiler model using actual feed intakes.

5.2 RESULTS

At 6 weeks of age, the birds weighed 2.23 kg, had a feed conversion efficiency (FCE) of 1.80 and a total mortality of 1.55%. There were significant room differences in most measurements (means not reported due to confounding of room and photoperiod). The birds in the continuous lighting environment were heavier, had a poorer FCE, had greater breast meat yield and had higher mortality than the birds in the light/dark environment. Room x dietary treatment interactions were not significant with the exception that FCE from 3 to 6 weeks exhibited a room x methionine interaction (P<0.05). Increasing the level of methionine in the diet improved FCE from 1.99 to 1.93 in the continuous lighting room (P<0.01). There was no difference in FCE in the restricted lighting room: FCE was 1.91 and 1.92 for dietary methionine levels of NRC and 112% NRC respectively. The effects of dietary treatment on body weight and feed conversion are given in Table 21. Body weight increased with increasing methionine at 6 weeks but not at 3 weeks. Three week body weight decreased slightly with increasing lysine level but there was no difference in body weight due to lysine at 6 weeks. There were no effects of lysine on FCE.

Carcass results are presented in Table 22a. A significant methionine x lysine interaction which accounted for 35% of the total treatment sums of squares, was observed for dressing percentage. At the NRC level of methionine there was no lysine effect, but at the 112% NRC level of methionine there was a significant (P<0.01) quadratic effect on dressing percentage. A positive response in breast meat yield was achieved by increasing methionine. There was a significant cubic response in breast meat yield to

Table 21. Experiment 1. Effects of dietary methionine and lysine on male broiler body weight gain and feed conversion efficiency (FCE).

Diet	Body weight (g)		FCE		
	3 week	6 week	0-3 wk	3-6 wk	0-6 wk
		Means			
Methionine:					
NRC	665	2,221	1.47	1.95	1.81
112% NRC	663	2,248	1.46	1.92	1.79
Lysine:					
NRC	668	2,227	1.47	1.95	1.81
106% NRC	664	2,234	1.48	1.94	1.81
112% NRC	666	2,238	1.46	1.94	1.80
118% NRC	657	2,240	1.46	1.91	1.79
Statistics:					
SEM	3.2	5.6	0.003	0.007	0.005
Source of Variation:					
Methionine	0.495 *	0.009	0.162	0.083	0.005
Lysine	0.033	0.800	0.466	0.321	0.349
Lys linear	0.012				
Lys quadratic	0.455				
Lys cubic	0.159				
Met x Lys	0.360	0.408	0.119	0.690	0.672

* Hypothesis probability

Table 22a. Experiment 1. Effects of dietary methionine and lysine on male broiler carcass and breast meat yield (least square means ± SE) at 6 weeks of age

Methionine	Lysine	n	Carcass %BW	Breast meat %BW
			Means	
NRC	NRC	35	64.27±.48	13.78±.21
	106% NRC	29	63.60±.54	13.16±.23
	112% NRC	35	65.00±.50	13.96±.22
	118% NRC	36	65.30±.47	13.78±.20
112% NRC	NRC	41	64.67±.43	13.72±.19
	106% NRC	36	66.32±.50	14.16±.22
	112% NRC	30	65.66±.50	14.46±.22
	118% NRC	40	65.08±.44	14.15±.19

Statistics:

Source of Variation	Carcass %BW		Breast meat %BW
Methionine	0.010 *		0.002
Lysine	0.270		0.053
Lys linear	0.055~	0.754#	0.058
Lys quadratic	0.370	0.010	0.670
Lys cubic	0.205	0.236	0.039
Met x lys	0.021		0.098

* Hypothesis probability
~ at methionine = NRC
# at methionine = 112% NRC

Table 22b. Experiment 1. Regression analysis of lysine and methionine intake (g/bird) on breast meat yield (% BW), forward method

Parameter	Coefficient	SE	PR>T	R^2 = .24
Intercept	-36.3205	24.0592	.138	
Lys intake	2.1085	1.0783	.056	
(Lys intake)^2	-.0238	.0120	.053	
Lys x met	.0049	.0020	.017	

increasing lysine ($P<0.05$). The results of the multiple regression analysis of breast meat yield on methionine and lysine intake are given in Table 22b and Figure 3. The model chosen contained linear and quadratic terms for lysine and a lysine x methionine interaction.

5.3 DISCUSSION

The results in Table 21 indicate that the NRC (1984) requirement for methionine is probably too low for the period from 3-6 weeks both in terms of growth rate and feed efficiency. The fact that increased methionine improved feed conversion only with the continuously lighted group was somewhat surprising. One could speculate that the higher growth associated with the continuously lighted birds resulted in a concomitant increase in methionine requirement. The topic of lighting regimens and their effect on amino acid requirements warrants further research.

The small negative effect of lysine on 21 day body weight had disappeared by 42 days. Analysis of the starter feed for lysine indicated that the highest concentration was 1.51%. This concentration is enough to depress feed consumption (Gous and Morris, 1985).

The effects of lysine on breast meat yield are inconclusive. The analysis of variance hypothesis probability ($P=0.053$) does not allow us to clearly accept or reject the null hypothesis. Multiple regression analysis

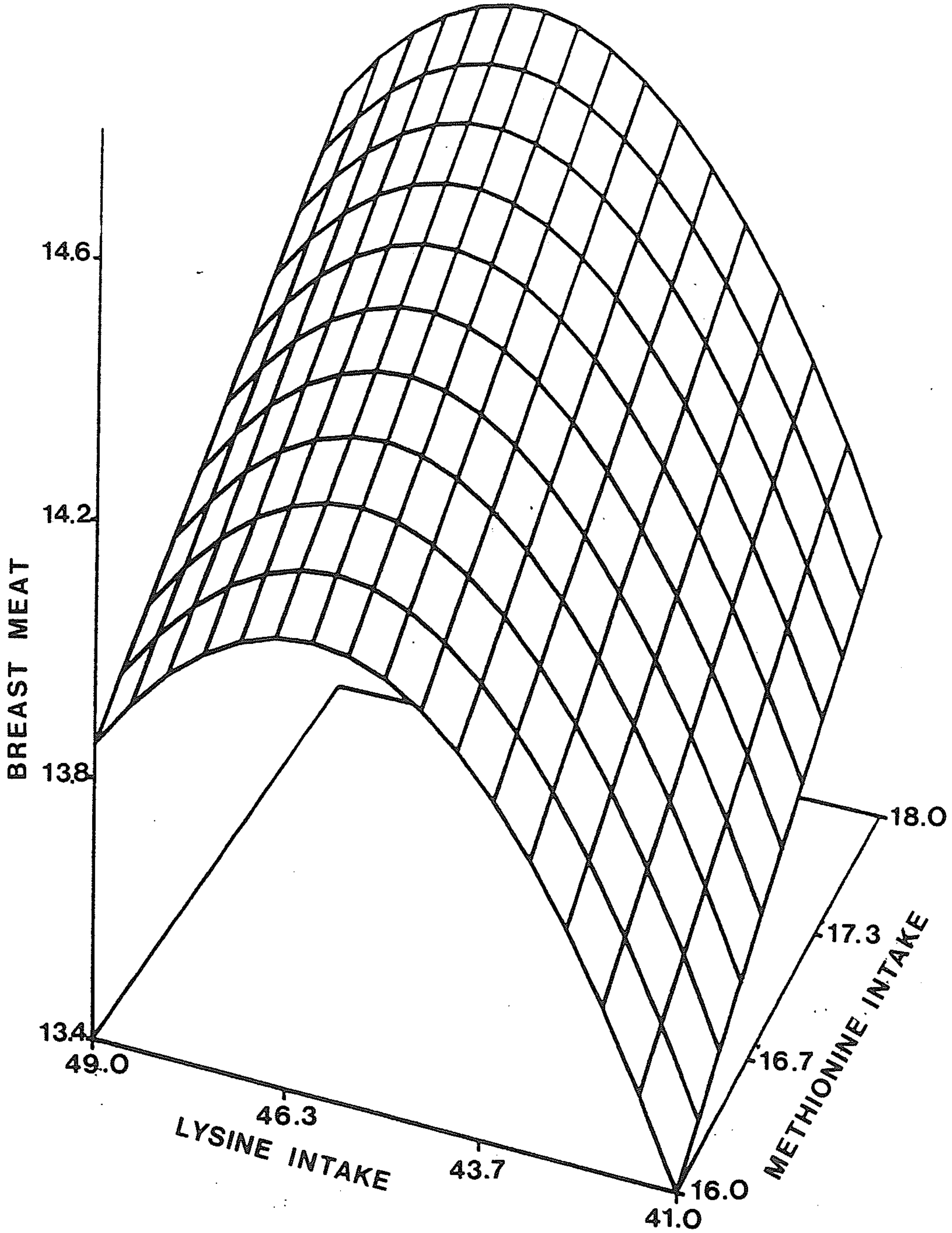

Figure 3. Experiment 1. Effect of dietary lysine and methionine intake (g/bird) on broiler breast meat yield (% body weight).

supports a classical dose-response relationship between dietary lysine and breast meat yield although it should be noted that the coefficient of determination is low. On balance, the data supports the original hypothesis that essential amino acids at levels higher than those required for maximum growth will improve meat yield. This result is in agreement with a recent study (Moran, 1988) in which it was reported that increasing lysine in the grower diet increased cooked breast meat yield. However, in another recent study Summers et al. (1988) found no difference in broiler breast meat yield when diets were supplemented with methionine and lysine.

The interaction between methionine and lysine effects on dressing percentage supports the hypothesis that dietary methionine levels do influence the response to lysine.

An increasing muscle mass with no increase in growth suggests a decrease in fat content and an anticipated improvement in feed efficiency. Since a breast meat response to lysine was demonstrated while a feed conversion response was not, it is likely that feed conversion is a cruder measurement of response than meat yield.

It is clear that these responses to diet are relatively small (<5%) and that individual bird yield variability is fairly large (breast meat as a % of live body weight had a CV of >8%). Large numbers of birds are needed to demonstrate statistical significance in these types of experiments.

5.4 MODEL VALIDATION

The model validation results are presented in Table 23. The results indicate that the thesis model predicts a methionine plus cystine limitation at the lower dietary methionine level which the data confirms. The model slightly overestimated 3 and 6 week body weight. The model did not predict the observed depression in 3 week body weight with increasing dietary lysine.

The model underestimated breast meat yield but the model did predict the same degree of breast meat increase with increasing lysine or methionine that was actually observed.

Table 23. Experiment 1. Actual and model predicted body weights (g) and breast meat yields (% BW).

Diet Met	Lys	Act. BW 3 wk	Pred BW 3 wk	Act/Pred (A/P)	Limit AA
NRC	NRC	670	659	1.017	lys/tsaa
	106% NRC	660	672	.982	lys/tsaa
	112% NRC	670	688	.973	tsaa
	118% NRC	660	671	.984	tsaa
112% NRC	NRC	670	651	1.029	lys
	106% NRC	660	672	.982	lys
	112% NRC	670	679	.986	lys
	118% NRC	650	670	.970	-

Diet		6 week Body weight Act	 Pred	 A/P	 Breast meat Act	 Pred	 A/P	Limit AA
NRC	NRC	2220	2304	.96	13.78	11.87	1.161	lys
	106% NRC	2210	2376	.93	13.16	12.15	1.083	tsaa/lys
	112% NRC	2230	2388	.93	13.96	12.19	1.145	tsaa
	118% NRC	2230	2366	.94	13.78	12.15	1.134	tsaa
112% NRC	NRC	2230	2297	.97	13.72	11.87	1.156	lys
	106% NRC	2260	2399	.94	14.16	12.20	1.161	lys
	112% NRC	2250	2477	.91	14.46	12.51	1.156	lys
	118% NRC	2250	2544	.88	14.15	12.75	1.110	tsaa/lys

A/P Hypothesis probability that treatment effect = 0

	BW 3 wk	BW 6 wk	Breast meat
Met	.870	.452	.496
Lys	.012	.243	.534

6. EXPERIMENT 2. THE EFFECTS OF DIETARY METHIONINE AND LYSINE ON BROILER BREAST MEAT YIELD UP TO 7 WEEKS OF AGE.

6.0 INTRODUCTION

The results of the first experiment indicated that dietary amino acids above NRC (1984) had a positive effect on breast meat yield. Once the basic effect was demonstrated, a fuller quantitative description of the effect was warranted if a practical use is to be made of the results. Several questions remain. 1. The response to methionine intake was linear. Would a curvilinear effect be noted if a greater number of methionine levels were used? 2. Would the response be evident on a lower plane of nutrition ie. when there may not be enough energy to support high levels of protein accretion? 3. What is the effect at different ages? Information on age and body weight effects would facilitate economic optimization of breast meat yield. 4. What happens to other carcass components eg. abdominal fat, feathers?

With these questions in mind, a second study was undertaken. The resulting data would also be used for validation of the broiler model.

6.1 MATERIALS AND METHODS

The trial was conducted in the same facilities that were used for experiment 1. The design was a central composite design where 9 different combinations of dietary methionine and lysine were fed in the grower phase (3-7 weeks). The birds were fed a common starter diet for the first 21 days. The composition of the starter (crumbled) and the basal grower (pelleted) diets is given in Table 24. Synthetic L-lysine and DL-methionine were added to the basal grower diet to make the treatment diets. The analyzed amino acid levels in the basal adjusted grower diets were; mean (SD): lys 1.05 (.06), met .40 (.04) and met + cys .82 (.04).

Feather-sexed male broilers from a commercial Ross x Arbor Acres cross were used. There were 1620 day-old birds placed in 27 pens with 60 birds per pen. Water was provided ad libitum and the birds were under continuous light. At 21 days, treatments were assigned to pens so that each diet was fed to 3 pens. The birds in each pen were group weighed on days 1, 21 and 42 (after overnight fasting). Pen feed consumption was measured for the periods 1-21 and 22-42 days. Starting at day 30, randomly selected birds (with body weights within 1 SD of the room mean) were removed from each pen and were processed in the following manner (after an overnight fast). They were individually weighed, pithed and jugular bled, reweighed, plucked, reweighed, abdominal fat pad removed and weighed, evicerated and cut to dress, reweighed, water chilled, breast removed and weighed, and pectoralis muscles removed and weighed. This procedure was conducted on days 30, 31, 32, 35, 36, 38, 43, 45 and 49 of

Table 24. Composition of diets used in Experiment 2.

Ingredient	Starter (%)	Grower (%)
Wheat	61.0	66.0
Soybean meal (46.5)	31.0	26.0
Sunflower oil	3.2	4.5
L-lysine	.18	-
DL-methionine	.05	-
Limestone	1.6	1.3
Monocal Phosphate	1.4	1.4
Salt	.3	.3
Other *	1.27	.50

Nutrient	Calculated Analysis	
	Starter	Grower
Crude Protein, %	23.7	21.9
Dig. Protein, %	21.1	19.4
Crude Fat, %	4.8	6.1
ME, kcal/kg	2898	3029
Calcium, %	1.02	.90
Phosphorus, %	.73	.71
Lysine, %	1.21	.95
Met + Cys, %	.91	.77
Met, %	.50	.38
Dig. arg, %	1.28	1.15
Dig. his, %	.52	.48
Dig. lys, %	1.09	.84
Dig. trp, %	.24	.22
Dig. phe + tyr, %	1.84	1.56
Dig. phe, %	1.15	.97
Dig. met + cys, %	.78	.66
Dig. met, %	.43	.33
Dig. thr, %	.74	.66
Dig. leu, %	1.57	1.44
Dig. ile, %	.95	.86
Dig. val, %	.99	.90

* To supply/kg feed the same levels of micronutrients as in Experiment 1.

Synthetic L-lysine HCl and DL-methionine were added to the basal grower diet to make the various treatment diets.

the experiment. For the first 5 test periods, 1 bird from each pen was sampled. For the last 4 periods, 3 birds from each pen were sampled. A total of 459 birds were thus individually sampled.

The data was analyzed using Forward, Backward, Stepwise and Response surface regression techniques (SAS 1987). The models contained lysine, methionine and age or BW (where appropriate) independent variables, their quadratic terms and interactions. Where different techniques resulted in different prediction equations, the simplest model with the most improved coefficient of determination was selected. Further analysis of abdominal fat and breast meat was done with age or BW as a covariate.

The broiler model was validation-tested using the actual 3-6 week feed intake to estimate output at 42 days.

6.2 RESULTS

After 3 weeks on the basal starter diet the birds had an average weight of 504 g and a FCE of 1.31. The effects of dietary methionine and lysine on 6 week body weight, 3-6 week BW gain, 3-6 week feed efficiency and SDS mortality are given in Table 25. There was a 3.9% decrease ($P<0.05$) in 3 to 6 week body weight gain with increasing lysine. There were no dietary effects on feed efficiency. There was a decrease ($P<0.01$) in SDS mortality with increasing lysine and methionine.

Table 25. Experiment 2. Effects of dietary lysine and methionine on 6 week body weight (g) (1), 3-6 week body weight gain (g) (2), 3-6 week feed efficiency (3) and SDS mortality (%) (4). Numbers in parentheses are Standard Errors.

			Lysine (%)		
Methionine (%)	.95	1.00	1.05	1.10	1.15
			Mean		
.46			1 1807 (17) 2 1311 (15) 3 1.93 (.02) 4 2.2 (1.1)		
.44		1823 (13) 1309 (18) 1.96 (.04) 3.9 (.6)		1751 (19) 1260 (8) 1.93 (.05) 2.2 (1.5)	
.42	1825 (20) 1308 (20) 1.94 (.02) 5.0 (1.0)		1767 (25) 1271 (26) 1.99 (.04) 2.2 (.6)		1772 (11) 1264 (2) 2.00 (.05) 1.7 (1.7)
.40		1798 (49) 1288 (35) 1.94 (.01) 3.3 (2.5)		1776 (11) 1274 (16) 1.96 (.02) 3.9 (1.1)	
.38			1766 (45) 1269 (27) 1.95 (.03) 7.2 (1.1)		

Regression analysis:

1. BW gain (3-6 weeks) dependent on lysine and methionine (full quadratic model with interaction).

Parameter	Estimate	SE	PR>T	R^2 = .17
Intercept	1549.484	116.6375	.0001	
Lys	-253.141	110.9158	.0312	

2. SDS mortality (%) dependent on lysine and methionine (full quadratic model with interaction).

Parameter	Estimate	SE	PR>T	R^2 = .26
Intercept	20.133	5.6376	.0015	
Lys x met	-37.674	12.7451	.0067	

The effects of dietary lysine and methionine on abdominal fat pad, feather and breast meat yield (% live BW) are shown in Table 26. These results are the average of all the ages. They are presented in this format to permit convenient viewing, although it should be noted that there are age x nutrient effects. The results indicate an increasing abdominal fat pad with increasing methionine and age. Feather content also increased with increasing methionine concentration. Regression analysis (Table 27) indicates that breast meat percentage increases linearly due to age x lysine and age x methionine effects. Over the data range, there is a 16.7% increase in breast meat with age, a 2.8% increase with lysine and a 3.5% increase with methionine (at average values of remaining independent variables).

The effect of age on breast meat yield is shown in Figure 4 (again ignoring age x nutrient interactions). Breast meat yield increases with age in a linear fashion. Covariate-adjusted regression analysis confirmed the positive lysine and methionine effect on breast meat yield.

6.3 DISCUSSION

It should be noted that the environmental temperatures were very high during this experiment; barn temperature was regularly greater than 32 degrees Celcius. As a consequence, body weight gain was poor during the grower

Table 26. Experiment 2. Effects of dietary lysine and methionine on abdominal fat pad (% BW) (1), feathers (% BW) (2) and breast meat (% BW) (3). Numbers in parentheses are Standard Errors.

	Lysine (%)				
Methionine (%)	.95	1.00	1.05	1.10	1.15
			Mean		
.46			1 1.64 (.17) 2 6.67 (.10) 3 12.67 (.16)		
.44		1.44 (.13) 6.51 (.10) 12.52 (.14)		1.48 (.08) 6.62 (.15) 12.76 (.15)	
.42	1.26 (.07) 6.72 (.09) 12.41 (.16)		1.53 (.09) 6.28 (.13) 12.52 (.19)		1.31 (.07) 6.41 (.11) 12.66 (.17)
.40		1.34 (.07) 6.53 (.11) 12.43 (.16)		1.34 (.07) 6.34 (.10) 12.56 (.17)	
.38			1.23 (.06) 6.29 (.13) 12.23 (.14)		

Regression analysis: experimental unit = pen

1. Abdominal Fat (% BW) dependent on lysine, methionine and age (full quadratic model with interactions).

Parameter	Estimate	SE	PR>T	R^2 = .16
Intercept	.2368	.1742	.1752	
Age x met	.0681	.0101	.0001	

2. Feathers (% BW) dependent on lysine, methionine and age (full quadratic model with interactions).

Parameter	Estimate	SE	PR>T	R^2 = .03
Intercept	4.7075	.7035	.0001	
Met	4.2298	1.6722	.0121	

Table 27. Experiment 2. Regression analysis of breast meat yield on dietary lysine and methionine to 6 weeks of age. Experimental unit = pen.

1. Breast meat (% BW) dependent on age (quadratic model).

Parameter	Estimate	SE	PR>T	R^2 = .44
Intercept	8.3791	.2817	.0001	
Age	.1024	.0074	.0001	

2. Breast meat (g) dependent on BW (quadratic model).

Parameter	Estimate	SE	PR>T	R^2 = .93
Intercept	-37.0507	3.3772	.0001	
BW	.1492	.0020	.0001	

3. Breast meat (% BW) dependent on lysine, methionine and age (full quadratic model with interactions).

Parameter	Estimate	SE	PR>T	R^2 = .50
Intercept	8.4294	.2696	.0001	
Age x lys	.0437	.0128	.0008	
Age x met	.1318	.0321	.0001	

4. Breast meat (g) dependent on lysine, methionine and BW (full quadratic model with interactions)/

Parameter	Estimate	SE	PR>T	R^2 = .97
Intercept	-8.0199	11.0238	.4676	
BW	.0900	.0151	.0001	
Lys x met x BW	.0471	.0116	.0001	
BW^2	.00001	.000004	.0054	

5. Breast meat (% BW) dependent on lysine and methionine (full quadratic model with interaction), age as covariate.

Parameter	Estimate	SE	PR>T	R^2 = .04
Intercept	-1.7595	.5365	.0012	
Lys x met	3.9943	1.2125	.0011	

6. Breast meat (g) dependent on lysine and methionine (full quadratic model with interaction), BW as covariate.

Parameter	Estimate	SE	PR>T	R^2 = .04
Intercept	-29.8357	8.9470	.0010	
Lys x met	67.7178	20.2183	.0009	

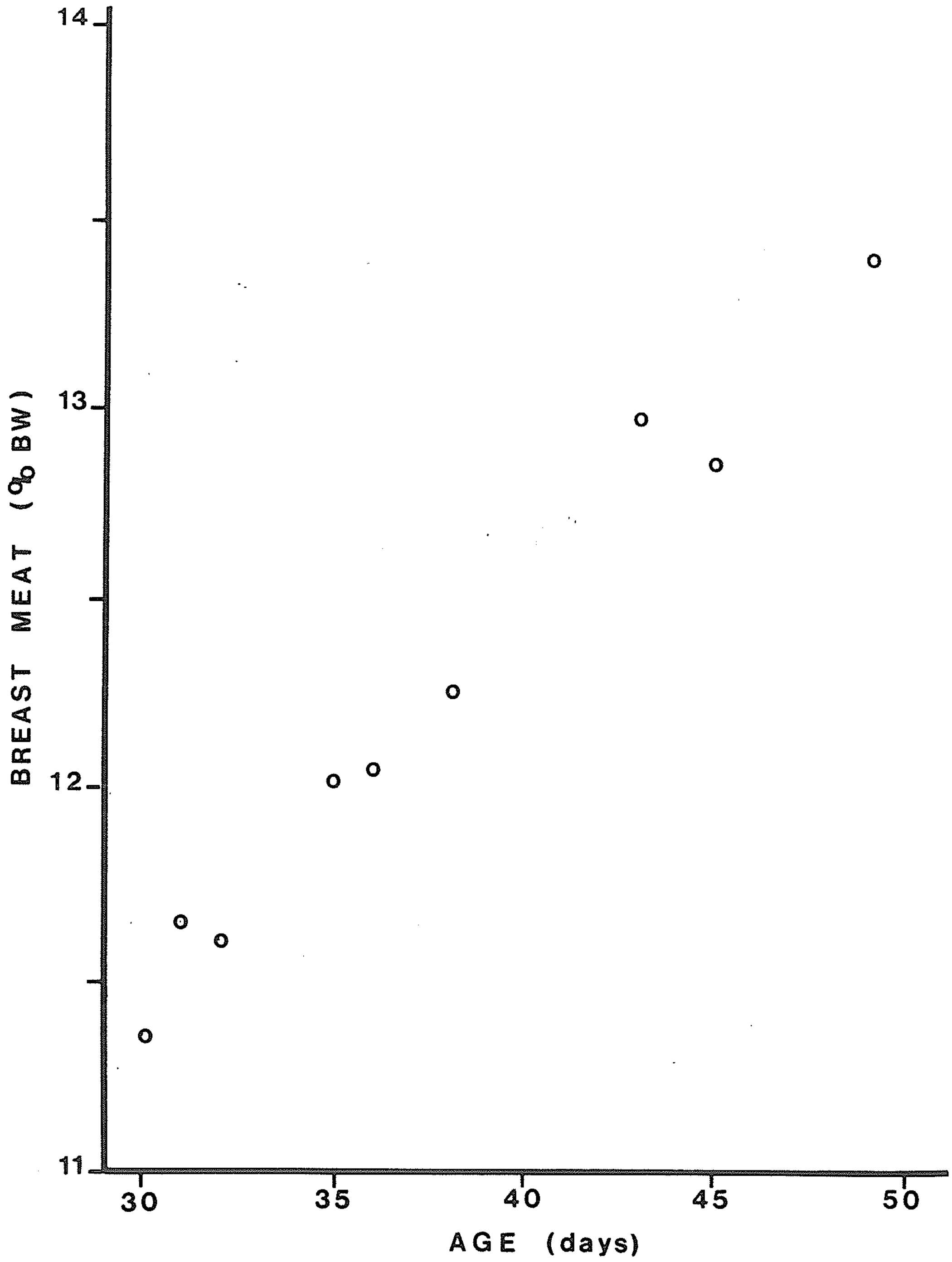

Figure 4. Experiment 2. Effect of age on broiler breast meat yield (% body weight).

period.

The positive effect of lysine and methionine on reducing SDS mortality was not anticipated. There have been no previous reports linking these amino acids with SDS.

The positive effect of methionine on increasing abdominal fat pad is surprising. An increase in amino acid supplementation should decrease fat deposition as long as they are not in excess.

The positive effects of lysine and methionine on breast meat yield confirm the results of Experiment 1, although the increase in yield was less than the 5% improvement noted in the first experiment for similar amino acid levels. This may be in part due to the lower energy diets and in part due to supplementation only in the grower phase in this experiment. The high temperature effect on performance in this experiment may have prevented full potential dietary treatment effects from expressing themselves. Contrary to the anticipated curvilinear effect of methionine, a linear effect was observed for both amino acids.

The large positive effect of age on breast meat yield is interesting. The data of Leeson and Summers (1980) indicates that breast (bone in) as a percent of live BW increases about 10% from age 28 to 49 days and then levels off. Leeson and Summers found that there was a significant quadratic effect of age on breast as a percent of carcass from 0 to 70 days of age. This experiment looks at the period from 30 to 49 days of age in detail and finds a strong linear relationship between age and breast meat yield. An even stronger relationship exits between body weight and breast meat yield, which is to be expected from their functional relationship.

6.4 MODEL VALIDATION

The broiler model validation results are presented in Tables 28 and 29. The model overestimated body weight gain and the overestimate was greater at the highest lysine levels. This is in agreement with the previous validation of the Pesti experiments (Pesti and Fletcher 1983, Pesti et al. 1986) which found the greatest body weight overestimation at high protein levels.

The model underestimated abdominal fat % and the underestimation was greatest at high methionine levels. The high fat at high methionine levels observed in this experiment was not predicted by the model, although the model predicted that dietary methionine was not limiting. It would therefore be available for catabolism and lipogenesis.

Breast meat was also underestimated by the model and it may be underestimated by a greater amount at high methionine levels (P=.056).

Table 28. Experiment 2. Actual and model predicted body weight gain (g) from 3-6 weeks of age.

		Lysine (%)				
Methionine (%)		.95	1.00	1.05	1.10	1.15
.46	Act BW gain			1311		
	Pred BW gain			1403		
	Act/Pred			.934		
	Limit AA			lys/thr		
.44			1309		1260	
			1404		1335	
			.932		.944	
			lys		thr	
.42		1308		1271		1264
		1344		1402		1396
		.973		.907		.905
		lys		lys/thr		thr
.40			1288		1274	
			1357		1377	
			.949		.925	
			lys		thr	
.38				1269		
				1361		
				.932		
				lys/thr		

Regression analysis: Act/Pred BW gain dependent on lysine and methionine (full quadratic model with interaction).

Parameter	Estimate	SE	PR>T	R^2 = .52
Intercept	1.1924	.0940	.0001	
Lys	-.2467	.0894	.0281	

Table 29. Experiment 2. Actual and model predicted abdominal fat (% BW) and breast meat (% BW) from 3-6 weeks of age.

		Lysine (%)				
Methionine (%)		.95	1.00	1.05	1.10	1.15
.46	Act Abd. Fat (AF)			1.64		
	Pred AF			1.31		
	Act/Pred AF			1.252		
	Act Breast meat (BM)			12.67		
	Pred BM			11.97		
	Act/Pred BM			1.058		
.44			1.44		1.48	
			1.34		1.30	
			1.075		1.138	
			12.52		12.76	
			11.93		11.85	
			1.049		1.077	
.42		1.26		1.53		1.31
		1.40		1.31		1.30
		.900		1.168		1.008
		12.41		12.52		12.66
		11.70		11.97		11.98
		1.061		1.046		1.057
.40			1.34		1.34	
			1.33		1.30	
			1.008		1.031	
			12.43		12.56	
			11.85		11.94	
			1.049		1.052	
.38				1.23		
				1.30		
				.946		
				12.23		
				11.89		
				1.029		

Regression analysis: Act/Pred dependent on lysine and methionine (full quadratic model with interaction).

1. Act/Pred Abdominal Fat (% BW).

Parameter	Estimate	SE	PR>T	R^2 = .53
Intercept	.3621	.2509	.1922	
Met^2	3.9356	1.4096	.0268	

2. Act/Pred Breast meat (% BW).

Parameter	Estimate	SE	PR>T	R^2 = .43
Intercept	.9079	.0635	.0001	
Met	.3458	.1509	.0556	

7. EXPERIMENT 3. THE EFFECTS OF DIETARY METHIONINE AND LYSINE ON BROILER BREAST MEAT YIELD UP TO 9 WEEKS OF AGE

7.0 INTRODUCTION

The results of the second experiment again demonstrated a positive effect of dietary lysine and methionine on breast meat yield. This final experiment was conducted with the objective of providing further quantification of the effect. In addition, several points arising from the second experiment needed confirmation: the lower incidence of SDS mortality at low methionine levels, the higher proportion of abdominal fat at high methionine levels. Also, the relationship between breast meat yield and age was linear in the second experiment from 30 to 49 days. An objective of this experiment was to extend the experimental period to 9 weeks of age (to achieve a typical roaster market weight) to determine if the effect remained linear.

7.1 MATERIALS AND METHODS

The trial was conducted in the same room of the broiler barn as Experiment 2. The design was again a central composite design where 9 different combinations of dietary lysine and methionine were fed in the grower (3-6 weeks) and the roaster (6-9 weeks) phases. The birds were fed a common starter diet for the first 21 days. The composition of the starter (crumbled) and the basal grower and roaster (pelleted) diets is given in Table 30. Synthetic L-lysine and DL-methionine were added to the basal diets to make the treatment diets. The amino acid analysis results of the basal adjusted grower and finisher diets are; mean (SD): grower: lys 1.04 (.09), met .37 (.04) and met + cys .72 (.04); finisher: lys .80 (.05), met .32 (.02) and met + cys .65 (.03).

Feather-sexed male broilers from a commercial Ross x Arbor-Acres cross were used. There were 1920 day old birds placed in 32 pens with 60 birds per pen. Feed and water were provided ad libitum and the birds were under continuous light. At 21 days, treatments were assigned to pens so that the corner and center diets of the design were fed to 4 pens and the remaining 4 intermediate treatment diets were fed to 3 pens each. The birds in each pen were group weighed (after an overnight fast) on days 1, 21, 42 and 63. Pen feed consumption was measured for the periods 1-21, 22-42 and 43-63 days. Starting at day 29, randomly selected birds were removed from each pen and were processed in the following manner (after overnight fasting). They were individually weighed, pithed and jugular bled, plucked, abdominal fat pad removed and weighed, evicerated and cut to dress, reweighed, water chilled, and pectoralis muscles removed and weighed. This procedure was conducted on days 29, 36, 43, 50, 57 and 64. For the first test day 2 birds from each pen were sampled. For the remaining 5 test days,

Table 30. Composition of diets used in Experiment 3.

Ingredient	Starter (%)	Grower (%)	Finisher (%)
Wheat	63.0	69.0	74.0
Soybean meal (46.5)	30.0	23.5	18.0
Sunflower oil	3.0	4.0	4.5
Limestone	1.5	1.4	1.4
Monocal Phosphate	1.4	1.4	1.4
Salt	.3	.3	.3
L-lysine	.07	-	-
DL-methionine	.14	-	-
Other *	.89	.4	.4

Nutrient	Calculated Analysis		
	Starter	Grower	Finisher
Crude Protein, %	22.8	20.4	18.1
Dig. Protein, %	20.5	18.3	16.3
Crude Fat, %	4.6	5.6	6.1
ME, kcal/kg	2909	3015	3075
Calcium, %	1.00	.91	.89
Phosphorus, %	.74	.70	.68
Lysine, %	1.20	.97	.78
Met + Cys, %	.84	.68	.59
Met, %	.43	.35	.29
Dig. arg, %	1.26	1.09	.91
Dig. his, %	.52	.46	.40
Dig. lys, %	1.07	.85	.70
Dig. trp, %	.24	.21	.19
Dig. phe + tyr, %	1.68	1.49	1.31
Dig. phe, %	1.05	.93	.82
Dig. met + cys, %	.75	.61	.51
Dig. met, %	.40	.33	.27
Dig. thr, %	.73	.63	.54
Dig. leu, %	1.55	1.37	1.19
Dig. ile, %	.94	.82	.70
Dig. val, %	.98	.86	.75

* To supply/kg feed the same levels of micronutrients as in Experiment 1.

Synthetic L-lysine HCl and DL-methionine were added to the basal grower and finisher diets to make the various treatment diets.

3 birds from each pen were sampled. A total of 544 birds were thus individually sampled.

The data was analyzed using Forward, Backward, Stepwise and Response surface regression techniques (SAS, 1987). The models contained lysine, methionine and age or BW (where appropriate) independent variables, their quadratic terms and interactions. Where different techniques resulted in different prediction equations, the simplest model with the most improved coefficient of determination was selected. Further analysis of abdominal fat and breast meat yield was done with age as a covariate.

The broiler model was validation-tested. The data for 3-6 week and 6-9 week feed intake was used as input to the model to estimate output at 6 and 9 weeks of age.

7.2 RESULTS

The mean for 3 week body weight was 586 g and the mean for 0-3 FCE was 1.61. Body weight and feed efficiency results are presented in Tables 31 and 32. There were no significant effects of dietary treatment on either 6 or 9 week body weight gain or feed efficiency. Total SDS mortality to 9 weeks of age was not influenced by dietary treatment.

Abdominal fat and breast meat yield results are presented in Table 33. Abdominal fat showed a curvilinear increase with age but was not influenced by dietary

Table 31. Experiment 3. Effects of dietary lysine and methionine on 6 week body weight (g) (1), 3-6 week body weight gain (g) (2) and 3-6 week feed efficiency (3). Numbers in parentheses are Standard Errors.

			Lysine (%)		
Methionine (%)	.97	1.02	1.07	1.12	1.17
			Mean		
.45			1 2107 (14) 2 1524 (14) 3 1.99 (.02)		
.425		2101 (21) 1521 (17) 2.00 (.01)		2042 (15) 1485 (13) 1.97 (.02)	
.40	2088 (17) 1511 (14) 2.06 (.01)		2080 (45) 1501 (33) 1.99 (.04)		2101 (20) 1513 (17) 1.99 (.01)
.375		2043 (17) 1472 (17) 1.97 (.03)		2075 (14) 1505 (14) 1.96 (.01)	
.35			2091 (18) 1514 (10) 2.08 (.07)		

Regression analysis: Variable dependent on lysine and methionine (full quadratic model with interaction).

1. BW gain (3-6 weeks).

Parameter	Estimate	SE	PR>T	R^2 = .01
Intercept	1488.7694	36.6511	.0001	
Met^2	133.7696	277.8630	.6337	

2. FCE (3-6 weeks).

Parameter	Estimate	SE	PR>T	R^2 = .11
Intercept	2.2709	.1406	.0001	
Lys x met	-.7723	.4044	.0658	

Table 32. Experiment 3. Effects of dietary lysine and methionine on 9 week body weight (g) (1), 6-9 week body weight gain (g) (2), 6-9 week feed efficiency (3) and SDS mortality (%) (4). Numbers in parentheses are Standard Errors.

	Lysine (%)				
	.78	.82	.86	.90	.94
Methionine (%)			Mean		
.37			1 3440 (21) 2 1333 (17) 3 3.25 (.20) 4 6.7 (2.4)		
.35		3436 (60) 1336 (40) 3.18 (.05) 7.8 (2.2)		3344 (37) 1301 (25) 3.04 (.06) 6.6 (1.7)	
.33	3359 (22) 1271 (16) 3.20 (.01) 7.9 (1.7)		3410 (54) 1331 (32) 3.32 (.17) 6.3 (1.0)		3374 (41) 1273 (32) 3.13 (.04) 10.4 (1.0)
.31		3390 (21) 1347 (10) 3.11 (.13) 7.2 (2.4)		3431 (8) 1355 (11) 3.11 (.05) 5.6 (2.0)	
.29			3446 (23) 1355 (35) 3.01 (.05) 6.7 (2.0)		

Regression analysis: Variable dependent on lysine and methionine (full quadratic model with interaction).

1. BW gain (6-9 weeks).

Parameter	Estimate	SE	PR>T	R^2 = .002
Intercept	1344.8545	90.7752	.0001	
Lys^2	-25.4691	96.6155	.7939	

2. FCE (6-9) weeks).

Parameter	Estimate	SE	PR>T	R^2 = .06
Intercept	2.5599	.4269	.0001	
Met	1.6566	1.1836	.1719	

Table 33. Experiment 3. Effects of dietary lysine and methionine on abdominal fat pad (% BW) (1) and breast meat (% BW) (2). Numbers in parentheses are Standard Errors.

			Lysine (%)		
Methionine (%)	.875	.92	.965	1.01	1.055
			Mean		
.41			1 1.50 (.07) 2 13.21 (.15)		
.3875		1.53 (.08) 13.22 (.18)		1.38 (.06) 13.12 (.20)	
.365	1.60 (.07) 13.09 (.17)		1.53 (.06) 13.33 (.15)		1.56 (.06) 13.36 (.17)
.3425		1.52 (.07) 13.38 (.18)		1.50 (.07) 13.00 (.18)	
.32			1.52 (.14) 13.38 (.14)		

Regression analysis: Abdominal Fat (% BW) dependent on lysine, methionine and age (full quadratic model with interactions).

Parameter	Estimate	SE	PR>T	R^2 = .32
Intercept	-.4352	.4640	.3494	
Age	.0648	.0204	.0017	
Age^2	-.0005	.0002	.0292	

treatment. Breast meat yield regression analysis results are presented in Table 34. There was no positive effect of lysine or methionine on breast meat yield. In fact there is some indication that breast meat yield decreased with increasing methionine. There is a strong effect of age and body weight on breast meat yield, with body weight having the greater influence as observed in experiment 2.

Breast meat (% BW) as a function of age is plotted in Figure 5. There is a greater curvilinear relationship apparent than was found in experiment 2.

7.3 DISCUSSION

The carcass yield results of this experiment do not confirm those of the previous experiment with respect to positive effects of lysine and methionine on breast meat yield. It may be that unexplained differences in feed intake between the different treatments clouded any treatment effect on breast meat yield. This will be discussed further in the next section on model validation.

This experiment did confirm the relationships between breast meat yield and age and body weight observed in experiment 2.

7.4 MODEL VALIDATION

The model validation results are shown in Tables 35-38. The model overestimated 3-6 week BW gain, and underestimated

Table 34. Experiment 3. Regression analysis of breast meat yield on dietary lysine and methionine to 6 and 9 weeks of age. Experimental unit = pen

1. Breast meat (% BW) dependent on age (quadratic model).

Parameter	Estimate	SE	PR>T	R^2 = .61
Intercept	7.3129	.8310	.0001	
Age	.1886	.0366	.0001	
Age^2	-.0013	.0004	.0010	

2. Breast meat (g) dependent on BW (quadratic model).

Parameter	Estimate	SE	PR>T	R^2 = .98
Intercept	-45.1147	3.5010	.0001	
BW	.1537	.0014	.0001	

3. Breast meat (% BW) dependent on lysine, methionine and age (full quadratic model with interactions).

Parameter	Estimate	SE	PR>T	R^2 = .61
Intercept	7.3129	.8310	.0001	
Age	.1886	.0366	.0001	
Age^2	-.0013	.0004	.0010	

4. Breast meat (g) dependent on lysine, methionine and BW (full quadratic model with interactions).

Parameter	Estimate	SE	PR>T	R^2 = .98
Intercept	-39.8767	4.3769	.0001	
BW	.1615	.0042	.0001	
Met x BW	-.0282	.0143	.0505	

5. Breast meat (% BW) dependent on lysine and methionine (full quadratic model with interaction), age as covariate.

Parameter	Estimate	SE	PR>T	R^2 = .01
Intercept	-.8881	.8210	.2808	
Lys	.9921	.8495	.2443	

6. Breast meat (g) dependent on lysine and methionine (full quadratic model with interaction), BW as covariate.

Parameter	Estimate	SE	PR>T	R^2 = .02
Intercept	18.1412	9.1718	.0494	
Met	-50.0040	25.0888	.0477	

7. Breast meat (g) dependent on BW. Experiments 2 & 3 combined. Mean at each sampling period as experimental unit.

Parameter	Estimate	SE	PR>T	R^2 = .99
Intercept	-41.0324	2.4506	.0001	
BW	.1520	.0013	.0001	

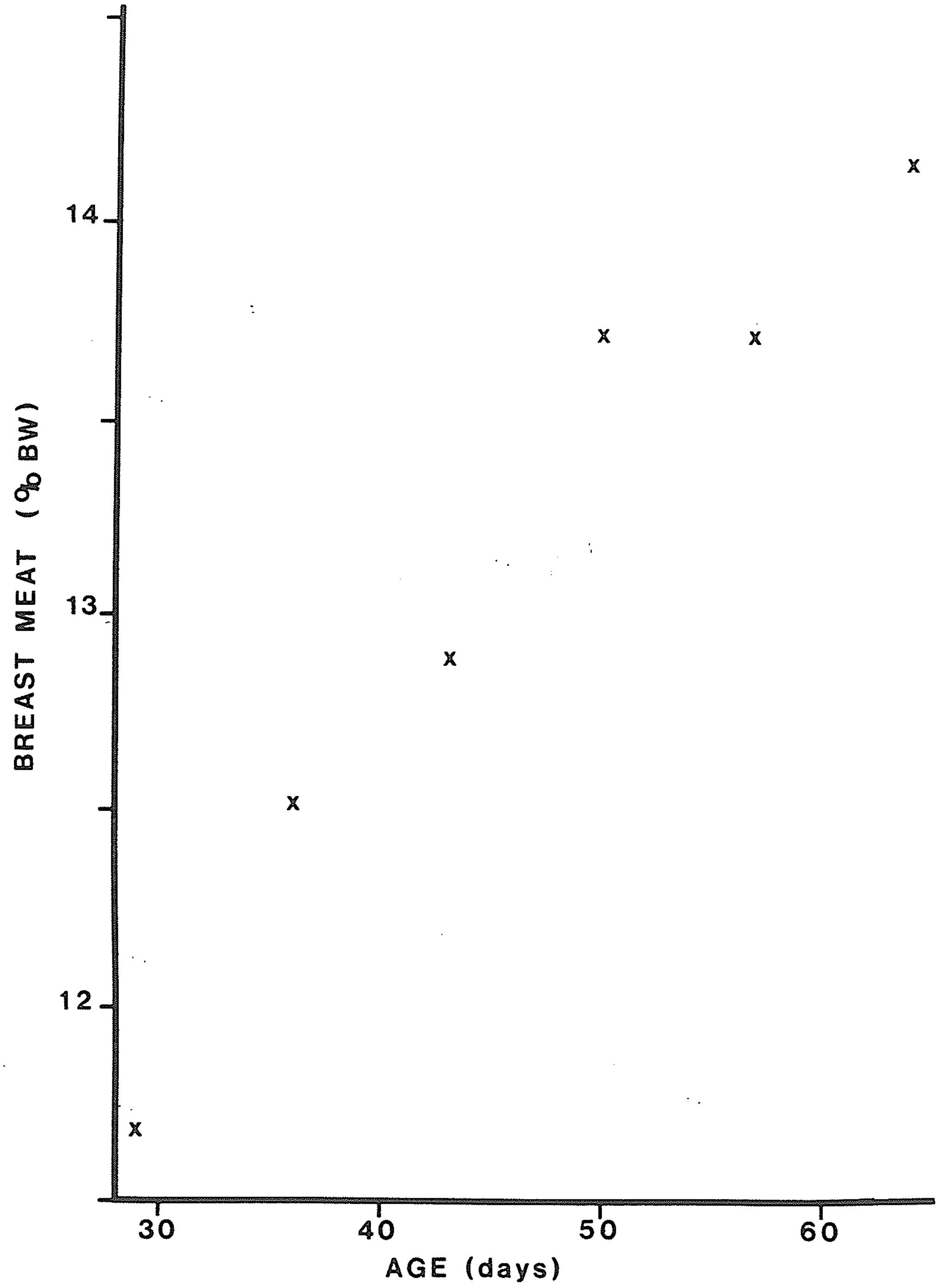

Figure 5. Experiment 3. Effect of age on broiler breast meat yield (% body weight).

Table 35. Experiment 3. Actual and model predicted body weight gain (g) from 3-6 weeks of age.

				Lysine (%)		
		.97	1.02	1.07	1.12	1.17
Methionine (%)						
.45	Act BW			1524		
	Pred BW			1726		
	Act/Pred			.883		
	Limit AA			lys		
.425			1521		1484	
			1665		1674	
			.914		.886	
			lys		thr	
.40		1511		1501		1513
		1639		1694		1727
		.922		.886		.876
		lys		lys		thr
.375			1472		1505	
			1581		1690	
			.931		.891	
			lys		thr	
.35				1514		
				1801		
				.841		
				lys		

Stepwise regression analysis: Act/Pred BW gain dependent on lysine and methionine (full quadratic model with interaction).

Parameter	Estimate	SE	PR>T	R^2 = .36
Intercept	1.1776	.1438	.0001	
Lys	-.2667	.1342	.0873	

Table 36. Experiment 3. Actual and model predicted abdominal fat (% BW) and breast meat (% BW) from 3-6 weeks of age.

		Lysine (%)				
Methionine (%)		.97	1.02	1.07	1.12	1.17
.45	Act AF			1.51		
	Pred AF			1.37		
	Act/Pred AF			1.102		
	Act BM			13.54		
	Pred BM			12.67		
	Act/Pred BM			1.069		
.425			1.38		1.37	
			1.46		1.35	
			.945		1.015	
			13.09		12.18	
			12.39		12.61	
			1.056		.966	
.40		1.67		1.68		1.45
		1.57		1.37		1.34
		1.064		1.226		1.082
		12.56		12.63		13.33
		12.16		12.61		12.72
		1.033		1.002		1.048
.375			1.51		1.52	
			1.44		1.35	
			1.049		1.126	
			12.70		12.49	
			12.28		12.64	
			1.034		.988	
.35				1.54		
				1.40		
				1.10		
				13.26		
				12.74		
				1.041		

Stepwise regression analysis: Act/Pred dependent on lysine and methionine (full quadratic model with interaction).

1. Act/Pred Abdominal Fat (% BW).

Parameter	Estimate	SE	PR>T	R^2 = .08
Intercept	1.3601	.3682	.0077	
Met	-.7033	.9182	.4687	

2. Act/Pred Breast meat (% BW).

Parameter	Estimate	SE	PR>T	R^2 = .10
Intercept	1.2155	.2128	.0001	
Lys	-.1767	.1986	.4032	

Table 37. Experiment 3. Actual and model predicted body weight gain (g) from 6-9 weeks of age.

		Lysine (%)				
Methionine (%)		.78	.82	.86	.90	.94
.37	Act BW gain			1333		
	Pred BW gain			1802		
	Act/Pred			.740		
	Limit AA			lys		
.35			1335		1301	
			1679		1676	
			.795		.776	
			lys		lys	
.33		1271		1330		1273
		1514		1849		1718
		.839		.719		.741
		lys		lys		m+c/lys
.31			1347		1355	
			1661		1804	
			.811		.751	
			lys		m+c/lys	
.29				1355		
				1639		
				.827		
				m+c/lys		

Stepwise regression analysis: A/P BW gain dependent on lysine and methionine (full quadratic model with interaction).

Parameter	Estimate	SE	PR>T	R^2 = .51
Intercept	1.1013	.1215	.0001	
Lys x met	-1.1403	.4266	.0319	

Table 38. Experiment 3. Actual and model predicted abdominal fat (% BW) and breast meat (% BW) from 6-9 weeks of age.

				Lysine (%)		
Methionine (%)		.78	.82	.86	.90	.94
.37	Act AF			1.99		
	Pred AF			1.57		
	Act/Pred AF			1.268		
	Act BM			13.97		
	Pred BM			13.35		
	Act/Pred BM			1.046		
.35			1.78		1.81	
			1.61		1.45	
			1.106		1.248	
			14.08		14.37	
			13.13		14.43	
			1.072		1.070	
.33		1.88		1.74		1.94
		1.65		1.59		1.41
		1.139		1.094		1.376
		14.52		14.10		14.25
		12.88		13.35		13.59
		1.127		1.056		1.049
.31			1.92		1.74	
			1.62		1.51	
			1.185		1.152	
			13.88		14.30	
			13.07		13.46	
			1.062		1.062	
.29				1.46		
				1.56		
				.936		
				13.95		
				13.21		
				1.056		

Stepwise regression analysis: Act/Pred dependent on lysine and methionine (full quadratic model with interaction).

1. Act/Pred Abdominal Fat (% BW).

Parameter	Estimate	SE	PR>T	R^2 = .55
Intercept	.1840	.3406	.6057	
Lys x met	3.4639	1.1956	.0231	

2. Act/Pred Breast meat (% BW).

Parameter	Estimate	SE	PR>T	R^2 = .75
Intercept	5.2675	1.4385	.0106	
Lys	-9.4667	3.3505	.0301	
Lys^2	5.3125	1.9471	.0343	

3-6 week abdominal fat and breast meat yield. There was no influence of dietary treatment on the degree of over or underestimation. It is interesting to note that the model predicted a positive response in breast meat yield to increasing lysine and methionine in experiment 2 which was actually observed. The model predicted only a lysine effect in this experiment but no effect was observed. Examination of the feed intake data reveals high variability which may reflect a large experimental error.

In the 6-9 week period, the model severely overestimated growth. The model apparently is less accurate at older ages. This may be due to an overestimate of nutrient utilization efficiency (both amino acids and energy) at old ages. There was a small effect of dietary treatments on the actual/predicted residuals in this 6-9 week period.

8. MODEL ECONOMIC EVALUATION

There are two basic economic objectives of commercial broiler production that the model can help resolve. For the "whole bird" market, the objective is to produce a bird of specified body weight at least cost. For the "further processing" market, the objective is to determine when the increased meat production from increasing age and feed consumption is economically offset by increasing input costs. Both of these objectives will be addressed.

A whole bird body weight objective of 1.8 kg was chosen as a typical bird size used by fast food chicken piece retail operations. A typical starter diet (Table 39) was offered to the model which resulted in a bird weight of 600 g at 21 days. Grower diets containing various protein (proportional amino acids) and energy levels (Table 40) were offered to the model from 3 weeks onward. The age at which the model predicted a BW of 1.8 kg and grower feed consumption were recorded. The various diets were also least-costed with linear programming using the ingredient costs in Table 39. The results are shown in Table 40. Performance continued to improve with increasing protein and energy but the lowest feed cost was within the diet matrix. The grower feed cost ($/bird) was subjected to response surface regression analysis (SAS, 1986). The model had a minimum of $.412/bird at a protein concentration of 20.6% and a ME of 3163 kcal/kg (Figure 6). This is close to both

Table 39. Feed ingredients and nutrient composition of diets used in economic evaluation of broiler model

Ingredient	Cost/T ($)
Barley	110
Corn	160
Wheat	130
Soybean meal	250
Tallow	350
L-lysine	4000
DL-methionine	3000

Nutrient		Composition	
	Starter	Grower	Finisher
Cost/T ($)		197	184
Crude Protein, %	23.0	21.0	19.0
Dig. Protein, %	20.6	18.4	17.4
Crude Fat, %	6.6	7.1	6.9
ME, kcal/kg	3100	3200	3200
Dig. arg, %	1.21	1.10	1.00
Dig. his, %	.50	.46	.42
Dig. lys, %	1.17	.99	.85
Dig. trp, %	.23	.21	.20
Dig. phe + tyr, %	1.64	1.50	1.40
Dig. phe, %	1.02	.92	.86
Dig. met + cys, %	.88	.71	.64
Dig. met, %	.54	.41	.35
Dig. thr, %	.70	.67	.59
Dig. leu, %	1.51	1.44	1.32
Dig. ile, %	.91	.82	.75
Dig. val, %	.95	.87	.80

Table 40. Broiler model predicted grower feed requirement and cost to attain 1.8 kg BW

1 Age at 1.8 kg BW (market age, days)
2 Feed intake (kg/21 - market age)
3 Feed cost ($/kg)
4 Feed cost/bird ($ grower feed)

		Protein (%)				
		19	20	21	22	23
ME (kcal/kg)						
3000	1	43.0	42.5	42.5	43.0	43.0
	2	2.388	2.376	2.400	2.412	2.460
	3	.178	.180	.183	.187	.192
	4	.425	.428	.439	.451	.472
3100		42.5	42.0	41.5	41.5	42.0
		2.304	2.220	2.208	2.208	2.232
		.183	.1855	.189	.1935	.199
		.422	.412	.417	.427	.444
3200		42.5	41.5	41.0	41.0	41.0
		2.268	2.172	2.088	2.064	2.064
		.190	.193	.197	.202	.208
		.431	.419	.411	.417	.429
3300		42.5	41.5	41.0	40.5	40.0
		2.244	2.148	2.064	1.992	1.944
		.199	.2025	.207	.2125	.219
		.447	.435	.427	.423	.426

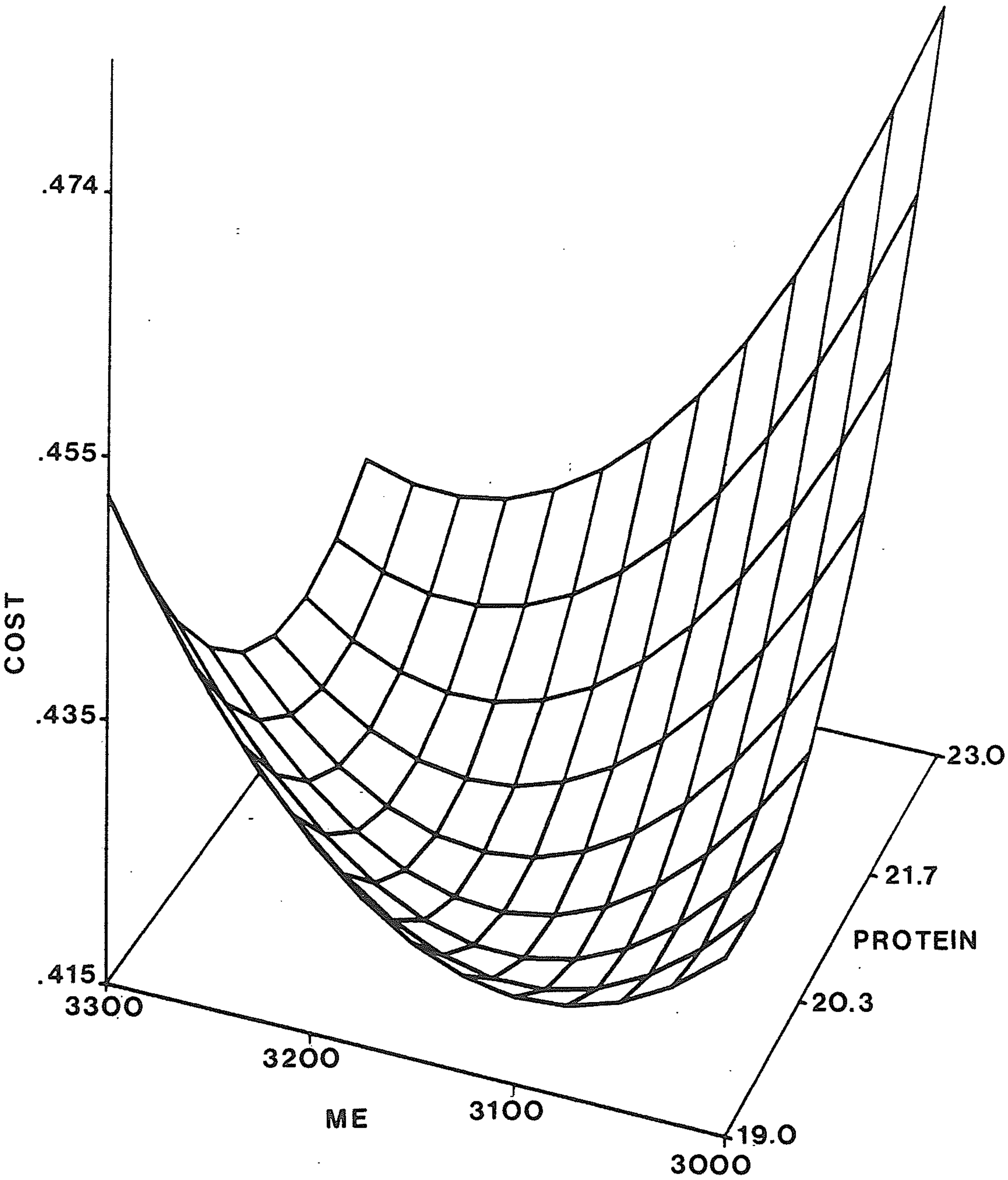

Figure 6. Broiler grower feed cost ($/bird) to reach 1.8 kg body weight, as a function of dietary metabolizable energy (kcal/kg) and protein (%).

recommended NRC (1984) nutrient concentrations (21% protein and 3200 kcal/kg) and commercial feed specifications. This agreement indirectly supports the model's validity and capability of optimizing "whole bird" production economics.

The "further processing" exercise involved offering the model a standard finisher diet (Table 39) from 43 to 70 days of age and monitoring breast meat yield and feed consumption. The results are presented in Table 41. Unlike the first example, age is an important variable in this exercise. Mortality increases with age and there are other fixed costs from keeping birds longer. Accordingly the profit objective function was adjusted for a mortality rate of .2%/day and a fixed cost of $.01/bird/day. A revenue value of $5/kg was assumed for breast meat. Unlike the first example, no function maximum was reached. Profit continued to increase to 10 weeks of age. This is consistent with the current (and relatively recent) practice of the industry to grow broilers to 11 - 12 weeks of age if they are to be used for further processing. Unfortunately, the model is only calibrated to 10 weeks of age and is therefore not capable of evaluating the industry practice.

Table 41. Model predicted breast meat yield, finisher feed utilization and profit from 6 to 10 weeks of age

	Age (days)						
	42	45	50	55	60	65	70
BW (g)	1800	1986	2325	2697	3102	3540	4010
Breast meat (g)	207	236	284	338	399	467	544
Extra meat (g)	0	29	77	131	192	260	337
Mortality adj. (.2%/day) extra meat	0	28	75	127	184	247	317
Extra revenue ($5/kg meat)	0	.140	.375	.635	.920	1.235	1.585
Feed int. (kg)	0	.411	1.166	2.000	2.916	3.915	4.995
Feed cost ($.184/kg)	0	.076	.215	.368	.537	.720	.919
Extra Fixed costs ($.01/bird/day)	0	.03	.08	.13	.18	.23	.28
Extra profit ($)	0	.034	.080	.137	.203	.285	.386

9. DISCUSSION

9.1 BREAST MEAT YIELD

The breast meat yield data from experiments 2 and 3 were combined and a linear model relating mean breast meat yield (weight) at different sampling times to body weight was fit. The results are shown in Figure 7 and Table 34. It is evident that body weight is an excellent predictor of breast meat yield.

It is very interesting that breast meat yield continues to increase linearly with increasing BW up to at least 3500 g BW. This would suggest that broiler processors interested in maximizing breast meat yield should process birds that are at least 9 weeks old. This is confirmed in the economic evaluation of the model.

Therefore, both the model and the empirical predictions of breast meat yield can be used to predict breast meat yield. The use of the model is preferable because the nutrient effects are incorporated into it. Some of the empirical predictive equations, especially those derived from the data in experiment 2 could be used to account for dietary lysine and methionine effects on breast meat yield.

9.2 MODEL

A final validation of the model is illustrated in Figure 8. A scatter plot of actual versus predicted body weight

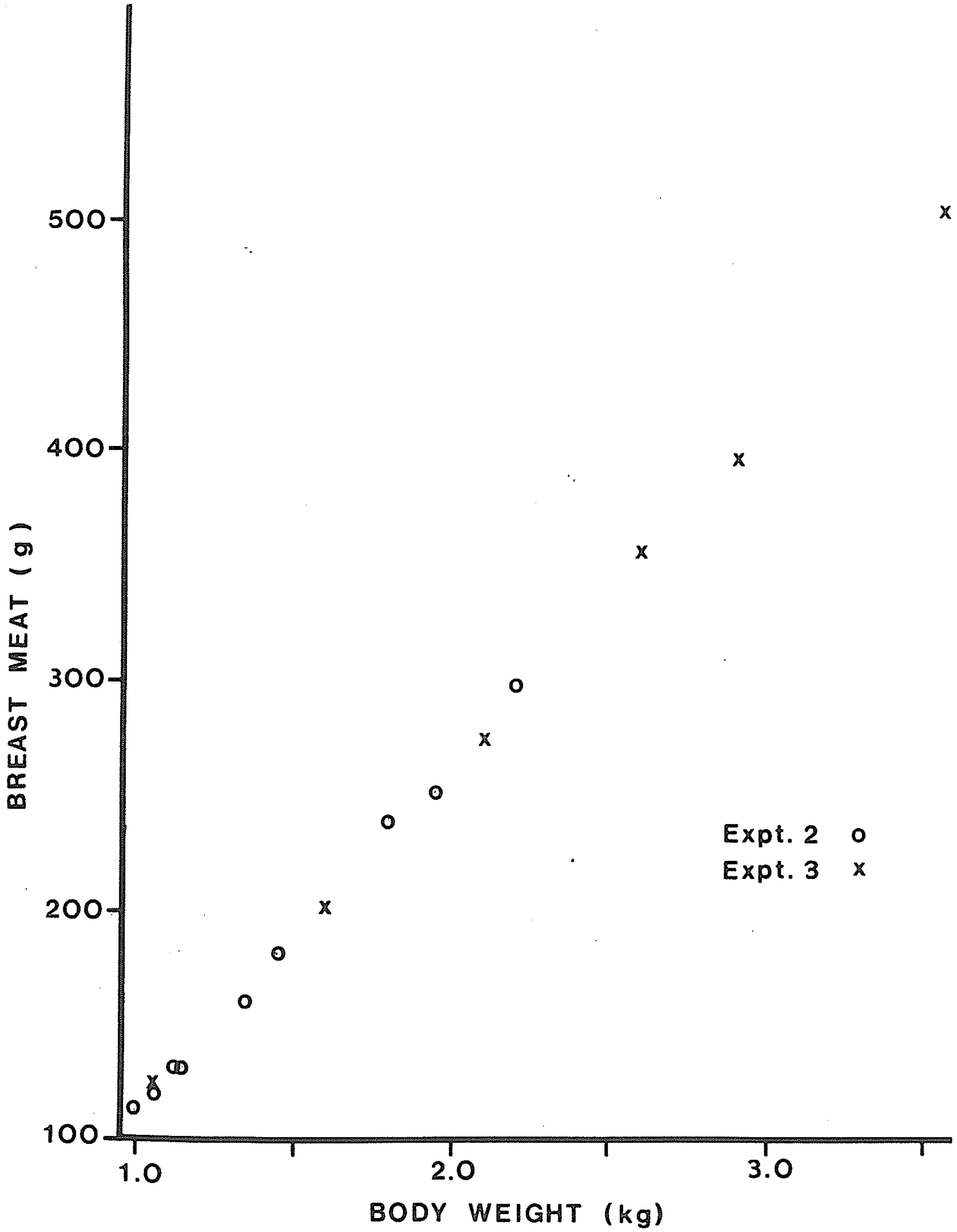

Figure 7. Experiments 2 & 3. Effect of body weight on broiler breast meat yield (g).

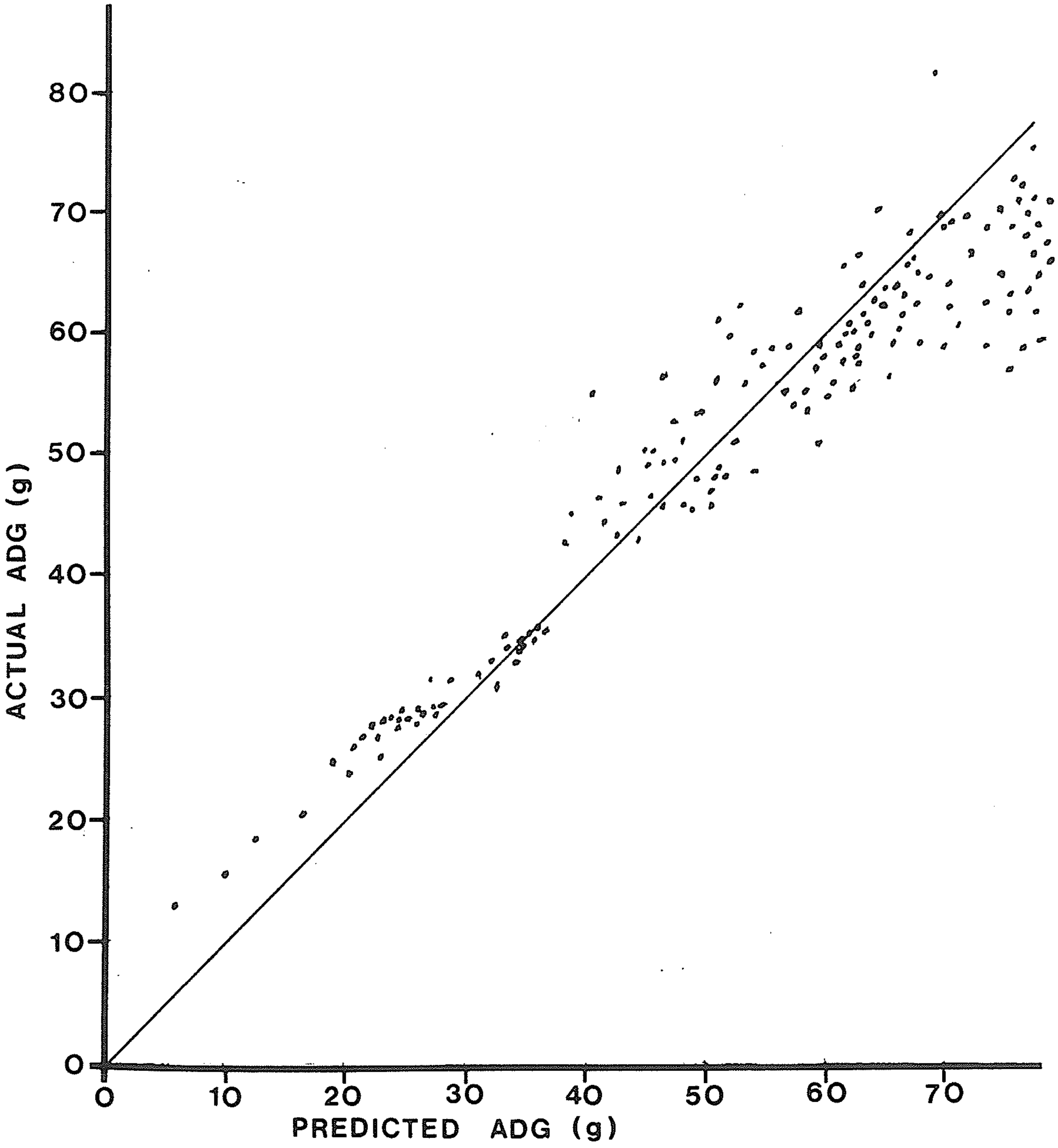

Figure 8. Scatter plot of model actual versus predicted body weight average daily gain (ADG) using all model validation data sets. The straight diagonal line is the case of perfect regression.

average daily gain (ADG) shows a strong relationshipe (R^2 = .89) for the linear model. The linear model has a slope of .76 as compared with the ideal value of 1.0. The intercept was 11.2983 which was significantly different from zero (P=.0001). Interestingly, a quadratic model gave a slightly better fit.

ADG (g/day) = -.8881 + 1.3365 x Pred - .0058 x Pred^2)

PR>T = .7101 .0001 .0001

R^2 = .91

The results indicate that the model overestimates daily gain above 60 grams which corresponds to ages older than 7 weeks. The model has a limitation of basic data at these ages which should be addressed.

Nevertheless, the broiler model is capable of predicting broiler performance over a wide variety of ages and nutritional regimes. It is mechanistically based and should therefore have wide application. Future improvements in the model are anticipated in many areas. Improved knowledge in the areas of amino acid utilization efficiency, fasting heat production, activity heat, protein fractional synthetic rate, thermoregulation heat as influenced by age and body weight, amino acid profile of maintenance and feed intake prediction, to name a few topics, will improve model accuracy. The advantage of this type of mechanistic model is that once the initial structure is established, then any improvement to any component of the model will always improve the model's accuracy.

Practical application of the model would be facilitated by linking it with a least cost feed formulation system and by putting the whole system in an iterative loop with the objective of maximizing profit relative to the responses of economic interest, eg. fixed body weight, meat yield.

REFERENCES

Almquist, H.J., 1953. Interpretion of amino acid requirement data according to the law of diminishing returns. Archives of Biochemistry and Physics 44:245-247

Arbor Acres, 1987. Broiler feeding and management. Glastonbury, Connecticut, U.S.A.

Barbato, G.F., P.B. Siegel, J.A. Cherry and I. Nir, 1984. Selection for body weight at eight weeks of age. 17. Overfeeding. Poult. Sci. 63:11-18

Bartov, I., 1987. Combined effect of age and ambient temperature on the comparative growth of broiler chicks fed tallow and soy bean oil. Poult. Sci. 66:273-279

Bedford, M.R. and J.D. Summers, 1985. Influence of the ratio of essential to nonessential amino acids on performance and carcass composition of the broiler chick. Brit. Poult. Sci. 26:483-491.

Block, R.S. and K.W. Weiss, 1956. Amino Acid Handbook. C.C. Thomas Publisher, Springfield, Ark. p.278

Brue, R.N., and J.D. Latshaw, 1985. Energy utilization by the broiler chicken as affected by various fats and fat levels. Poult. Sci. 64:2119-2130

Charles, D.R., C.M. Groom and T.S. Bray, 1981. The effects of temperature on broilers: interaction between temperature and feeding regime. Brit. Poult. Sci. 22: 475-481

Combs, G.F., 1964. Predicting amino acid requirements of chicks based on growth rate, body size and body composition. Fed. Proc. 23:46-51.

Damme, K., F. Pirchner, H. Willeke and H. Eichinger, 1987. Fasting metabolic rate in hens. 1. Effects of body weight, feather loss, and activity. Poult. Sci. 66:881-890

Edwards, H.M., F. Dennan, A. Abou-Ashour and D. Nugara, 1973 Carcass composition studies 1. Influences of age and type of dietary fat supplementation on total carcass and fatty acid composition. Poult. Sci. 52:934-948

Emmans, G.C., 1981. A model of the growth and feed intake of ad libitum fed animals, particularly poultry. in Computers in Animal Production. G.M. Hillyer, C.T. Whittmore and R.G. Gunn eds. Occasional Publication No. 5. pp. 103-110. British Society of Animal Production.

Emmans, G.C., 1987. Growth, body composition and feed intake. World's Poult. Sci. J. 43:208-227.

Emmans, G.C. and C. Fisher, 1986. Problems in nutritional theory. in Nutrient Requirements of Poultry and Nutritional Research. C.Fisher and K.N. Boorman eds. Butterworths, London. pp. 9-39.

Farjo, G.Y., A.S. Al-Saigh and I.K. Ibrahim, 1986. Effects of dietary dilution with sand on broiler performance to 8 weeks of age. Brit. Poult. Sci. 27:385-390

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

Fisher, C. and R.K. Skougall, 1982. A note on the amino acid composition of the turkey. Brit. Poult. Sci. 23:233-237.

Fisher, C., 1988. Formal methods of calculating amino acid requirements of growing poultry. Heartland Lysine Symposium. Georgia Nutrition Conference.

Fisher, M.L., 1981. Predicting amino acid specifications of broiler diets. MSc. Thesis. University of Guelph.

Fisher, M.L., S. Leeson, W.D. Morrison, and J.D. Summers, 1981. Feather growth and feather composition of broiler chickens. Can. J. Anim. Sci. 61:769-773.

Forbes, J.M., 1988. Relationships between feed intake, energy balance and adiposity. in Leaness in Domestic Birds, Genetic, Metabolic and Hormonal Aspects. B. Leclercq and C.C. Whitehead eds. Butterworths, London pp. 97-107.

Fraps, G.S., 1943. Relation of protein, fat and energy of the ration to the composition of chickens. Poult. Sci. 22:421

Gous, R.M. and T.R. Morris, 1985. Evaluation of a diet dilution technique for measuring the response of broiler chickens to increasing concentrations of lysine. Brit. Poult. Sci. 26:147-161.

Hakansson, J., S. Eriksson and S.A. Svensson, 1978. Influence of feed energy level on chemical composition of tissues and on the energy-protein utilization by broiler chicks. Report No. 59. Swedish University of Agricultural Sciences, Dept. of Animal Husbandry.

Heartland Lysine, 1990. The 1990 reference table for poultry amino acid digestibility. Heartland Lysine Inc. Chicago, Il.

Holmes, W.B., D.M. Massey and P.J. Owen, 1963. The amino acid composition of broiler cockerels in relation to their dietary amino acid requirement. Brit. Poult. Sci. 4:285-290

Howlider, M.A.R. and S.P. Rose, 1987. Temperature and the growth of broilers. World's Poult. Sci. J. 43:228-237.

Howlider, M.A.R. and S.P. Rose, 1989. Rearing temperature and the meat yield of broilers. Brit. Poult. Sci. 30:61-67.

Hsieh, H., and L.O. Rowland Jr., 1983. Effect of dietary sand on the performance and body composition of young broilers fed varying protein and energy levels. Poult. Sci. 62:1436

Hurwitz, S., D. Sklan, and I. Bartov, 1978. New formal approaches to the determination of energy and amino acid requirements of chicks. Poult. Sci. 57:197-205.

Hurwitz, S., M. Weiselberg, U. Eisner, I. Bartov, G. Reisenfeld, M. Sharvit, A. Niv and S. Bornstein, 1980a. The energy requirements and performance of growing chickens and turkeys as affected by environmental temperature. Poult. Sci. 59:2290-2299.

Hurwitz, S., I. Plavnik, I. Bartov and S. Bornstein, 1980b. The amino acid requirements of chicks: Experimental validation of model-calculated requirements. Poult. Sci. 59:2470-2479

Hurwitz, S., 1988. Use of models in the estimation of amino acids and energy requirements. North Carolina Nutrition Conference.

Isariyodom, I., I. Tasaki, J. Okumura and T. Muramatsu, 1988. Construction of a mathematical model for predicting broiler performance. Jap. Poult. Sci. 25:191-200.

Jackson, M.E., 1987. The development of computer models to estimate nutrient requirements of the broiler chicken. PhD. Thesis. University of Arkansas.

Jones, S.J., E.D. Aberle and M.D. Judge, 1986. Skeletal muscle protein turnover in broiler and layer chicks. J. Anim. Sci. 62:1576-1583

Kang, C.W., M.L. Sunde and R.W. Swick, 1985. Growth and protein turnover in the skeletal muscles of broiler chicks. Poult. Sci. 64:370-379.

Keller, J.S., 1980. Fasting heat production as a function of growth rate in the chicken. Arch. Geflugelk. 44:168-172.

Kino, K. and J. Okumura, 1986. The effect of single essential amino acid deprivation on chick growth and nitrogen and energy balances at ad libitum and equalized food intakes. Poult. Sci. 65:1728-1735

Kino, K. and J. Okumura, 1987. Whole-body protein turnover in chicks fed control, histidine or methionine plus cystine - free diets. Poult. Sci. 66:1392-1397

Kirkwood, J.K. and A.J.F. Webster, 1984. Energy - budget strategies for growth in mammals and birds. Anim. Prod. 38:147-155

Kita, K., T. Muramatsu, I. Tasaki and J. Okumura, 1989. Influence of dietary non-protein energy intake on whole-body protein turnover in chicks. Brit. J. Nutr. 61:235-244

Leclercq, B., 1983. The influence of dietary protein content on the performance og genetically lean or fat growing chickens. Brit. Poult. Sci. 24:581-587.

Leeson, S. and J.D. Summers, 1980. Production and carcass characteristics of the broiler chicken. Poult. Sci. 59:786-798.

Leeson, S., 1989. Implications of differential growth patterns of broiler chickens. Monsanto Nutrition Update. Vol. 7 No. 2.

Leveille, G.A. and H. Fisher, 1958. The amino acid requirement for maintenance in the adult rooster I. Nitrogen and energy requirements in normal and protein depleted animals receiving whole egg protein in amino acid diets. J. Nutr. 66:441-453.

Marks, B., A. Robinson, E.F. Beach and H.H. Williams, 1945. Amino acids in the production of chicken egg and muscle. Poult. Sci. 24:459-464

Mateos, G.G. and J.L. Sell, 1981. Nature of the extrametabolic effect of supplemental fat used in semi-purified diets for laying hens. Poult. Sci. 60:2114-2119

Mendonca, C.X. and L.S. Jensen, 1989. Influence of protein concentration on the sulfur-containing amino acid requirements of broiler chickens. Brit. Poult. Sci. 30:889-898.

Miller, B.R., R.A. Arraes and G.M. Pesti, 1986. Formulation of broiler finishing rations by quadratic programming. South. J. Agric. Econ. 18:141-150.

Moran, E.T. Jr., 1988. Dietary lysine and broiler meat yield. Proceedings of the California Animal Nutrition Conference. pp. 46-52. March 16-18, 1988. Centre Plaza Holiday Inn, Fresno, California.

Muramatsu, T. and J. Okumura, 1985. Whole body protein trunover in chicks at early stages of growth. J. Nutr. 115:483-490.

National Research Council, 1981. Nutritional Energetics of Domestic Animals & Glossary of Energy Terms. 2nd Rev. Natl. Acad. Press, Washington, D.C.

National Research Council, 1982. United States - Canadian Tables of Feed Composition. 3rd Rev. Natl. Acad. Press, Washington, D.C.

National Research Council, 1984. Nutrient Requirements of Domestic Animals. Nutrient Requirements of Poultry. 8th ed. Natl. Acad. Press, Washington, D.C.

Onwudike, O.C., 1986. The effects of dietary sand on the usage of diets containing brewer's dried grains by growing chicks. Poult. Sci. 65:1129-1136

Pesti, G.M., and D.L. Fletcher, 1983. The response of male broiler chickens to diets with various protein and energy contents during the growing phase. Brit. Poult. Sci. 24:91-99

Pesti, G.M., R.A. Arraes and B.R. Miller, 1986. Use of quadratic growth response to dietary protein and energy concentrations in least-cost feed formulation. Poult. Sci. 65:1040-1051.

Plavnik, I., and S. Hurwitz, 1983. Organ weights and body composition in chickens as related to energy and amino acid requirements: effect of strain, sex and age. Poult. Sci. 62:152-163.

Prescott, N.J., C.M. Wathes, J.K. Kirkwood and G.C. Perry, 1985. Growth, food intake and development in broiler cockerels raised to maturity. Anim. Prod. 41:239-245.

Proudfoot, F.G. and H.W. Hulan, 1982. Effects of reduced feeding time using all mash or crumble-pellet dietary regimens on chicken broiler performance, including the incidence of acute death syndrome. Poult. Sci. 61:750-754

Robbins, K.R., and J.E. Ballew, 1984. Utilization of energy for maintenance and gain in broilers and Leghorns at two ages. Poult. Sci. 63:1419-1424.

Rogers, S.R. and G.M. Pesti, 1988. Influence of method of analysis on estimating the relationship between fasting heat production and body size of the domestic fowl. Poult. Sci. 67:Supp. 1 p. 146

Rogers, S.R., G.M. Pesti and H.L. Marks, 1987. Comparison of three non linear regression models for describing broiler growth curves. Growth 51:229-239.

Salmon, R.E., H.L. Classen and R.K. McMillan, 1983. Effect of starter and finisher protein on performance, carcass grade and meat yield of broilers. Poult. Sci. 62:837-845

SAS Institute. 1985. SAS/STAT Guide for Personal Computers, Version 6 Edition. SAS Institute Inc. Cary, NC.

Saunders, A.J., J.P.H. Wessels and R.M. Gous, 1977. Carcass amino acid composition and utilization of dietary amino acids by chickens. S. Afr. J. Anim. Sci. 7:111-115

Scott, M.L., M.C. Nesheim and R.J. Young, 1969. Nutrition of the Chicken. Scott & Associates, Ithaca, New York, Table 3.19.

Sibbald, I.R. and M.S. Wolynetz, 1986. Effects of dietary lysine and feed intake on energy utilization and tissue synthesis by broiler chicks. Poult. Sci. 65:98-105.

Summers, J.D., S. Leeson and D. Spratt, 1988. Yield and composition of edible meat from male broilers as influenced by dietary protein level and amino acid supplementation. Can. J. Anim. Sci. 68:241-248.

Taylor, St., C.S., 1980. Genetic size-scaling rules in animal growth. Anim. Pord. 30:161-165

Van Kampen, M., 1976. Activity and energy expenditure in laying hens. 1. The energy cost of nesting activity and oviposition. J. Agric. Sci. Camb. 86:471-473

Van Kampen, M., 1976. Activity and energy expenditure in laying hens. 2. J. Agric. Sci. Camb. 87:81?85

Waterlow, J.C., P.J. Garlick and D.J. Millward, 1978. Protein Turnover in Mammalian Tissues and in the Whole Body. Amsterdam:Elsevier, North Nolland.

Whittmore, C.T. and R.H. Fawcett, 1974. Model responses of the growing pig to the dietary intake of energy and protein. Anim. Prod. 19:221-231.

Whittmore, C.T. and R.H. Fawcett, 1976. Theoretical aspects of a flexible model to simulate protein and lipid growth in pigs. Anim. Prod. 22:87-96.

APPENDIX

COMPARISON OF LEFT AND RIGHT MUSCLE WEIGHTS OF BROILERS

Prior to conducting the experiments on breast meat yield, a study was done to practice meat dissection techniques and to evaluate potential variability between different operators. Twenty chilled carcasses of 42 day old male broilers were obtained from a commercial processor. The carcasses were weighed (neck removed), and the pectoralis muscles were removed (manual cutting) and weighed. Two operators each removed the breast meat from 10 birds.

The results are shown in Table 42. The pectoralis major muscles were 3.0% heavier ($P<.01$) and the pectoralis minor muscles were 4.8% heavier ($P<.05$) and the total 3.3% heavier ($P<.001$) on the left side than on the right side of the bird. There was an operator effect on the demonstration of differences. Both the pectoralis major and minor muscles removed by the first operator were heavier on the left side, while only the total pectoralis muscles removed by the second operator were significantly heavier on the left side.

Table 42. Appendix. Mean left versus right pectoralis muscle weight differences of 42 day old male broilers

Parameters	Operator 1	Operator 2	Combined	SE
Number of broilers	10	10	20	
Carcass weight (g)	1280	1275	1277	11
Left				
P. major (g)	110.4	110.3	110.4	2.0
P. minor (g)	34.8	33.4	34.1	.6
Total (g)	145.2	143.7	144.4	2.4
Right				
P. major (g)	106.5	108.1	107.3	2.2
P. minor (g)	32.3	33.0	32.7	.7
Total (g)	138.8	141.1	140.0	2.4
Difference (%)				
P. major	3.8	2.2	3.0	.9
P. minor	8.1	1.4	4.8	2.1
Total	4.6	1.9	3.3	.8
Statistics: Paired t test (Left>Right)				
P. major	.0243*	.0632	.0028	
P. minor	.0115	.7257	.0487	
Total	.0031	.0352	.0003	

* Hypothesis probability