BROILER GROWTH MODELS DYNAMICALLY INTERFACING METABOLIC EFFICIENCY WITH THE PRODUCTION ENVIRONMENT

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

INTRODUCTION

Within the last century, broiler production in the United States has evolved from small "backyard" flocks into a multi-million dollar sector of agriculture. Overall, U.S. broiler meat production for 2005 is projected to be close to 16 million metric tons, which is approximately 40% of the total animal protein market (Haley, 2005). The broiler industry's success in part can be attributed to its vertically integrated corporate structure, which to a certain extent provides continuity among broiler flocks. Nonetheless, due to differing facilities and equipment, as well as environmental and animal welfare concerns, broilers are inevitably reared under varying circumstances, particularly from a global perspective.

Nonnutritive factors such as stocking density (Cravener et al., 1992; Puron et al., 1997), lighting program (Buyse et al., 1996; Ingram et al., 2000), ventilation (Lott et al., 1998; Yahav et al., 2004) and feed form (Acar et al., 1991; Scheideler, 1995; Moritz et al., 2001) are well documented throughout the literature to impact bird performance. Though the precise mode of action by which such nonnutritive factors impact broiler performance may be subject to debate, one could surmise each as having a nutritional consequence to the bird. Given the varying conditions in which broilers are reared throughout the world, and that the nutritional positive or negative consequences of those

conditions are more or less a guess, the expression “nutrition is more of an art than a science” has credence.

Broiler management aside, there is an inherent caloric cost associated with accretion of lean and lipid tissues, the associated inefficiencies of which contribute to heat production. In an effort to quantify these costs, Kielanowski (1965) subdivided retained energy as follows: $ME = ME_m + (1/k_p \times ERP) + (1/k_f \times ERF)$, where: ME = metabolizable energy intake, ME_m = metabolizable energy required for maintenance, ERP = energy retained as protein, ERF = energy retained as fat, k_p = efficiency of energy utilization for protein, and k_f = efficiency of energy utilization for fat. And through regression analysis obtained values for ME_m, k_p, and k_f. Proposed values for k_p and k_f are shown in Table 1. This regression approach, however, has received criticism due to the autocorrelation among the variables (Emmans, 1994; Noblet et al., 1999), and its inability for separating metabolizable energy into contributing dietary substrates (Noblet et al., 1993). Utilizing mechanistic models based on theoretical biochemical costs and returns has been suggested as a solution to these criticisms (van Milgen, 2002). However, as Birkett and de Lange (2001) pointed out, solid experimental observations are lacking and the metabolic detail required in a mechanistic model is essentially noise when viewed at the higher spatial level.

Any approach to estimating the efficiency of energy utilization for tissue accretions requires a sound understanding of energy required for maintenance. Errors or assumptions made relative to the maintenance energy requirement carries-over resulting in an over or under estimation of energy available for gain and ultimately false estimates for the metabolic costs of tissue accretion. Nonetheless, relatively little research as of

late that has been directed at understanding maintenance energy need in broilers or factors that may alter maintenance energy requirement.

Mathematical models have long been utilized to describe broiler growth (Zoons et al. 1991), evaluate feedstuffs (MacLeod, 2000), compute nutrient requirements (Oviedo-Rondon and Waldroup, 2002) and understand managerial consequences on broiler performance (Cobb Vantress, 2003). Provided that the body of data is such to underpin proposed predictive models, these equations serve as an invaluable tool in making decisions. However, application of such models require either that conditions mimic those under which the model was developed or the flawed assumption that nutrition and management are separate entities of broiler production. The latter introduces error into the predicted values, potentially resulting in spurious interpretations.

Historically, comparative slaughter has been the most commonly used method for evaluating nutritional and/or managerial effects on broiler body composition. This methodology, however, is time consuming, difficult to apply to an entire growth curve, and requires bird destruction as well as the assumption that the composition of birds initially examined are the same as those incorporated into an experiment (Blaxter, 1967). Recently, dual energy x-ray absorptiometry (DEXA) has been proposed as a method for measuring bone density and content in poultry (Schreiweis, 2003; and Onyango, 2004). Additionally, a large body of evidence exists validating the use of this technology for assessing soft tissues in swine (Lukashi et al., 1999; Chauhan et al., 2003; and Koo et al., 2004). An experiment conducted by Mitchell et al. (1997), however, is the only known evaluation of DEXA for quantifying lean and lipid tissues in poultry. Though this report was largely inconclusive, it did suggest that DEXA could potentially be utilized to

rapidly quantify broiler body composition and enable the option of returning that bird back to production. More work is needed, however, to validate this technology.

Studies described herein were designed with the intent of addressing areas outlined above where current knowledge is lacking. More specifically, in Chapter 3, DEXA was evaluated as a method for rapidly quantifying broiler body composition. Chapters 4 and 5 focus on developing mathematical models to describe the caloric costs associated with broiler management decisions that impact activity energy expenditure. Chapter 6 utilizes this methodology in evaluating dietary nutrient-calorie ratio under varying broiler management conditions. Lastly in Chapter 7, experiments were directed at first, quantifying metabolizable energy required for maintenance and tissue accretion, and second, to propose methodology for calculating the efficiencies of metabolizable energy use for protein and lipid tissue accretion.

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CHAPTER II

REVIEW OF LITERATURE

ENERGY EVALUATION

Energy value of feedstuffs may be expressed in a variety of ways as illustrated in Figure 1. Gross or combustible energy is certainly the simplest most straight forward measure, however from a nutritional perspective, gross energy offers little meaningful information relative to a feedstuffs energy value. Gross energy minus the energy from the combustion of the feces yields digestible energy, which with the use of indigestible tracers, is also easily quantified in mammals. In avian species however, digestible energy is difficult to attain as feces and urine are excreted together via the cloaca. Conversely, because birds excrete feces and urine simultaneously, quantification of metabolizable energy (gross energy minus the energy excreted as feces and urine) is simplified. Overall, net energy offers the most accurate assessment of dietary energy available to an animal, as calories lost as heat due to maintenance of basal metabolism, activity, and production (i.e., tissue and eggs) are accounted.

Though net energy fully accounts for energetic inefficiencies, a net energy system is difficult to establish. The difficulty lies not only with the experimental facilities and equipment (i.e., calorimetric chambers) required for net energy determination, but also with the practical application given the numerous factors that influence heat production such as tissue type synthesized (MacLeod, 1997), ambient temperature (Beker, 1996), as

well as rearing condition effects on broiler activity (Jensen, 1962; Ohtani and Leeson, 2000; McKinney and Teeter, 2004). As a consequence of these obstacles, and the fact that metabolizable energy can be rapidly and precisely determined (Sibbald, 1976; McNab and Blair, 1988) and adjusted to account for nitrogen excretion (8.22 kcal/g nitrogen retained; Hill and Anderson, 1958) and endogenous losses, metabolizable energy remains the standard measure for evaluating energy available for maintenance and production for poultry.

BROILER MANANGEMENT

Flock managers face making broiler husbandry decisions daily. Decisions that ultimately impact growth and the efficiency of feed utilization for maintenance and production. For example, feed processing techniques such as pelleting have been touted for beneficial effects on poultry performance (Acar et al., 1991; Scheideler, 1995; Moritz et al., 2001). Likewise numerous managerial – husbandry decisions related to stocking density (Cravener et al., 1992; Puron et al., 1997), lighting program (Buyse et al., 1996; Ingram et al., 2000), and ventilation (Lott et al., 1998) are well known to impact BW and feed conversion ratio (FCR). Though the precise mode of action by which such nonnutritive factors impact poultry performance is considered disjoint from nutrition in application, their use is critical to successful poultry production. However, since growth rate and FCR are also related to nutrition, the traditional approach of separating nonnutritive factors that impact average daily gain and FCR from nutrition must be questioned.

PELLETING AS A NONNUTRITIVE INFLUENCING BROILER PERFORMANCE

A general definition of the pelleting process is “the agglomeration of small particles into larger particles by the means of a mechanical process in combination with moisture, heat, and pressure” (Falk, 1985). Pelleting was introduced to the united states in the 1930’s and today virtually all broiler and turkey feeds undergo this process. In addition to growth performance benefits obtained by feeding pellets, pelleting improves feed handling characteristics (i.e. dustiness and flowability) and reduces the incidence of pathogenic organisms (Fairfield, 1994). However, the most commonly touted advantages to pelleting is the growth and feed efficiency improvements realized (Acar et al., 1991; Scheideler, 1995; Moritz et al., 2001).

There has been much debate as to the mode of action by which broilers benefit from pelleting. Initially, it was thought that via steam conditioning and extrusion of the feed through the pellet die, the integrity of the starch granules and proteins were disrupted in a manner that improved diet digestibility (Behnke, 1996). This may indeed be an accurate conclusion with respect to swine (Hancock and Behnke, 2001). However with poultry, the majority of evidence does not support any pelleting effects on protein or energy digestion (Husser and Roblble 1962; Bolton, 1960; Sibbald, 1977).

It was work reported by Jensen (1962) that brought forth the notion that pelleting enhances bird performance by reducing energy expenditure for prehension thereby yielding more energy available for tissue accretion. In this study (Jensen, 1962) birds were provided either mash or pellets and then observed for time spent feeding, number of times the feeder was visited, and feed disappearance. It was reported that birds fed mash

spent approximately 14.3% of a 12 hour day eating verses 4.7% observed for birds fed pellets.

In accepting the premise that pelleting enhances bird performance by reducing activity energy expenditure, emphasis must be given to pellet quality. Indeed, obtaining feeds where zero pellet breakage occurs is practically unattainable. However several factors determine the amount of pellet breakage that takes place (Figure 2). Within the feed mill, diet formulation, particle size of the mash, conditioning time and temperature, pellet die thickness, and cooling and drying time, contribute to pellet quality (Behnke, 1996). The proportion of intact pellets presented to the bird further depends on feed delivery systems on the trucks and within the broiler house (Scheideler, 1995).

Paramount among nutritional goals is the reasonable balance between dietary provision of nutrients and energy. However, numerous nonnutritive factors, such as those related to feed processing and general husbandry that modify broiler behavior (Skinner-Noble, 2005), are generally not considered as variables directly influencing the desired ration formula. This failure to account for variations in calories lost or spared due to broiler activity modification eventually has the net result of creating an uncertain ratio of ingested energy available for tissue accretion to dietary protein and other nutrients.

PELLETING AND DIETARY LYSINE REQUIREMENT

In practical corn-soybean meal based broiler diets, methionine is considered first limiting followed by lysine, arginine, valine, and threonine (Han et al., 1992). However, lysine is the amino acid to which all others are proportionally related (Baker and Han, 1994; Baker, 1997). This is because lysine has no major precursor role and has been the

subject of extensive evaluation under a wide range of dietary and environmental circumstances (Han and Baker, 1993; Emmert and Baker, 1997). Furthermore, lysine is generally expressed in ratio with dietary caloric density, as dietary energy largely regulates voluntary consumption (Leeson et al., 1996; McKinney and Teeter, 2004). By expressing dietary nutrients on a digestible basis, and in proportion to one another, nutritionists are better able to adjust nutrient specification in the face of changing nutritional needs (i.e., climate, sex) or feedstuff source, while maintaining an "ideal" balance of dietary amino acids and energy.

As lysine is viewed as a pivotal amino acid in broiler rations, recent work has focused on evaluating whether lysine need is influenced by pelleting (Greenwood et al., 2004a, 2004b). The basis for this stems from a report compiled by Jensen (1965), in which diets of sub-optimal lysine and protein levels were fed either as mash or pellets to broad breasted bronze turkeys. It was concluded that pelleting exacerbated the lysine deficiency because pelleting enhanced the productive energy of the diet (Reddy et al., 1962), thereby resulting in an energy-lysine imbalance.

This was re-evaluated by Greenwood et al. (2004) in an experiment of factorial design, where dietary lysine (0.85, 0.95, and 1.05%), caloric density (3,050 and 3,200 kcal ME/kg diet), and feed form (mash verses pellets) were fed to broilers. Greenwood et al. (2004) reported significantly higher body weight gain in broilers fed pellets and the highest level of protein. It was concluded that pelleting provides more energy for weight gain (via reduced activity energy expenditure) thus increasing the need for lysine to support tissue accretion.

Interestingly, feeding the low energy (3,050 kcal ME/kg diet) diet as pellets compared with the higher energy (3,200 kcal ME/kg diet) diet, fed as mash, resulted in similar growth performance. One could surmise from this that birds do not differentiate between energy spared from reduced activity and energy provided in the diet. If this is the case, activity energy expenditure should be considered in establishing nutrient:energy ratios.

DUAL ENERGY X-RAY ABSORPTIOMETRY AS A METHOD FOR RAPIDLY DETERMINING BODY COMPOSITION IN POULTRY

Numerous methods exist for estimating the body composition of animals used in nutritional studies (Hendrick, 1983; Topel and Kauffman, 1988). Historically though, body composition assessment of poultry has been most often achieved by comparative slaughter. This method is time consuming, difficult to apply to an entire growth curve, and requires bird destruction as well as the assumption that the composition of birds initially examined is the same as those incorporated into an experiment (Blaxter, 1967).

Advancements in dual energy x-ray absorptiometry (DEXA) have resulted in the availability of instruments that utilize a slit collimator coupled with multidetector array (fan beam x-ray pattern; Koo et al., 2004). This decreases the time required to complete a scan, as compared with the pencil beam type instruments, without yielding accuracy or precision (Koo et al., 2004).

This has sparked interest in the use of DEXA technology as a non-invasive method for assessing body compositional responses to nutritional regimes in animals reared for consumption. Dual energy x-ray absorptiometry assesses body composition via algorithems that differentiate between the absorption of high (70 keV) and low (38 keV) energy x-rays (Mitchell et al., 1997; Kelly, 2004). By relating this measure with x-ray

absorptive characteristics of pure tissues (Mitchell et al., 1997), fat and lean tissue mass can be estimated. An example of information attained from scan analysis is shown in Figure 3.

A large body of data exists validating DEXA for accurately measuring soft tissues (lean and fat tissues) and bone mineral content in swine (Lukashi et al., 1999; Chauhan et al., 2003; and Koo et al., 2004), as piglets are use extensively as a model for human infant studies (Fiorotto et al., 1986). However, little evidence is available verifying its use for poultry.

Chauhan et al. (2003) and Koo et al. (2004) reported DEXA as a method for accurately measuring bone mineral content and density in layers. However, an experiment conducted by Mitchell et al. (1997) is the only known evaluation of DEXA for quantifying lean and lipid tissues in poultry. They found the technology to fall short of accurately assessing bird lean and lipid content, but did suggest that the technique may be applicable with software and or hardware modifications. If DEXA technology is to be accepted as a method for estimating body composition in poultry research, more work is need proving its accuracy and precision.

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Table 1. Reported estimates for efficiencies of metabolizable energy use for protein (k_p) and fat (k_f) tissue accretion

Reference	k_p	k_f	Species
Kielanowski, 1965	0.70	0.79	Pigs
Puller and Webster, 1977	0.45	0.74	Rats
Boekholt et al., 1994	0.66	0.86	Poultry
van Milgen and Noblet, 1999	0.51	0.92	Swine
Sakomura, 2004	0.45	0.69	Poultry

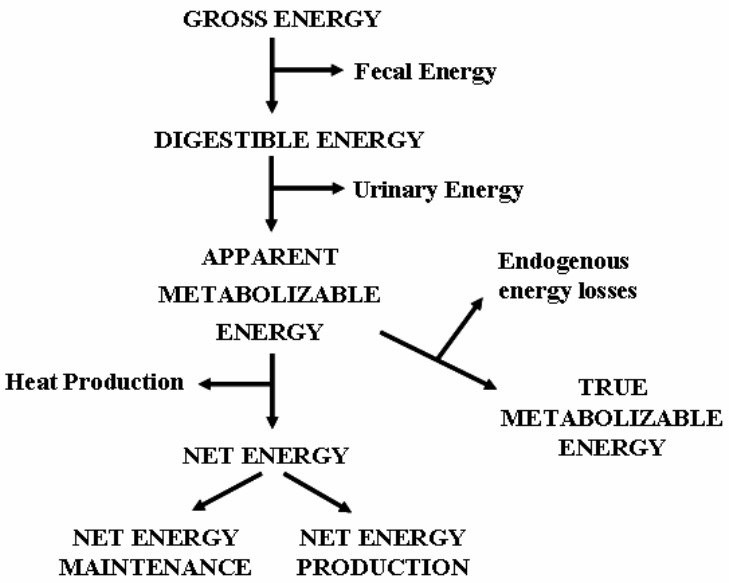


Figure 1. Schematic of energy evaluation systems (adapted form Leeson and Summers, 2001)

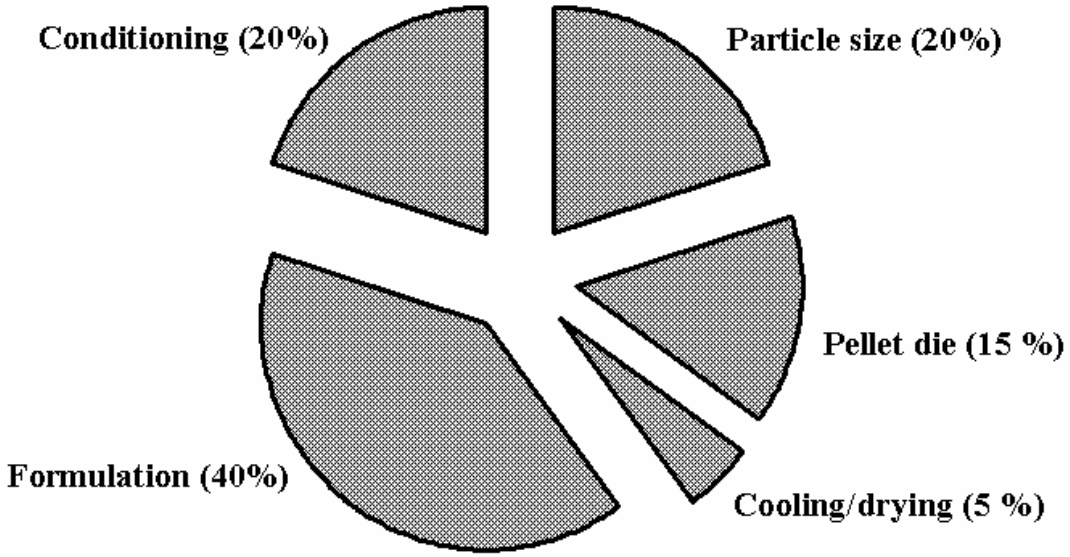
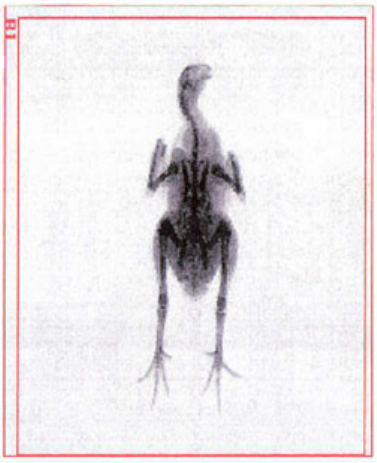


Figure 2. Factors affecting pellet durability (adapted from Behnke, 1996)



DXA Results Summary:

Region	Area (cm^2)	BMC (g)	BMD (g/cm^2)	
GLOBAL	334.56	56.20	0.168	
RI	334.56	56.20	0.168	
NETAVG	334.56	56.20	0.168	
	Fat (g)	**Lean+BMC (g)**	**Total Mass (g)**	**% Fat**
GLOBAL	325.3	2614.8	2940.1	11.1
RI	325.0	2615.1	2940.1	11.1
NETAVG	325.3	2614.8	2940.1	11.1

TBAR1073

Figure 3. Dual energy x-ray absorptiometry scan image and results of a chicken.

CHAPTER III

Refinement of Novel Estimations of Poultry Body Composition and Evaluation Dual Energy X-Ray Absorptiometry as a Method for Rapid Broiler Body Composition Assessment

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RUNNING TITLE: Body composition of poultry by DEXA

Abbreviation Key: DEXA = dual energy x-ray absorptiometry, BMC = bone mineral content, CNB = carbon and nitrogen balance

ABSTRACT

Two experiments were conducted to validate and or refine methodologies for quantifying body composition in poultry. In the first experiment, constants classically used to derive body composition in C and N balance studies were evaluated for application in poultry. In Experiment 2, the efficacy of using dual energy x-ray absorptiometry (DEXA) to rapidly assess body composition in poultry was examined. In Experiment 1, broilers ranging in body weight from 1,660 to 2,240 g were sacrificed, and used for either measuring whole bird composition or determining the composition of the protein and lipid fractions. In Experiment 2, broilers ranging in body weight from 280 to 3,075 g were sacrificed, and DEXA measurements of lean, fat, and bone mineral content were obtained. The birds were then chemically assayed to determine protein, lipid, and ash for comparison. Results from Experiment 1 demonstrate that though poultry protein and lipid tissue do not greatly differ in composition compared to other species, the differences may significantly impact the assessment of body composition, and should therefore be considered as a source of error in C and N balance studies using poultry. Results from Experiment 2 demonstrate that DEXA measurements failed to accurately quantify the body composition of poultry when direct comparisons are made. Instead, DEXA measurements must be applied to regression equations that inter-relate DEXA measurements with compositions obtained by chemical analysis.

(*Key words:* carbon nitrogen balance, dual energy x-ray absorptometry, body composition, poultry)

INTRODUCTION

The principle goal of poultry producers is to consistently meet consumer demand for product taste and nutritional acceptability in a profitable manner. Accomplishing this requires that the end product be defined and that the criteria for success be centered on obtaining that defined product, and not entirely on live performance characteristics. As demonstrated by McKinney and Teeter (2004), body weight and FCR improvements obtained by increasing dietary caloric density did not in all cases equate into increased lean mass but rather greater amounts of carcass fat. Assuming fat to be at some level a waste product undesirable to the consumer, production decisions based solely on body weight and FCR are potentially misguided. Therefore, nutritional, environmental, and managerial decision consequences on body composition must be quantified.

Though numerous methods exist for estimating the body composition of animals used in nutritional studies (Hendrick, 1983; Topel and Kauffman, 1988), comparative slaughter has historically been the method applied in experiments with poultry. This methodology, however, is time consuming, difficult to apply to an entire growth curve, requires bird destruction, and the assumption that the composition of birds initially examined is the same as those incorporated into an experiment (Blaxter, 1967). However, according to work presented by Wolynetz and Sibbald (1987), the initial slaughter group may not be necessary for comparison purposes, which would result in a considerable reduction in the required resources.

Measures of C, N, and energy content of the feed and excreta, and CO_2 production have also been used for assessing body composition in poultry (Farrel, 1974). Advantages of using C and N balance (CNB) as compared to comparative slaughter are

measurements of the same animal can be repeated over time, as animal sacrifice is not required, and that the importance of initial body composition uniformity is negated (Blaxter, 1967). As outlined by Farrel (1974), there are assumptions associated with CNB: 1) that energy is retained only in the form of fat and protein tissue; 2) the composition of fat and protein are constant; and 3) poultry protein and lipid tissue are not significantly different in composition compared to other species.

Regarding the latter assumption, one would not expect sizable tissue compositional differences to exist between species. However, as CNB is already susceptible to analytical errors (Blaxter, 1967), examination of this assumption is warranted. Additionally, estimates for fat and protein tissue constituents are dated (Armsby, 1903; Blaxter and Rook, 1953; and Brouwer, 1965).

Advancements in dual energy x-ray absorptiometry (DEXA) have resulted in the availability of fan beam technology, which enables faster scan acquisition (Koo et al., 2004). This has sparked interest in the use of DEXA technology as a non-invasive method for assessing body composition in experiments with animals reared for consumption. A large body of data exists validating DEXA for accurately measuring soft tissues (lean and fat tissues) and bone mineral content in swine (Lukashi et al., 1999; Chauhan et al., 2003; and Koo et al., 2004) as piglets are used extensively as models for human infant studies (Fiorotto et al., 1986). However, little evidence is available verifying DEXA use for poultry.

An experiment conducted by Mitchell et al. (1997) is the only known evaluation of DEXA for quantifying lean and lipid tissues in poultry. They found the technology to fall short of accurately assessing bird lean and lipid content, but did suggest that the

technique may be applicable with software and or hardware modifications. However, this conclusion was based on results of simple linear regression analysis. Perhaps more sophisticated statistical models are needed.

Therefore, two experiments were conducted with the first directed at validating and/or refining estimations of protein and fat constituents with specificity to poultry. In the second experiment, DEXA was evaluated for accuracy and precision in quantifying soft tissue (lean and fat tissue) and bone mineral content (BMC) in poultry.

MATERIALS AND METHODS

Experiment 1 – Validation and or refinement of constants for poultry tissue constituents

Twenty-four broilers ranging in body weight from 1,660 to 2,240 g were obtained commercially, fasted (24 h), and euthanized by carbon dioxide asphyxiation. After autoclaving (20 h; 11 psi; 116 °C), the birds were equilibrated to ambient temperature. Each bird was then homogenized (including feathers) with a commercial grade blender and samples of each homogenate were obtained and frozen (20°C) until analysis. Twelve of the samples were randomly selected and partitioned by ether extraction into protein and lipid factions for analysis of DM, N, ash, (AOAC, 1990) and C (Harjo, 1994). The remaining homogenates of the whole bird were analyzed for DM, ash, ether extract C and N (AOAC, 1990). These samples were used to evaluate whether whole bird ether extract could be accurately estimated using the compositions of the protein and lipid fractions determined from the first 12 samples analyzed. Equations used were as follows:

(Eq. 1) TP = N x (1 / % N in P)

(Eq. 2) PC = TP x % C in P

(Eq. 3) LC = TC – PC

(Eq. 4) EE = LC / % C in L

where: TP = total protein (g), P = pure protein (g), PC = carbon as protein (g), TC = total carbon (g), L = pure lipid (g), LC = carbon as lipid (g), and EE = estimated whole bird ether extract (%).

Experiment 2 – Evaluation of DEXA for measuring body composition in poultry

All scans were obtained using a fan beam dual energy x-ray absorptiometer operated in the infant whole body mode. Rat-scan software was used for scan analysis. A total of 35 broilers ranging in body weight from 280 to 3,075 g were obtained commercially, and fasted and euthanized as described in Experiment 1. Previous work in this laboratory (unpublished) and that of Lukaski et al. (1999) demonstrated that animal positioning on the scanning surface does not impact scan results. However, for consistency all birds were scanned individually (5 times) in a prostrate position with the long axis of the bird perpendicular to the length of the table. After scanning the birds were immediately autoclaved and sampled for chemical analysis as previously described.

Data Analysis

In both experiments, bird served as the experimental unit. Regression analysis was used initially to compare DEXA measurements of body composition with those obtained by proximate analysis. Subsequently the effectiveness of these developed regression models in relating DEXA results with measures obtained through proximate analysis were evaluated using General Linear Models of SAS (2000).

RESULTS AND DISCUSSION

Experiment 1 – Validation and or refinement of constants for poultry tissue constituents

The C and N content of protein and lipid determined herein (Tables 1) were in close agreement with those values traditionally accepted (Armsby, 1903, Blaxter and Rook, 1953 and Brouwer, 1965) and utilized in assessing body composition through CNB techniques. For example, nitrogen as a percent of protein averaged 15.9 ± 0.06%, essentially matching that which is generally applied (16.0%) across numerous protein sources. Carbon as a proportion of protein and lipid was determined as 52.96 ± 0.14 and 74.0 ± 1.4%, respectively. The latter of which exhibited the most variability across samples measured and averaged slightly lower than the other constants evaluated (Table 2). Nonetheless, values determined herein for the C and N contents of protein and lipid resulted in the best overall estimation of whole bird ether extract when applied to equations 1 through 4 (Table 2). In comparison, estimates obtained with protein and lipid C and protein N estimates of Armsby (1903) and Blaxter and Rook (1953) resulted in roughly an 8% overestimation of whole bird ether extract (Table 2; Figure 1). Using constants proposed by Brower (1965), whole bird ether extract estimates were still inflated, but only slightly (approximately 2%). As it was successfully demonstrated that whole bird ether extract could be accurately computed from the composition of protein and lipid determined from independent samples, this approach was accepted as a means for estimating whole bird ether extract. Therefore, procedures were modified for Experiment 2 in that ether extract was estimated by determined C and N constants rather than AOAC (1990) methods. However, for simplification, ether extract estimated in this manner may be referred to as fat determined by proximate analysis.

Experiment 2 – Evaluation of DEXA for measuring body composition in poultry

An example of a DEXA scan and the information that appears in the scan report is shown in Figure 2. Note that lean tissue is not further subdivided in the report into its protein and water constituents. Thus, in order to directly compare DEXA measurements from the report with values obtained from proximate analysis, actual bird water content must be determined. To estimate this, the difference between the body weight of the bird and the sum of its protein, lipid, and ash (dry matter basis) were determined. Bird protein and fat were then regressed on the estimated bird water content. As indicated by the lack of a significance coefficient (Table 3), zero bird water content was associated with the lipid parameter. This was expected as the water in adipose tissue is predominantly associated with its vasculature and connective tissues (Pitts et al., 1971; Digirolamo and Owens, 1976). As a result, direct comparisons could be made between DEXA measures of lean, and the protein determined by chemical analysis plus the estimated bird water content (Figure 3). However, this was done only to illustrate direct relationships. Bird water content and protein were not coupled when developing regression models.

On the basis of simple linear regression, DEXA failed to accurately measure lipid and ash as determined by proximate analysis (Table 4), which agrees with conclusions reached by Mitchell et al. (1997). Error associated with BMC as it relates to ash are most likely a consequence of the hollow bone structure of poultry, as programming software was developed for mammals (Kelly, 2004). Additionally, BMC was not determined per se, rather the ash content of the whole body was measured. This potentially explains the consistent under-estimation of DEXA measure of ash.

In an attempt to correct for these errors, forward stepwise regression procedures (Neter, 1990) were used to develop more complex predictive models (Table 4), incorporating more parameters and their cross-products. Indeed, with these equations, the accuracy in which DEXA measurements could be inter-related with chemically determined values increased markedly. This was demonstrated through comparisons between DEXA measurements adjusted using these regression equations (αDEXA) and those obtained through chemical analysis (Table 5). No significant ($P > 0.05$) differences were detected between predicted (αDEXA) and determined values for any of the variables monitored. Additionally, the sum of αDEXA estimates of protein, lipid, water, and ash closely matched the body weights of the birds when they were initially scanned.

An inherent limitation of the proposed predictive models is the fact that the body weights of birds used in the experiment did to completely encompass the entire growth curve, depending on the end product desired (i.e., Cornish hen verses birds reared for breast meat). As such, using these equations to estimate the body composition of birds weighing more than 3,000 grams requires extrapolating beyond the models inference base, which with polynomial equations particularly, leads to erroneous estimations of the dependent variable.

This limitation of the models was clearly observed in an effort to quantify broiler body compositions using DEXA in a study designed to compare broiler rearing conditions typically found in different parts of the world. As part of this study, broilers were selected to represent body weights of approximately 500, 1,500, 2,500, and 3,500 grams. Application of the predictive equations to DEXA measurements appeared to work well (based on body weight accountability: the sum of the predicted body components vs.

gravimetric weight) in every case except for birds outside the inference base of the models. For birds weighing more the 3,000 grams, the predicted protein and lipid (as a % of body weight) was greatly underestimated. Concomitantly, predicted water content was largely exaggerated. As drastic changes of this manner were viewed as physiologically infeasible, the only logical explanation was that the models were failing in this zone of body weights.

In pending data to expand the inference base of the models, equations were modified by first fitting, for each body composition measure, trend lines to data that fell within the scope of the original equations (Figure 5). In assuming that these trend lines represent mid-points or bird population means, αDEXA estimates for protein, lipid, water, and ash were assigned to each trend line. Subsequently, DEXA measures were regressed on these mid-points to modify the equations so as to encompass the entire growth curve (Table 6). Note, however, that variability among birds is attenuated with these modified equations and thus would only be of use when describing a population as was the case here (Figure 6).

In conclusion, research reported herein has demonstrated that though poultry protein and lipid tissue may not appear to differ significantly in composition compared to other species, these differences significantly impact the assessment of body composition and should therefore be considered as a source of error in C and N balance studies with poultry. Furthermore, DEXA technology can be used to rapidly assess body composition in poultry, however, not directly. For this technology to be of value, regression equations inter-relating DEXA measurements of BMC, and lean and lipid tissue, with PA determined protein, ether extract, ash, and water content are required.

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Table 1. Carbon and nitrogen concentrations in the whole carcass and protein and lipid factions of broilers

	Sample number													
Faction[1], %	1	2	3	4	5	6	7	8	9	10	11	12	Mean	SEM
Total														
Carbon	61.0	58.8	61.1	60.6	61.2	58.5	58.5	59.2	60.1	59.3	57.0	57.5	59.4	0.41
Nitrogen	10.9	12.4	11.0	10.8	9.6	10.2	10.3	10.0	9.6	9.9	10.0	11.3	10.5	0.24
Protein														
Carbon	52.9	53.4	52.9	52.5	53.6	52.6	52.2	53.6	52.5	53.5	52.7	53.3	52.9	0.14
Nitrogen	15.5	15.9	15.9	15.7	16.0	15.7	15.6	16.3	16.0	15.9	15.9	15.8	15.9	0.06
Ether Extract[2]														
Carbon	80.0	79.9	79.5	78.9	74.3	70.6	71.6	69.9	72.9	71.0	65.3	68.9	74.0	1.4

[1]Dried, ash-free basis.
[2]Nitrogen averaged 0.2 percent.

Table 2. Ether extract predicted from protein and lipid tissue carbon and nitrogen concentrations

Reference	Tissue	Carbon (%)	Nitrogen (%)	Predicted ether extract[1] (%)	Predicted ether extract error[2] (%)
Armbsy, 1903	Protein	52.5	16.7		
	Lipid	76.5	–	24.7	8.62[a]
Blaxter and Rook, 1953	Protein	51.2	16.0		
	Lipid	74.8	–	24.5	7.94[a]
Brouwer, 1965	Protein	52.0	16.0		
	Lipid	76.7	–	23.3	2.19[b]
Present experiment	Protein	52.9	15.9		
	Lipid	74.0	–	22.8	0.01[b]

[a,b]Means within a column with different superscripts differ ($P < 0.05$).

[1]Calculated as: total carbon – (protein x protein carbon) / lipid carbon).

[1]Ether extract (EE) determined by proximate analysis (AOAC, 1990) was 22.8 percent.

[2]Calculated as: ((EE determined by proximate analysis – EE predicted) / EE determined by proximate analysis) x 100.

Table 3. Regression equation of water content (W) on protein (P) and lipid (L) in whole bird carcasses (W = a + b P + c L)

Parameter	Coefficient	Standard error	Probability
a	78.23313	18.45308	0.0002
b	3.41462	0.20961	< 0.0001
c	-0.00639	0.21166	0.9761

Table 4. Regression equation coefficients relating dual energy x-ray absorptiometry (DEXA) measurements with proximate analysis values

	DEXA variables							
Dependent variable	Intercept	Lean	Lipid	Lean^2	Lipid^2	Lean x Lipid	Lean^2 x Lipid^2	R^2, %
Protein[1], g	-8.90481^{+}	0.21571**						96.91
	-11.13536**	0.18779**	0.15961**					99.42
	-15.14152**	0.19686**	0.15655**	-2.99e^{-6}				99.43
	-15.15759**	0.2024**	0.11615**	-4.0e^{-6*}	4.494e^{-5*}			99.44
	-15.14395**	0.20176**	0.12014**	3.5e^{-6}	4.909e^{-5+}	4.07e^{-6}		99.44
	-10.9351^{**4}	0.2019**	-7.42e^{-3}	7.0e^{-6*}	1.5831e^{-4**}	9.223e^{-5**}	-4.4712e^{-11**}	99.49
Lipid[2], g	Intercept	Lipid	Lean	Lipid^2	Lean^2	Lean x Lipid	Lean^2 x Lipid^2	
	102.47233**	0.60302**						58.54
	-44.29583**	0.21388**	0.17341**					96.27
	-39.60899**	0.07553	0.18212**	1.5789e^{-4}				96.42
	-12.03683	0.14717**	0.11281**	1.0157e^{-4+}	2.184e^{-5**}			96.75
	-11.97534	0.16515**	0.10993**	1.2025e^{-4+}	2.409e^{-5**}	1.835e^{-5}		96.76
	-4.94566[4]	-0.04790	0.11017**	3.0268e^{-4**}	1.825e^{-5**}	1.4249e^{-4*}	-7.4679e^{-11**}	96.88
Ash[3], g	Intercept	BMC	Lean	Lipid	Lean x BMC	Lipid x BMC	Lean x Lipid	
	7.2132**	1.29866**						82.64
	-0.46329	0.42645**	0.02246*					99.02
	-0.24389	0.30121**	0.02344**	7.24^{-3*}				99.05
	-1.59568**	0.383**	0.02479**	7.61e^{-3**}	-5.672e^{-5**}			99.10
	-2.17225**	0.43985**	0.02713**	8.57e^{-3}	-1.2359e^{-4**}	3.0354e^{-4**}		99.15
	-1.64751^{**4}	0.16682^{+}	0.02813**	0.01159	-5.8e^{-6}	5.1384e^{-4**}	1.634e^{-5**}	99.20
Water[3], g	Intercept	Lean	Lipid	Lean^2	Lipid^2	Lean x Lipid	Lean^2 x Lipid^2	
	41.99924**	0.73998**						97.06
	34.0781**	0.64084**	0.5668**					99.76
	18.63859*	0.6758**	0.55503**	-1.153e^{-5**}				99.76
	18.65469*	0.67025**	0.5955**	-1.052e^{-5*}	-4.501e^{-5}			99.76
	18.66013*	0.66999**	0.5971**	-1.032e^{-5+}	-4.3366e^{-5}	-1.62e^{-6}		99.76
	8.33059[4]	0.66965**	0.91016**	-1.76e^{-6}	-3.1142e^{-4**}	-2.3796e^{-4**}	1.09734e^{-11**}	99.79

[1]Calculated as: nitrogen × 6.29.
[2]Calculated as: ((EE determined by proximate analysis – EE predicted) / EE determined by proximate analysis) x 100.
[3]Determined using AOAC (1990) procedures.
[2]Equation used to adjust DEXA measurements to proximate analysis data.
$^{+}$Significant ($P < 0.1$).
* Significant ($P < 0.05$).
** Significant ($P < .01$).

Table 5. Comparison of adjusted dual energy x-ray absorptiometry (αDEXA) and proximate analysis measurements of total broiler protein, fat, ash, water, and body weight[1,2,3]

	Total body constituents, g									
	Protein		Fat		Ash		Water		Body Weight	
Weight class	PA[4]	αDEXA	PA[5]	αDEXA	PA[6]	αDEXA	PA[6]	αDEXA	Scale	αDEXA
A	56	59	30	33	9	9	245	241	341	343
B	191	195	134	135	29	30	769	767	1,231	1,227
C	414	411	334	337	60	59	1,468	1,476	2,289	2,283
D	517	515	453	458	74	74	1,841	1,840	2,902	2,886

	Probability				
Source of variation	Protein	Fat	Ash	Water	Body Weight
Weight class	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
Method	NS	NS	NS	NS	NS
Weight class x method	NS	NS	NS	NS	NS
Pooled SEM[7]	0.14	0.17	0.14	0.13	0.14

[1] Adjusted using regression equations relating DEXA measurements with proximate analysis results.
[2]Log transformations of the data were performed for statistical analysis.
[3]Reported values are the anti-log of the resultant least square means.
[4]Calculated as: nitrogen × 6.29 based on Experiment 1 results.
[5]Calculated as: ((EE determined by proximate analysis – EE predicted) / EE determined by proximate analysis) x 100.
[6]Determined using AOAC (1990) procedures.
[7]Based on analysis of log transformed data.

Table 6. Proposed equation coefficients relating dual energy x-ray absorptiometry (DEXA) measurements with proximate analysis values for broilers weighing more than 3000 grams

	DEXA variables									
Dependent variable[1]	Intercept	BMC	Lipid	Lean	Lipid^2	Lean^2	Lean x Lipid	Fat x BMC	Lean x BMC	Lean^2 x Lipid^2
Protein	-6.13349*	–	0.1119*	0.18308*	3.567e^{-5}*	3.7e^{-6}*	4.728e^{-5}*	–	–	-1.252e^{-11}*
Lipid	-5.6813*	–	0.03129*	0.10041*	6.536e^{-5}*	2.336e^{-5}*	9.6e^{-5}*	–	–	-1.2042e^{-11}*
Water	5.79504*	–	0.76994*	0.68501*	-3.797e^{-5}*	-1.373e^{-5}*	-1.5077e^{-4}*	–	–	2.43437e-11*
Ash	-1.6675*	0.01579	0.02434*	0.02658*	–	–	1.44e^{-6}	-2.54e^{-6}	-3.95e^{-6}*	–

[1]Determined by trend-line analysis of adjusted dual energy x-ray absorptiometry measurements (αDEXA).
*Significant ($P < 0.05$).

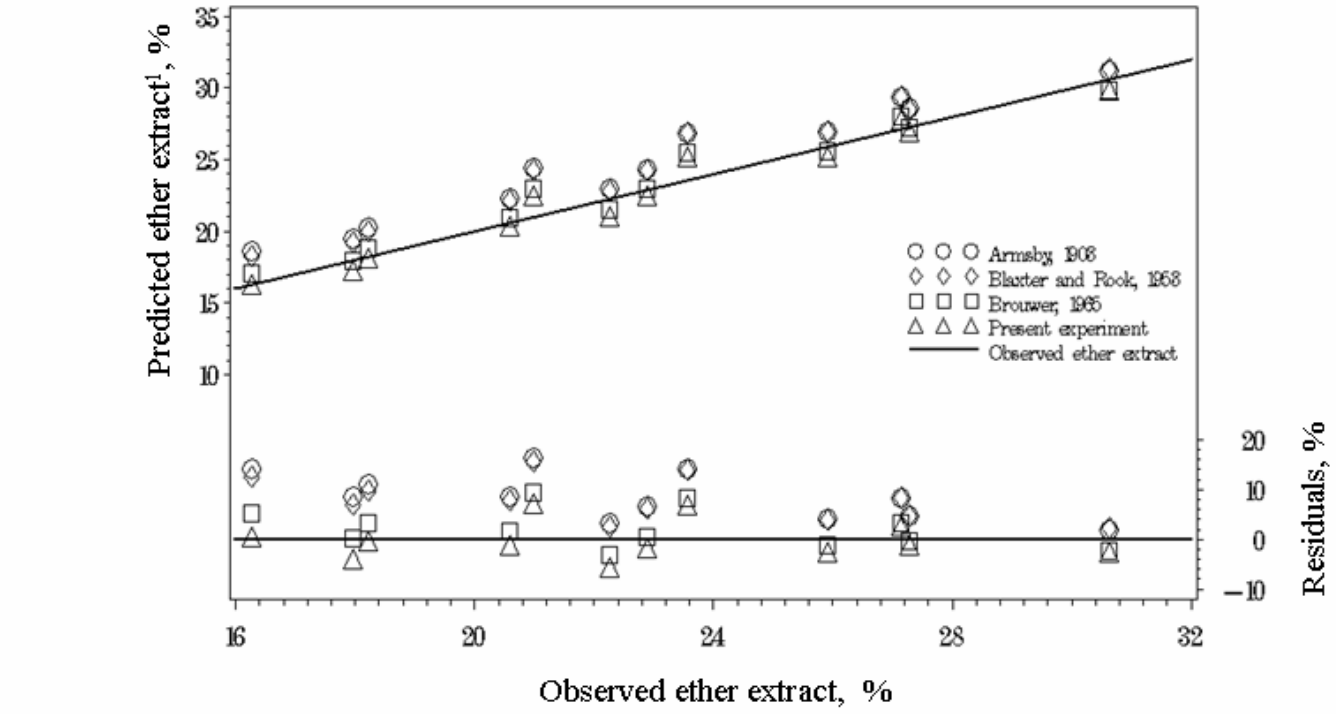
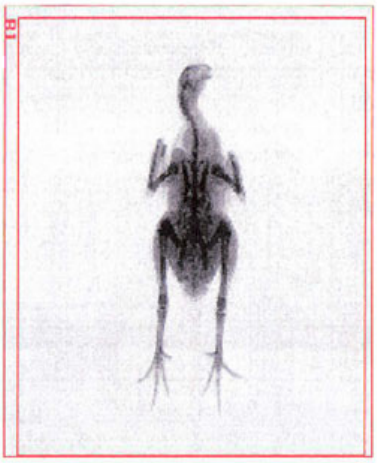


Figure 1. Ether extract estimated using proposed carbon and nitrogen contents of protein and lipid and the corresponding residual errors

[1]Calculated as: TC – (TP – C in P) / C in F, where: TC = total whole bird carbon, TP = total whole bird protein, P = protein, F = fat, and C = carbon.



DXA Results Summary:

Region	Area (cm^2)	BMC (g)	BMD (g/cm^2)	
GLOBAL	334.56	56.20	0.168	
RI	334.56	56.20	0.168	
NETAVG	334.56	56.20	0.168	
	Fat (g)	**Lean+BMC (g)**	**Total Mass (g)**	**% Fat**
GLOBAL	325.3	2614.8	2940.1	11.1
RI	325.0	2615.1	2940.1	11.1
NETAVG	325.3	2614.8	2940.1	11.1

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Figure 2. Dual energy x-ray absorptiometry scan image and results of a chicken.

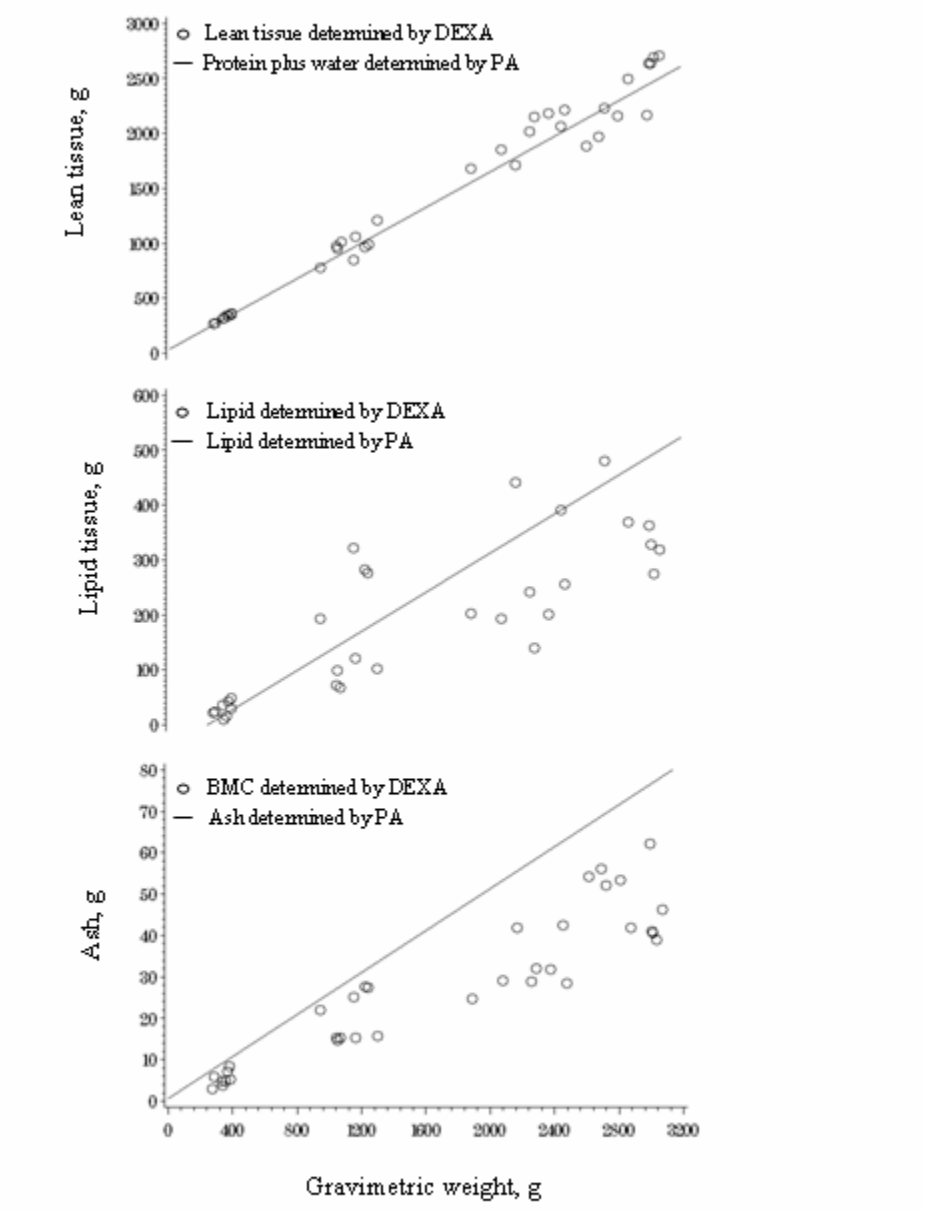

Figure 4. Relationship between body composition measured by dual energy x-ray absorptiometry (DEXA) and proximate analysis (PA)

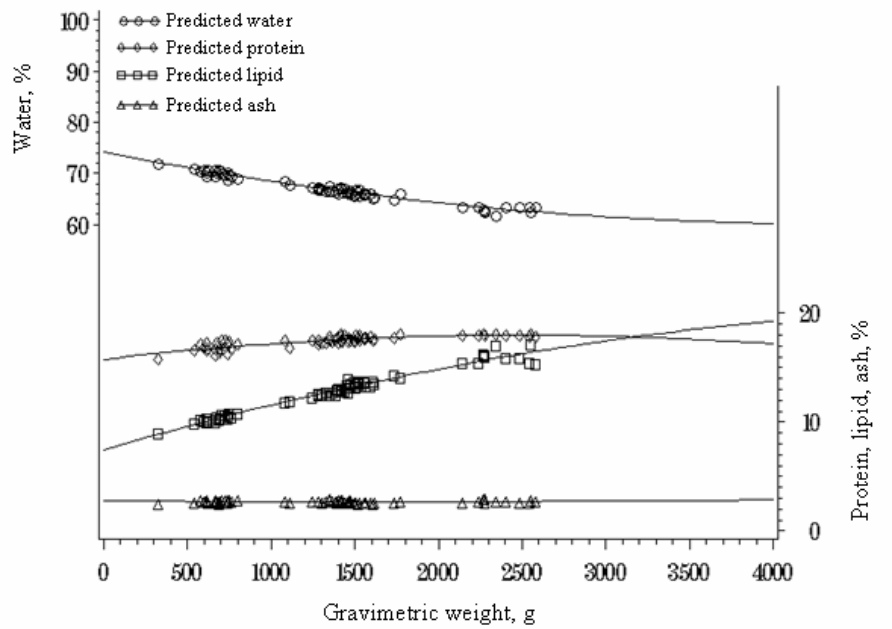

Figure 5. Independent application of regression equations that relate dual energy x-ray absorptiometry measurements to proximate analysis results and trend-line analysis to expand the applicable body weight range

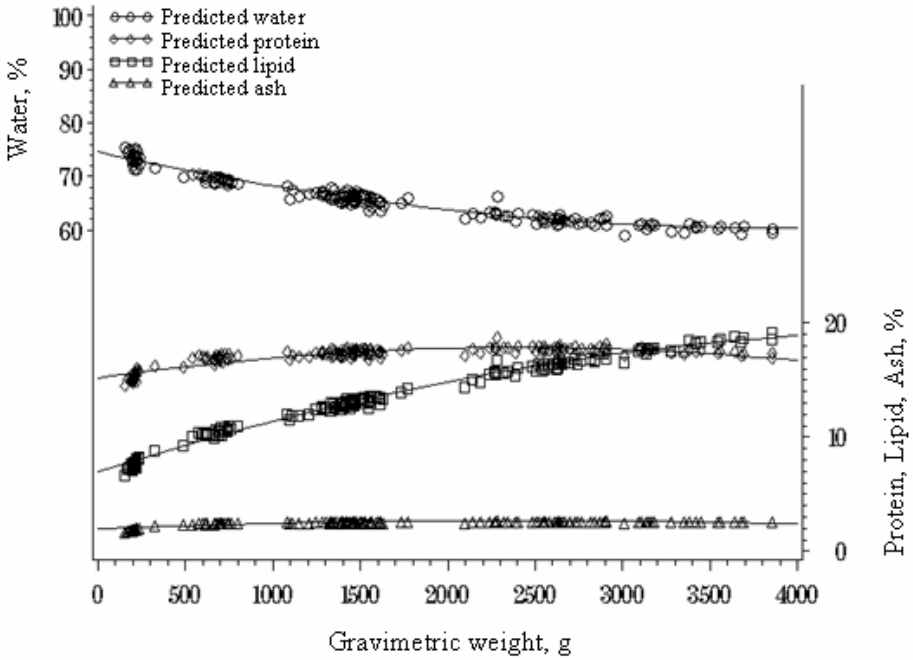

Figure 6. Broiler water, protein, lipid, and ash predicted from regression equations that relate DEXA measurements with proximate analysis results

CHAPTER IV

Predicting Effective Caloric Value of Nonnutritive Factors: I. Pellet Quality and II. Prediction of Consequential Formulation Dead Zones

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RUNNING TITLE: Caloric Value of Pelleting

Abbreviation Key: CD=caloric density; CFCR=cumulative feed conversion ratio; DFCR=daily feed conversion ratio; ECV=effective caloric value; FCR=feed conversion ratio; M=mash; PQ=pellet quality

ABSTRACT

Two experiments were conducted with male broilers to establish a methodology for predicting effective caloric value (ECV), defined as dietary caloric density (CD) necessary for broilers to achieve specific body weight (BW) and feed conversion ratio (FCR) combinations under standardized conditions, and to quantify the ECV attributable to pellet quality (PQ), defined as the pellet to pellet fines ratio in the feeder. In Experiment 1, chicks were reared to 56 d on diets varying in CD. Dietary caloric densities examined ranged from 2,650 to 3,250 kcal ME_n/kg. Pen BW, feed intake, and FCR were measured at 21, 42, and 56 d. On 42 and 56 d, carcass traits were measured. Increasing CD significantly enhanced BW, energy consumption, and FCR. Feed intake remained similar across the upper three CD treatments to 42 days. By day 56, feed consumption tended to decline as CD increased. Increasing CD beyond 3,066 kcal ME_n/kg diet did not increase lean tissue accretion, while fat deposition rose disproportionately. Experiment 1 results enabled creation of equations whereby CD, hence ECV, might be predicted using BW and FCR. In Experiment 2, 38-d old broilers were used to evaluate PQ effects on growth, feed intake, FCR, and behavior in a 7-d FCR assay. The BW gain and FCR were significantly enhanced by pelleting and were positively correlated with PQ. Feed intake was not affected by PQ. The Experiment 1 model was validated for Experiment 2, as it closely estimated the CD for diets of similar PQ used in Experiment 1. Results suggest pelleting contributes 187 kcal ECV to the diet at 100% PQ and that the ECV declines curvilinearly as PQ falls. Birds were observed eating less and resting more as PQ increased, suggesting that ECV of pelleting is mediated by energy expenditure for activity. These studies provide a method for

estimating ECV of nonnutritive factors that impact BW and/or FCR. Further, application reveals potential for creation of formulation "dead zones" whereby dietary changes to enhance CD may be offset due to reduced ECV.
(Key words: Pelleting, energy, behavior, effective caloric value, broiler performance)

INTRODUCTION

Numerous nonnutritive factors, such as those related to feed processing and general husbandry, are well documented throughout the literature to impact bird performance. For example, feed processing techniques such as pelleting have been touted for beneficial effects on poultry performance (Acar et al., 1991; Scheideler, 1995; Moritz et al., 2001). Likewise numerous managerial – husbandry decisions related to stocking density (Cravener et al., 1992; Puron et al., 1997), lighting program (Buyse et al., 1996; Ingram et al., 2000), and ventilation (Lott et al., 1998) are well known to impact BW and FCR. Though the precise mode of action by which such nonnutritive factors impact poultry performance is considered disjoint from nutrition in application, their use is critical to successful poultry production. However, since growth rate and FCR are also related to nutrition, the traditional approach of separating nonnutritive factors that impact average daily gain and FCR from nutrition must be questioned.

Bird energy retention is the net result of energy inputs minus expenditures as excreta and heat. The importance of excreta energy to retention is reduced when inputs are measured as ME_n. Though the basic precept of ration formulation programs is that ME_n values are generally independent of, for example, bird sex and age, its utilization for retention is reduced when heat production is elevated. Bird heat production is influenced

by a myriad of factors including ration composition and tissue type synthesized (MacLeod, 1997), intermittent lighting (Ohtani and Leeson, 2000), and activity among others. Indeed, energy expenditure for activity has been suggested to be influenced by nonnutritive factors as feed processing (Jensen et al, 1962) and lighting (Ohtani and Leeson, 2000). Failure to account for variations in heat production, regardless of source, eventually has the net result of creating an uncertain ratio of ingested ME_n calories available for tissue accretion to dietary protein and other nutrients. The amount of dietary ME_n available to promote BW and FCR is hereby defined as the effective caloric value (ECV) of ME_n. Under fixed experimental conditions, where nonnutritive factors impacting heat production are held constant, varying the calorie to protein ratio impacts BW and FCR (Sizemore and Siegel, 1993; Leeson et al., 1996; MacLeod, 1997). One might conversely anticipate that experimental variation of nonnutritive factors, with ration formulation held constant and BW and/or FCR changing, would be better expressed as a variant of ME_n that more closely represents feeding value as ability to achieve a specified BW and FCR.

The improved BW and FCR performance associated with processed feeds is an example of a nonnutritive factor impacting the ECV of the diet fed. Such results are presumably attributable to either enhanced feed value and/or a reduced nutrient need by the animal, whereby the net result is more efficient tissue accretion. Regarding this latter point, previous reports examining pelleting effects on energy digestibility indicate that either pelleting does not impact nutrient bioavailabililty (Bolton, 1960; Sibbald, 1977) or that the positive impact response upon nutrient bioavailabililty (Hussar and Robblee, 1962) is relatively small compared to bird response. Processing may also alter nutrient

need of the bird by reducing energy expenditure associated with feed consumption (Jensen et al., 1962). Though the true value of processing may be due to a combination of variables, methodology is desirable whereby the ECV of such nonnutritive alterations may be estimated and taken advantage of in other segments of the production cycle.

Nonnutritive factors encountered in the production enterprise, that are well known to impact BW and/or FCR, are generally not considered as variables (with exception of season and feed cost) directly influencing desired ration formula. This approach, however, is presumably attributable to a lack of methodology enabling value quantification. Nonetheless, the majority of poultry rations utilized today undergo some type of post-mixing processing, and production manuals (Cobb Vantress, 2003) contain many managerial-husbandry recommendations that impact BW and FCR in a manner that "takes away" or "adds to" consumed energy value. Methodology is needed to place caloric values on such relationships so that diets may be appropriately adjusted. Short of a net energy system development, this methodology should enable the general accounting of nonnutritive factor influence upon the ECV of ME_n under standardized conditions. Therefore, studies were conducted to develop a generalized growth and FCR relationship with dietary ME_n under standardized conditions and, further, to apply the methodology to examine the benefits and/or consequence of varying pellet quality as a nonnutritive variable.

MATERIALS AND METHODS

General

Two studies were conducted, with the first directed at establishing mathematical relationships between dietary caloric density, expressed as ME_n, with broiler growth and

FCR under fixed managerial conditions. This enabled the prediction of ME_n (expressed as ECV), from bird BW and FCR combinations as ECV. In the second study, the approach was used to estimate the ECV of diets with varying feed forms. Both studies utilized Cobb 500 male broilers that were obtained at hatching from a commercial hatchery. Floor pens utilized were equipped with two cylinder-shaped gravity feeders, nipple drinkers, and used litter (wood shavings) that was top-dressed with fresh litter. Stocking density in the floor pens was 40 birds per pen providing 0.03 m^3 of floor space per bird. Cages used for Experiment 2 were elevated (1.2 m) and constructed of plastic-coated-wire (46 x 60 x 60 cm). Birds were housed individually, and each cage was equipped with a stainless steel feeder and a nipple drinker. Unless stated, dietary nutrient concentrations met or exceeded those levels recommended by the National Research Council (1994), and feed and water were provided for ad libitum consumption.

Definition of Energy-Growth Relationships (Experiment 1)

Experiment 1 was designed to develop mathematical models describing relationships among CD, BW, and FCR of broilers. Additionally, dietary CD influences on carcass weight, dry matter, specific gravity, and composition were examined. One-day-old broilers (1,440 total) were allotted to 36 floors pens (40 birds/pen), which were sectioned into 9 blocks (based upon location within the floor pen house) of 4 pens per block. Experimental diets (Table 1) were formulated to 4 CD within each of the starter (0-21 d), grower (21-42 d), and finisher phases (42-56 d) while protein concentrations were adjusted maintaining a constant calorie:protein ratio across diets within feeding phases. Starter diets were fed as mash, while grower and finisher diets were pelleted.

The dietary CD (ME_n, kcal/kg diet) examined are presented in Table 1. Treatments were randomly assigned to pens within block, and pen BW, feed consumption, and FCR (g feed/g gain corrected for mortality by adding the BW of dead birds) were measured at 21, 42, and 56 d of age. Following 42 and 56 d of age, two and three birds, respectively, from each pen were randomly selected to determine dressing percentage, carcass specific gravity, abdominal fat weight, and breast weight (Belay and Teeter, 1994). Carcass specific gravity and dry matter results were then applied to predictive equations proposed by Wiernusz et al. (1999) to estimated carcass fat, protein, and ash.

Evaluation of pellet quality influences (Experiment 2)

Experiment 2 was conducted to independently test Experiment 1 methodology for ability to predict CD and to quantify PQ (defined as the ratio of pellets to pellet fines in the feeder) effects on growth, feed consumption, FCR, ECV, and activity of broilers. Broilers were reared to 31 days of age in floor pens on standard starter and grower diets, fed as mash (Skinner-Noble et al., 2002). On day 31, 192 broilers were transferred to cages and for 7-d adapted to cages and pellet treatments to be tested (Jensen et al., 1962). Subsequently, feeders were emptied and fresh treatments added. The WG gain, feed consumption, and FCR were measured from 38 to 45 days of age. Treatments were derived from a pelleted diet (Table 2) that was screened (0.3 cm sieve). Ration samples were collected for protein (N × 6.25) and carbon analysis. For each feeder, resultant pellet fines were re-blended with the pellets to form the designated pellet:fines ratio. Treatments were: 100) 100% pellets; 80) 80% pellets:20% pellet fines; 60) 60% pellets:40% pellet fines; 40) 40% pellets:60% pellet fines; and 20) 20% pellets:80%

pellet fines. Unprocessed mash (M) was included as a treatment to serve as a negative control representing unprocessed feeds. During the experiment, scan sample behavior observations (Skinner-Noble et al., 2001; 2003) were conducted so as to quantify PQ effects on ingestive and resting behaviors. Birds were observed at 1000 and 1400 h on 3 different days of the 7 d FCR test. During these observations, the observer passed by each cage 10 times within 45 minutes. At the conclusion of the experiment, all remaining feed in each feeder was sieved and the actual consumption of pellets and pellet fines were estimated by difference such that any potential preferential consumption of pellets or pellet fines could be identified. The experiment 1 model was used to transform the second study BW and FCR responses, attributable to PQ, into ECV.

Data Analyses

For the studies, pen (Experiment1) and cage (Experiment 2) served as the experimental unit. Data were analyzed using General Linear Models of SAS (2000), with probability values of $P < 0.05$ considered significant. Actual *P*-values are noted and not considered significant if $0.05 < P < 0.10$. When a significant F-statistic was detected, least square means were used for treatment comparisons. Experiment 1 was designed and analyzed as a randomized complete block with pen location within house serving as the blocking factor. Multiple regression coefficients for predicting dietary CD (Experiment 1) were as follows: first, BW and feed consumption were regressed upon bird age to enable prediction of these values for each day of the study; second, daily weight gain and feed consumption were computed as the difference between day_x and day_{x+1}; third, daily FCR was computed; fourth, bird daily performance values (BW, FCR) were regressed upon CD. The resulting regression equations predicted CD from BW and FCR. Model

selection was based on forward stepwise regression (Neter et al., 1990). Factors were added to the regression model until three conditions were met: 1) adding factors to the model did not result in a substantial (R^2 improvement < 2 %) increase in the model R^2; 2) all factors in the model were significant at $P \leq 0.10$; and 3) the resulting model matched known properties of the independent variables (e.g., BW increases cubically, whereas FCR increases quadratically). Experiment 2 was designed and analyzed as a completely randomized experimental design. Experiment 1 equation predicting CD from BW and FCR was applied to PQ data in order that the ECV attributable to PQ might be estimated for each replicate. Treatment means were separated as described for Experiment 1.

RESULTS AND DISCUSSION

Experiment 1. Definition of Energy-Growth Relationships

The CD effects on body weight, feed and energy consumption, and FCR (total feed/BW) are shown in Table 3. Results of CD effects on carcass traits are presented in Table 4. Each CD increase resulted in greater ($P < 0.02$) 21 and 42-d BW. Though increasing CD continued to result in greater 56-d BW, only the upper (Treatments C and D) and lower (Treatment A and B) pairs of CD treatments differed ($P < 0.05$). Increasing the CD of the diet also resulted in prominent FCR differences ($P < 0.001$). At both 42 and 56 days of age, FCR was reduced with each CD increase. Feed consumption remained similar across Treatments B, C, and D through 42 days of age. At that point, only birds fed the lowest CD responded by increasing ($P < 0.01$) feed intake. By day 56, feed consumption for birds fed Treatment B did not differ ($P < 0.06$) from Treatment A birds. Also, there was a prevalent feed intake decline as diet CD increased. This

response supports the dogma that birds eat to fulfill energy need (Rice and Botsford, 1956; Moreng and Avens, 1985). However, such a governing effect was less notable at higher CD, as energy consumption increased quadratically ($P < 0.001$) with CD. Birds fed Treatment C consumed similar total energy (0-56 d) compared to birds fed Treatments A ($P < 0.07$) and B ($P < 0.07$). Moreover, birds fed the diet with 3,250 kcal ME_n / kg diet (Treatment D) had similar ($P < 0.09$) energy intakes as birds fed Treatment C.

Indeed, increasing CD positively influenced both BW and FCR. However, attention must also be given to the final sellable product. Assuming that fat is a product of minimal value compared to lean tissue, increasing CD would only be of benefit if lean mass also increased. Such was true as CD increased from 2,700 to 3,066 kcal ME_n / kg diet. Feeding Treatment C resulted in greater ($P < 0.01$) carcass weights, dressing percentages, breast mass, and carcass protein, compared to the lowest CD treatment, with intermediate responses observed for Treatment B. Though abdominal fat appeared to increase with CD, carcass fat was similar for Treatments A, B, and C. Fate of energy consumed shifted, however, when CD exceeded 3,066 kcal ME_n/kg, providing additional energy failed to result in greater breast percent, breast mass, or carcass protein. At that point, lean tissue accretion plateaued. Conversely, feeding the diet with 3,250 kcal ME_n/kg diet resulted in disproportionate increases of abdominal fat and carcass lipid. The observed plateau of lean tissue accretion as CD increased suggests that if adequate nutrients are available to the bird, maximal lean tissue accretion is genetically predetermined. Nonetheless, increasing CD resulted in heavier more efficient birds even though gains for the highest CD were principally fat. The data indicate that providing

energy in excess to that required for lean tissue accretion will improve FCR, but does so without elevation in sellable lean mass. Consequently, the improved FCR presumably occurs as a dilution of maintenance energy needs in proportion to energy consumption and not water content associated with lean accretion.

The negative impact of increasing BW on FCR was apparent and presumably the result of increasing energy need for maintenance and lipid deposition as BW increases. Therefore, the influence of CD on FCR is not disjoint from BW. Hence, BW and CD were collectively used in modeling FCR. Resulting regression equations are presented in Table 5. Linear, quadratic, and interactive combinations of BW and FCR were regressed on CD to create equations enabling CD prediction. The best equations utilized interactive BW and FCR components. The selected regression equations demonstrating the interrelationships among CD, BW, and FCR are illustrated as 3-dimensional plots (Figures 1 and 2). In Figure 1, FCR is expressed cumulatively (CFCR) based on predicted cumulative feed consumption and BW relationships throughout the experiment. The second approach (Figure 2) created a more dynamic model by expressing BW and CD values in relation to FCR utilizing predicted daily feed intake / predicted daily BW gain (DFCR). Though both approaches have acceptable R^2 (0.88 to 0.98), it is anticipated that equations based upon daily values will more accurately estimate CD values in settings where only segments of the growth curve are utilized, as in Experiment 2. For that reason, values obtained from DFCR values will be used hereafter.

Experiment 2. Evaluation of pellet quality influences

Results will be discussed first as PQ effects on broiler feed consumption, BW gain, and FCR (feed intake / weight gain; Table 6). Secondly, results will be discussed as

PQ caloric consequences on ECV (Table 7, Figure 3) as modeled from Experiment 1, and PQ effects on broiler behavior (Table 6, Figure 3).

Neither pelleting nor PQ significantly impacted feed consumption (Table 6; $P = 0.5$). There was a numerical elevation in feed intake for birds that were fed pelleted treatments, compared to M, which agrees with other studies (Choi et al., 1986; Nir and Hillel, 1995). Though feed consumption did not appear to be associated with PQ, birds did selectively consume pellets over pellet fines in some treatments. For example, birds offered a combination of 80% pellets and 20% pellet fines consumed (on average) 87% pellets and 13% pellet fines. This preferential consumption of pellets over pellet fines was dependent upon the ratio of pellets to pellet fines in the feeder. As the proportion of pellet fines increased and pellets decreased, either the preference for pellets or the ability to select pellets diminished and was not present for birds fed 20 % pellets. At that point, birds consumed the pellet:fines ratio provided.

When pellet treatments (from 20 to 80% pellets) were pooled and compared with M, pelleting increased ($P < 0.01$) BW gain 6% and improved ($P < 0.05$) FCR by 5%. The birds that received 100% pellets were excluded from the comparison so as to avoid inflating pelleting effects with a practically unattainable PQ. Other comparisons made between pellets and M have resulted in similar BW gain and FCR (Choi et al., 1986; Nir and Hillel, 1995; Plavnik et al., 1997) improvements.

The treatments significantly influenced weight gain ($P < 0.001$) and FCR ($P < 0.01$; Table 6). Responses to PQ appeared to be biphasic with an intermediate plateau in the 40 to 60% PQ range (Figure 3). This finding suggests there is little need to improve PQ above 40%, unless it will also be in excess of 60%. Keep in mind, however, that

birds will selectively consume pellets if possible. As a consequence, the proportion of pellets and pellet fines consumed could vary markedly from bird to bird. At the onset of the experiment the question posed was, at what pellet quality (if any) are growth performance benefits of pelleting lost? In other words, if a certain pellet quality is not achieved, is there any bird related advantage of pelleting as compared to feeding mash? Statistically, these data indicate that at 40% PQ and above, pelleting results in enhanced BW gain ($P < 0.05$) and FCR ($P < 0.07$), compared to a diet fed as M.

From Experiment 1, using CFCR in the model resulted in an equation better predicting diet CD (Table 5; $P < 0.0001$; $R^2 = 0.98$) compared to DFCR values ($P < 0.0001$; $R^2 = 0.88$). However, Experiment 2 was conducted for a relatively short interval of the latter stages of the growth curve. As such, using CFCR would dilute PQ effects. Therefore, daily values (DFCR) were used to increase the precision of estimating ECV for PQ. Across all Experiment 1 diets, the proportion of pellets to pellet fines in the feeder averaged 50 %. This average value was used to test the CD predictive equation derived from Experiment 1 for applicability in Experiment 2. This test involved predicting the CD of the average of the 40 and 60% PQ diets from Experiment 2 to simulate the 50 ± 10% PQ of Experiment 1 diets. The model predicted 3,225 kcal ME_n / kg diet, which exactly matched the calculated energy concentration of the diet (3,225 kcal ME_n). Consequently, the CD predictive equation was accepted as a methodology for estimating the ECV associated with PQ in Experiment 2 because of this confirmation from independent experiments. As such, Experiment 2 BW and DFCR were transformed into CD and then examined as deviations from the M so as to produce an estimate of the kcal ME_n /kg added to the M via pelleting.

The ECV of pelleting and pellet quality are displayed in Figure 3. As PQ increased, the apparent ECV of the diet became greater. Energy sparing attributable to pelleting peaked at 187 kcal ME_n/kg feed consumed for the 100% PQ treatment. The estimated energy sparing values diminish as the proportion of pellets to fines decreases, but still appears greater than zero for the 20% pellets (76 kcal ME_n / kg diet; Table 7). Considering proposed modes of action suggests that as pellet quality increases, either the bird expends less energy for consumption or the bioavailabililty of nutrients and/or energy increases. Regarding this latter point, previous reports examining pelleting effects on energy digestibility indicate that pelleting does not impact nutrient bioavailabililty (Bolton, 1960; Hussar and Robblee, 1962; Sibbald, 1977). In support of pelleted feeds modulating bird energy expenditure, Jensen et al. (1962) observed that birds provided pellets as compared to mash visited the feeder less frequently and spent less time at the feeder, while consuming similar amounts of feed. Behavior observations of the current study (Table 6, Figure 3) concur. As the proportion of pellets in the feeder increased, birds were observed eating less frequently ($P < 0.001$) and resting more ($P < 0.001$) frequently. Interestingly, plotting bird resting frequency and calories attributable to PQ on the same graph resulted in curves of very similar shapes. Given that feed intake did not differ across treatments, and that as pellet quality increased birds spent less time eating, the concept that BW gain and FCR differences are associated with altered nutrient need via decreased energy expenditure for obtaining food is supported. A consequence of reducing energy costs associated with the activity of feed consumption by pelleting or increasing PQ would allow the diverting of calories to tissue accretion (Jensen et al., 1962; Reddy et al., 1962). Credence for this proposed mechanism is the supporting

evidence that the M and pellet rations were similar for carbon (P = 0.50) and nitrogen content (P = 0.30) suggesting that treatment differences, attributable to blending, would indeed be due to feed form.

Final quality of the processed feed is the result of numerous factors influencing the feed form actually presented to the bird for consumption. With pelleted feeds, it is the percentage of intact pellets at the feeder and not the feed mill that determines processing efficacy. Fundamentally, pellet integrity is affected by diet formulation, plant operation, and feed handling during transport and delivery (Behnke, 1996). Of these, diet formulation is paramount. The ingredients used and their inclusion levels markedly influence the overall pellet integrity of the final product (Richardson and Day, 1976; Briggs et al., 1999). As such, interactions between ration composition and pellet quality may have counteractive effects with respect to bird performance. Though increasing dietary fat positively impacts feed efficiency (Leeson et al., 1996), when fat is added prior to pelleting it also reduces pellet quality (Richardson and Day, 1976, Behnke, 1996, Briggs et al., 1999).

Producers may face the expense of increasing CD by fat supplementation only to have it partially negated by feed form deterioration prior to bird consumption. Under circumstances where low quality fats are utilized, fat addition could eliminate the ECV. Formulation “dead zones”, whereby the addition of fat does not result in the addition of calories due to pellet quality degradation is possible. To ascertain the net caloric value (energy attributable to fat inclusion minus energy lost due to pellet degradation) of fat fortified-pelleted diets, both the caloric gain attributable to fat supplementation and the ECV (Table 8) of altered pellet quality must be considered.

Ideally, decisions regarding diet formula for broiler production settings would be interactive with the numerous managerial decisions impacting the nutrient and energy input/output balance. As noted from the studies reported herein, elevating CD enhances energy intake, bird accretion and FCR. However, the CD response does not necessarily improve lean tissue production. Though FCR improved with CD, it can do so via elevated lipid accretion independently of lean tissue. Consequently, the desired carcass composition should be first defined and birds fed to that outcome, rather than FCR. Similar to CD changes, nonnutritive factor manipulations such as alteration in PQ, impact BW gain and FCR. The data suggests that the PQ differences on bird performance are strongly related to a reduced bird activity with results approaching an ECV of 187 kcal ME_n/ kg diet. As a consequence, formula alterations should be coupled with their impact on PQ so that the ECV value is optimized. Indeed, the impact of such factors may occur independently of caloric value, measured as ME_n, and their "takes away" or "adds to" impact on activity energy expenditures divergently impact BW and/or FCR. Application of the ECV equations provided estimates for the nonnutritive variable impact examined herein. In conclusion, ECV offers the opportunity to place quantitative energy value upon non-nutritive factors influencing broiler production efficiency.

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Table 1. Composition of diets used in Experiment 1

	Phase[1]											
	Starter				Grower				Finisher			
Ingredient, %	A	B	C	D	A	B	C	D	A	B	C	D
Corn	46.03	57.22	62.10	54.23	50.38	61.96	69.82	63.32	51.16	62.73	74.50	68.40
Soybean meal	18.00	25.10	31.23	34.17	11.20	15.03	24.31	27.17	6.92	13.33	19.72	22.47
Meat & bone meal	2.64	2.64	2.64	3.40	2.64	2.64	2.64	3.40	2.69	2.69	2.69	3.47
Wheat middlings	30.68	12.38	–	–	33.42	17.94	–	–	37.26	19.28	1.11	–
Fat[2]	–	–	1.35	5.65	–	–	–	4.95	–	–	–	3.90
Dicalcium phosphate	1.20	1.20	1.20	1.05	0.80	0.90	1.05	0.85	0.50	0.76	0.86	0.70
Limestone	0.65	0.65	0.65	0.65	0.80	0.80	0.68	0.60	0.90	0.69	0.62	0.55
NaCl	0.33	0.38	0.38	0.38	0.28	0.30	0.30	0.30	0.20	0.22	0.24	0.24
Choline chloride	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
DL-methionine	0.16	0.16	0.18	0.20	0.14	0.13	0.14	0.16	0.13	0.11	0.11	0.13
Lysine-HCL	0.04	–	–	–	0.09	0.05	0.01	–	0.10	0.05	0.01	–
Vitamin premix[3]	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Trace mineral premix[4]	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
$CuSO_4$	0.03	0.03	0.03	0.03	0.02	0.02	0.03	0.03	–	–	–	–
Coccidiostat	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	–	–	–	–
Calculated Analysis												
ME_n (kcal / kg)	2,650	2,833	3,016	3,200	2,700	2,883	3,066	3,250	2,700	2,883	3,066	3,250
CP, %	18.98	20.24	21.54	22.66	16.61	17.71	18.89	20.00	15.30	16.30	17.30	18.30
Lys	0.97	1.07	1.19	1.28	0.83	0.83	1.01	1.08	0.74	0.81	0.88	0.96
Met	0.45	0.47	0.51	0.54	0.40	0.40	0.44	0.47	0.37	0.37	0.39	0.42
TSAA	0.82	0.85	0.90	0.94	0.74	0.73	0.79	0.83	0.69	0.69	0.72	0.76
Calorie:CP	140	140	140	141	163	163	162	163	176	177	177	178
Ca	0.85	0.85	0.85	0.91	0.81	0.82	0.82	0.83	0.78	0.76	0.75	0.78
P, available	0.39	0.36	0.34	0.31	0.31	0.30	0.30	0.27	0.26	0.28	0.27	0.23

[1]Starter phase: 0 to 21 days of age; grower phase: 21 to 42 days of age; finisher phase: 42 to 56 days of age.

[2]Animal-vegetable blend

[3]Supplied per kilogram of diet: vitamin A, 10,141 IU (retinyl acetate); cholecalciferol, 3,086 IU; vitamin E, 23.92 IU (dl-α-tocopheryl acetate); menadione, 2.87 mg; thiamine, 2.20 mg; riboflavin, 7.72 mg; niacin, 60.30 mg; d-pantothenic acid, 12.46 mg; pyridoxine, 3.75 mg; vitamin B_{12}, 0.017 mg; folic acid, 1.066 mg; d-biotin, 0.127 mg.

[4]Supplied per kilogram of diet: Ca,160 mg; Zn, 100 mg; Mn, 120 mg; Fe,75 mg; Cu, 10 mg; I, 2.5 mg.

Table 2. Composition of diet used in Experiment 2

Ingredient	%
Corn	62.00
Soybean meal (48% CP)	22.27
Wheat	6.10
Wheat middlings	1.01
Fat[1]	4.54
Dicalcium phosphate	1.63
Limestone	1.72
NaCL	0.23
DL-methionine	0.21
Lysine-HCL	0.07
Vitamin premix[2]	0.05
Trace mineral premix[3]	0.05
Choline chloride	0.04
$CuSO_4$	0.03
Selenium premix	0.0025
Coccidiostat	0.05
Calculated analysis	
ME, kcal/kg	3,225
CP, %	17.6
Lys	0.93
Met	0.48
TSAA	0.80
Calorie:protein	183
Ca	1.02
P, available	0.41

[1]Animal-vegetable blend

[2]Supplied per kg diet: vitamin A, 14,109 IU (retinyl acetate); cholicalciferol, 5,291 IU; vitamin E, 47.6 IU (dl-α-tocopheryl acetate); vitamin B_{12}, .014 mg; riboflavin, 8.82 mg; niacin 26.5 mg; d-pantothenic acid, 28.2 mg; choline, 705.5 mg; menadione, 1.16 mg; folic acid, 1.176 mg; pyridoxine, 3.52 mg; thiamin, 3.52 mg; d-biotin, 0.176 mg.

[3]Supplied per kilogram of diet: Ca, 160 mg; Zn, 100 mg; Mn, 120 mg; Fe, 75 mg; Cu, 10 mg; I, 2.5 mg.

Table 3. Body weight, feed and energy consumption, and feed conversion ratio by dietary treatment, Experiment 1

	Treatment[1]				Pooled
Variable	A	B	C	D	SE
Body weight, g					
(Age, days)					
1	40	40	40	40	–
21	548[d]	621[c]	682[b]	728[a]	4.52
42	1,972[d]	2,122[c]	2,285[b]	2,361[a]	10.28
56	3,010[b]	3,061[b]	3,205[a]	3,230[a]	18.30
Total feed consumption, g					
0-21	980[a]	883[b]	873[b]	905[b]	7.75
0-42	4,140[a]	3,921[b]	3,877[b]	3,878[b]	22.52
0-56	7,468[a]	7,002[b]	6,854[b]	6,705[b]	51.92
Total energy consumption, kcal					
0-21	2596[cd]	2502[d]	2634[bc]	2895[a]	22.09
0-42	11,128[c]	11,259[c]	11,843[b]	12,560[a]	65.27
0-56	20,116[b]	20,142[b]	20,972[ab]	21,748[a]	156.28
Feed conversion ratio[2]					
0-21	1.79[a]	1.42[b]	1.28[c]	1.24[c]	0.01
0-42	2.10[a]	1.85[b]	1.67[c]	1.64[d]	0.01
0-56	2.48[a]	2.29[b]	2.14[c]	2.01[d]	0.01

[a-d]Means within a row with different superscripts differ ($P < 0.05$).

[1]Treatments, ME_n, kcal/kg: starter phase: A = 2,650; B = 2,833; C = 3,016; D = 3,200; grower and finisher phases: A = 2,700; B = 2,883; C = 3,066; D = 3,250.

[2]Calculated as: Total feed consumption / body weight

Table 4. Carcass composition by dietary treatment, Experiment 1

Variable	Treatment[1] A	B	C	D	Pooled SE
Carcass weight, g					
(Age, d)					
42	1,336[c]	1,443[b]	1,547[a]	1,594[a]	15.50
56	2,199[b]	2,250[b]	2,500[a]	2,445[a]	24.71
Dressing percentage					
42	71.98	71.06	71.62	70.45	0.59
56	74.30[c]	75.86[bc]	78.91[a]	78.13[ab]	0.46
Dry matter, %					
42	35.86[b]	36.12[ab]	35.48[b]	36.65[a]	0.13
56	34.91	34.99	34.09	34.93	0.26
Specific gravity[2]					
42	1.048	1.047	1.045	1.046	0.001
56	1.043	1.044	1.043	1.039	0.001
Breast, g					
42	255.33[c]	285.5[b]	326.11[a]	314.59[a]	4.07
56	418.35[b]	460.57[ab]	503.69[a]	482.21[a]	8.86
Abdominal fat, g					
42	30.51[b]	27.35[b]	30.98[b]	36.43[a]	0.80
56	53.48[b]	54.50[ab]	65.59[a]	61.72[ab]	2.04
Carcass protein, g[3]					
42	236.38[c]	254.73[b]	272.41[a]	278.84[a]	2.80
56	394.66[b]	405.32[b]	450.29[a]	433.64[a]	4.48
Carcass fat, g[3]					
42	192.23[c]	211.16[bc]	219.95[b]	244.22[a]	3.38
56	297.74[b]	303.04[ab]	320.07[ab]	340.37[a]	6.68
Carcass ash, g[3]					
42	17.79[c]	19.40[bc]	19.69[b]	21.63[a]	0.30
56	25.67	26.75	27.52	27.28	0.55

[a-d]Means within a row with different superscripts differ ($P < 0.05$).

[1]Treatments, ME_n, kcal/kg: starter phase: A = 2,650; B = 2,833; C = 3,016; D = 3,200; grower and finisher phases: A = 2,700; B = 2,883; C = 3,066; D = 3,250.

[2] Specific gravity = carcass wt. in air/(carcass wt. in air - (carcass wt. in water x 0.10)).

[3]Calculated based on predictive equations proposed by Wiernusz et al., 1999

Table 5. Regression equation coefficients relating body weight (BW) and feed conversion ratio (FCR) and caloric density, expressed both as cumulative and daily values

Cumulative Equations

Intercept	BW	BW^2	BW^3	FCR	FCR^2	FCR^3	BW*FCR	BW^2*FCR^2	R^2 (%)
2,903	0.04+	-	-	-	-	-	-	-	1.82
3,656	-	-	-	-398.03**	-	-	-	-	31.82
4,040	0.24**	-	-	-865.11**	-	-	-	-	82.25
4,451	0.01	-	-	-1,112.79**	-	-	0.13**	-	84.09
5,032	0.02	6.6×10^{-5}**	-	-1,800.17**	248.83**	-	-	-	87.78
7,085	0.86**	1.8×10^{-4}**	-	-4,985.84**	1,472.84**	-	-0.69**	-	92.79
7,018	1.38**	-9.0×10^{-5}+	5.25×10^{-8}**	-5,201**	1,566.93**	-	-0.76	-	93.91
17,014	1.63**	-4.3×10^{-5}	4.66×10^{-8}**	-22,031**	10,689**	-1,581.30**	-0.96	-	97.72
15,919	1.43**	-6.95×10^{-5}*	6.32×10^{-8}**	-19,848**	9,296**	-1,302.72**	-0.77**	-1.71×10^{-5}*	97.82

Daily Equations

Intercept	BW	BW^2	BW^3	FCR	FCR^2	FCR^3	BW*FCR	BW^2*FCR^2	R^2 (%)
2,903	0.04+	-	-	-	-	-	-	-	1.82
3,014	-	-	-	-21.75	-	-	-	-	0.81
3,085	0.26**	-	-	-240.88**	-	-	-	-	22.74
4,771	-0.19**	-	-	-1,291.96**	-	-	-0.33**	-	77.79
4,825	0.05	1.6×10^{-4}**		-1,523.77**	164.76**	-	-	-	84.14
4,778	0.17**	2.7×10^{-4}**		-1,581.26**	256.59**	-	-0.22**	-	85.19
4,180[1]	1.17**	-3.0×10^{-4}**	1.36×10^{-7}**	-1,408.90**	272.21**	-	-0.37**	-	88.34
4,665	1.46**	-0.003**	1.43×10^{-7}**	-2,214.92**	641.57**	-29.58+	-0.59**	-	88.59
4,774	1.59**	-3.8×10^{-4}**	1.82×10^{-7}**	-2,395.09**	672.28**	-20.96	-0.57**	7.06×10^{-6}	88.69

+ $P < 0.10$

*$P < 0.05$

**$P < 0.01$

[1] This is the regression model used to predict effective caloric value from BW and FCR.

Table 6. Growth performance and behavior traits of 38-day old broilers fed a diet of varying pellet quality[1] during a 7 d assessment of feed conversion, Experiment 2

	Treatment[2]						Pooled
Performance trait	100	80	60	40	20	M	SE
Weight gain, g	725[a]	701[ab]	687[ab]	685[ab]	675[bc]	643[c]	6.16
Feed consumption, g	1,348	1,306	1,312	1,316	1,313	1,280	8.92
Feed conversion ratio	1.87[a]	1.88[a]	1.92[a]	1.93[ab]	1.95[ab]	2.02[b]	0.01
Behavior trait							
Pellets consumed[3], %	100[a]	87[b]	63[c]	42[d]	21[e]	0[f]	0.18
Eating frequency[4]	0.32[a]	0.52[a]	0.78[b]	0.84[b]	1.18[c]	1.31[c]	0.37
Resting frequency	8.61[a]	8.48[a]	8.09[b]	7.97[b]	7.48[c]	7.21[c]	0.06

[a-c]Means within a row with no common superscript differ ($P < 0.05$).

[1]Defined as the proportion (%) of pellets to post pellet fines.

[2]Treatments: 100 = 100 % pellets, 0 % fines; 80 = 80 % pellets, 20 % fines; 60 = 60% pellets, 40 % pellet; 20 = 20 % pellets, 80 % pellet; M = unprocessed mash.

[3]Pellets consumed = ((initial pellets offered – pellets remaining)/feed consumption) × 100.

[4]Eating or Resting frequency = times specific activity was observed / 10 observations. Other behaviors recorded, but not presented include: drinking, standing, walking, pecking, and preening.

Table 7. Dietary caloric value of changing pellet quality[1]

Pellet quality		Calorie change (ME_n/kg) attributable to pellet quality divergence							
	To								
From	100	90	80	70	60	50	40	30	20
100	0	-4	-18	-41	-74	-84	-89	-96	-111
90	4	0	-14	-37	-70	-80	-85	-92	-107
80	18	14	0	-23	-56	-66	-71	-78	-93
70	41	37	23	0	-33	-43	-48	-55	-70
60	74	70	56	33	0	-10	-15	-22	-37
50	84	80	66	43	10	0	-5	-12	-27
40	89	85	71	48	15	5	0	-7	-22
30	96	92	78	55	22	12	7	0	-15
20	111	107	93	70	37	27	22	15	0

[1]The calorific value of pellet quality change is attained by the intersection between initial and final pellet qualities. Negative values represent declining while positive values improving pellet quality change.

Table 8. Interactive effects of added fat and pellet quality on dietary caloric gain (ME_n/kg)

Added fat, %	Anticipated diet caloric value due to added fat, ME_n/kg	Anticipated pellet quality[1], %	Additional calories due to pelleting, ME_n/kg	Effective caloric value, ME_n/kg[2]	Incremental calorie change via added fat and pellet quality, ME_n/kg
0	2,977	90	183	3,160	–
1	3,014	82	173	3,187	27
2	3,049	78	165	3,214	27
3	3,084	71	149	3,233	19
4	3,120	68	140	3,260	27
5	3,157	49	103	3,260	0

[1]Based upon data reported by Richardson and Day (1976).
[2]Energy attributable to fat inclusion minus energy lost due to pellet degradation.

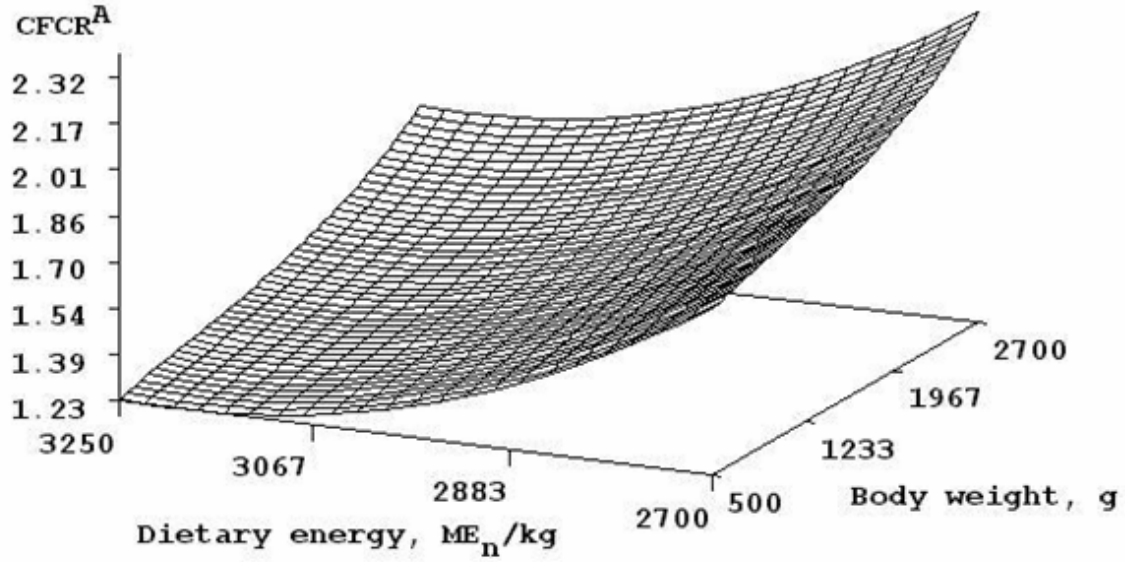

Figure 1. Relationships among body weight, conventionally-calculated feed conversion ratio (CFCR), and dietary energy
[A]Predicted daily body weight/predicted total feed consumption.
[A]See table 5 for equations relating body weight and feed conversion ratio with dietary energy

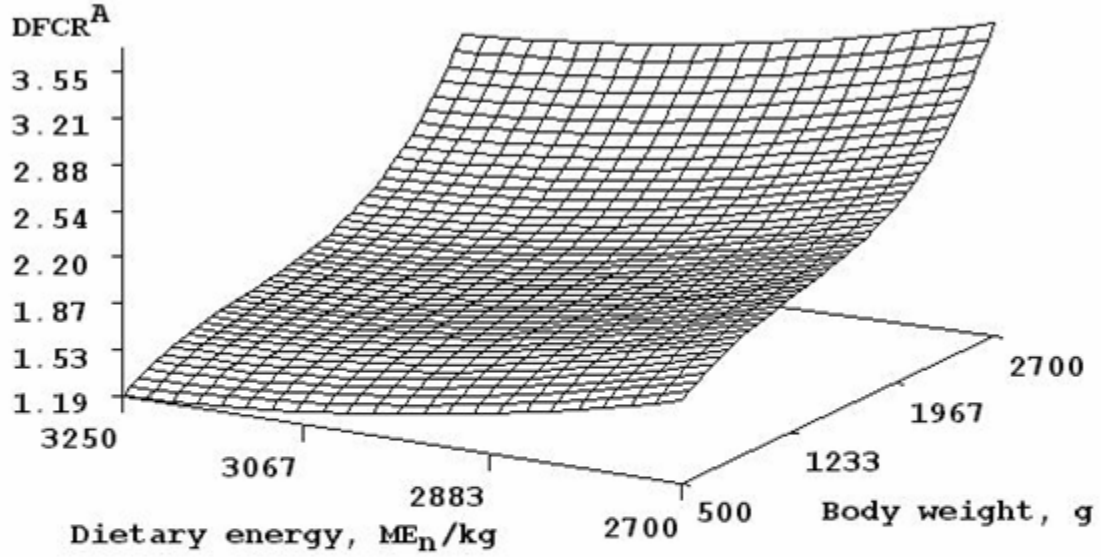

Figure 2. Relationships among body weight, feed conversion ratio calculated on a daily basis (DFCR), and dietary energy
[A]Predicted daily weight gain/predicted daily feed consumption.
ASee table 5 for equations relating body weight and feed conversion ratio with dietary energy

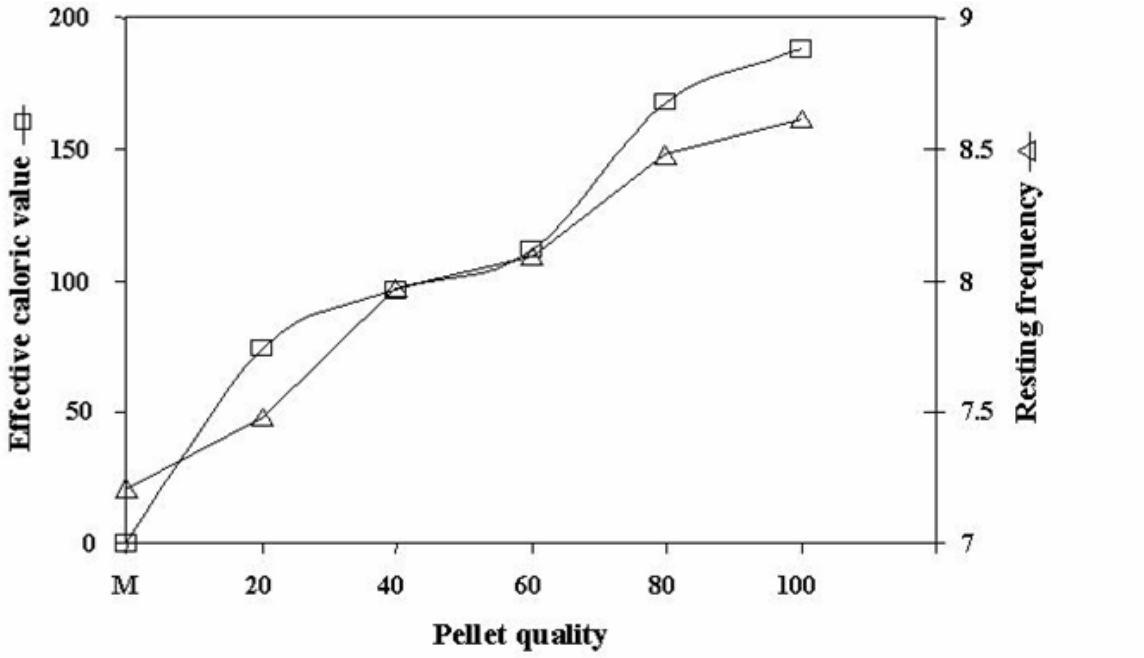

Figure 3. Pelleting and pellet quality effects on diet caloric value and broiler activity
[A]Times resting was observed per 10 observations
[B]Defined as proportion of pellets to pellet fines with M representing unprocessed mash.

CHAPTER V

Predicting Effective Caloric Value of Nonnutritive Factors: III. Feed Form Impacts Broiler Performance by Modifying Behavior Patterns

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Abbreviation Key: ECV=effective caloric value; FCR=feed conversion ratio; M=mash; NEg=net energy for gain; P=pellets; PQ=pellet quality

ABSTRACT

Two trials of an experiment were conducted to confirm the relationships among effective caloric value (ECV) of the diet, net energy for gain (NEg), BW, feed conversion ratio (FCR), and broiler behavior. Further the study sought to examine such factors with benefits of pelleting, including feed form history (pellets vs. mash) in females from two strains of commercial broilers. Composition of gain was measured on a sample of birds in both trials. In Trial 1 birds were reared to 23 d on feed in crumble form, at which time the birds were fed a feed in either pellet or mash form. Pelleting the feed increased ECV, total NEg, while decreasing eating, and increasing resting behavior. Significant correlations ($P < 0.05$) between resting, NEg, and ECV occurred. In Trial 2, birds were reared to 23 d on a crumble diet, then fed diet in either mash or pellet form to 36 d. At 37 d of age, half of the birds from each strain and feed form history combination were switched to the alternative feed form. Strain by grower feed form interactions were present for BW, initial fat, and energy content indicating that pelleted feed was required for optimum broiler performance of one strain. Grower feed form by finisher feed form interactions were present that demonstrated that birds switched to the alternate feed form consumed more feed in less than half the time of the birds that remained on their previous feed form. Significant correlations were observed in both trials between behaviors and FCR and ECV, while NEg reflected these differences in Trial 1 but not Trial 2. Regression analysis indicated that FCR (and subsequently ECV) was best predicted by lean gain, whereas NEg was best predicted by fat gain. Further, regression analysis established interactive equations where ECV was predicted ($R^2 > 0.99$) by eating and resting behavior. The results of these trials indicate that the effects of feed form are

caused by a modification of behavior patterns, that ECV is responsive to such behavior changes, and that ECV is an effective estimator of the relative caloric value of genetic, management, and husbandry influences.

(Key words: pelleting, net energy, effective caloric value, behavior, genotype by environment interactions)

INTRODUCTION

Paramount among nutritional goals is the reasonable balance between dietary provision of nutrients and energy. Consequently, rations are generally formulated to specific nutrient:energy ratios. Such ratios are usually not interactive with the genetics and managerial environment (NRC, 1994). One could surmise this to leave a lesser importance being attributable to nutritional and managerial interface. However, the interfacing of nutrition with the ambient and managerial environments has profound influence upon the extent and profitability of the poultry enterprise. For example, numerous managerial – husbandry decisions related to stocking density (Cravener et al., 1992; Puron et al., 1997), lighting program (Buyse et al., 1996; Ingram et al., 2000), ventilation (Lott et al., 1998), feed processing techniques as pelleting (Acar et al., 1991; Schiedeler, 1995; Moritz et al., 2001), and nutritional consideration (NRC, 1994) are well documented to have significant impact upon poultry performance. Coupling such observations with the suggestion that no cessation of selection response has been observed for increased BW of turkeys (Nestor et al., 1996), chickens (Dunnington and Siegel, 1996), and Japanese quail (Marks, 1996), even up to nearly 100 generations of

selection, indicates that mechanistic understanding of interactions for the aforementioned variables is needed.

Traditionally, studies examining genetic × nonnutritional × nutritional interactions are limited. Such is the case presumably due to the complexity of variable type, number of variables involved, and difficulty in manipulating the three components at multiple levels simultaneously. Paramount among nutritional influences upon broiler performance are factors influencing growth and FCR. Bird nutrient and energy requirements are closely related to performance as growth and FCR. McKinney and Teeter (2004) proposed a methodology that enables predicting dietary caloric density from boiler growth and FCR. Energy values so predicted, termed effective caloric value (ECV) of dietary ME_n, provide a relative value for combined dietary and non-dietary factors influencing broiler performance. That study went on to confirm the model and used pellet quality (PQ; defined as the ratio of pellets:pellet fines presented to the bird), as a nonnutritive variable. The authors concluded that pelleting results in up to an additional 187 kcal ME_n/kg of diet, and that PQ and resting behavior were well correlated. Consequently, a component of the aforementioned managerial influence upon broiler performance may well relate to energy expenditure associated with activity.

The traditional wisdom of poultry producers is that environmental variability, attributable to management-husbandry, elicits broiler behavioral responses, though such are not well documented in the literature. If the beneficial effects of feed form as reported by McKinney and Teeter (2004) were indeed due to alteration in bird behavior, it is thereby logical to assume that feed form inconsistencies would also be important. Whether among batches received from the feed mill or within house variation, feed form

inconsistencies (i.e., fluctuating PQ or mash vs. pellets) will inevitably exist. However, consequences of varying feed form or feed form history effects have yet to be demonstrated and may vary with the ability or inability of the various broiler strains to adapt to alternating feed form.

Selection for increased BW in turkeys has led to an apparent increase in resting behavior, and a decrease in walking behavior in terms of time spent walking and number of steps taken (Noble et al., 1996). If similar patterns are present with broiler chickens, it may be reasonable to assume that resting behavior in broilers has either increased with continued selection for improved BW and FCR, or is potentially influenced by bird strain. Given the relationship observed among PQ, resting behavior, FCR, and ECV (McKinney and Teeter, 2004), then improvements in FCR cannot be totally disjoint from correlated responses to selection on behaviors. Likewise, changes in behavior could be applied independent of selection to improve FCR and other broiler traits. The study reported herein was conducted: 1) to confirm the relationship among ECV, BW, FCR, and behavior of broilers; 2) to further describe benefits of pelleting by assessing pelleting effects on NEg; and 3) to determine the effects of strain, feed form history, and current pellet treatment on broiler performance, behaviors, ECV, and NEg.

MATERIALS AND METHODS

General.

Female broiler chicks (200 from each of strain A and B; 400 total) were obtained from a commercial hatchery following sexing and vaccination for Marek's disease. These strains used the same sire lines reported by Skinner-Noble et al. (2003b). Upon

arrival, all birds were wingbanded and placed into 12 floor pens. Birds were provided feed and water for ad libitum consumption while in floor pens (except as noted), and the lighting program used was 23L:1D from 0 to 7 d, 16L:8D thereafter in the floor pens, and 14L:10D while in FCR cages. All birds were fed a starter diet in crumble form containing 22.67% CP and 3,026 kcal ME_n/kg from hatching to 16 d of age. From 16 to 22 d, all birds were fed a grower diet containing 20.20% CP and 3,119 kcal ME_n/kg, again in crumble form. The grower diet was fed to 32 d of age, at which time birds were fed a finisher containing 17.33% CP and 3,199 kcal ME_n/kg diet. The amino acid levels of the diets fed matched current recommendations (NRC, 1994).

At 20 d of age, all birds were randomly assigned to one of four testing weeks, of which two are reported herein. All birds were handled, their wingbands read, and spray paint was applied to their wing bows to minimize additional handling as birds were used for the subsequent FCR testing. At 23 d of age, half of the birds from each strain were provided their diet in mash form, whereas the remaining birds were fed their diets in pellet form. Though feeds were changed from starter to grower at 16 d, and from grower to finisher at 32 d of age, treatments will be described as "grower feed form" to describe the feed form offered from 23 to 36 d of age, and "finisher feed form" to describe the feed form offered from 37 to 44 d of age.

When in FCR testing cages, scan sample behavior observations were conducted on three days of the 7-d FCR test. Birds were observed 5 times every 2 h during the light phase, and classified as eating, drinking, standing, resting, walking, pecking, preening, or any other behavior (as described by Skinner-Noble et al., 2003a). In addition to the aforementioned behavior categories, birds were also classified as dustbathing if their

body was in contact with the litter and actively moving it through their feathers. In each trial a sample of the birds (36 of 72 in Trial 1 and 32 of 72 in Trial 2) were assessed for initial and final body composition. In both trials birds were anesthesitized (by intramuscular injection of a solution of 75% Rompin and 25% Ace at a dose of 0.26 mL / kg of BW) and their body lean, fat, and bone mass measured using an x-ray densitometer[1]. Total energy content was calculated as the sum of: (fat mass x 9.31) and [(lean mass x 0.2477 x 5.65); Dixson, 2003]. The net energy for gain (NEg) was calculated as the difference between initial and final energy, and expressed both in total and per kg of diet consumed.

As birds were removed from the floor pens, the number of pens used was reduced to maintain constant stocking density. Differences between the two trials will be discussed as follows.

Trial 1.

At 22 d of age, 72 birds (36 per strain) were removed from their pens and fasted overnight in preparation for a 7-d assessment of feed conversion. At 23 d of age, 36 birds (18 per strain) were anesthesitized and their body composition measured. Following body composition measurement, all feeders were weighed, and all birds were weighed and placed into FCR testing cages (as described by Skinner-Noble et al., 2003a). In FCR cages, birds were provided the aforementioned grower diet in either pellet or mash form. At the end of the FCR test all feeders and birds were weighed, and the birds which were previously assessed for body composition had their body composition measured, after being euthanized by carbon dioxide inhalation. Treatments were arranged in a 2 strains (A vs. B) 2 grower feed forms (pellets vs. mash) factorial arrangement for this trial.

[1] Holdel QDR4500. Hologic Corporation, Waltham, MA 02154

Trial 2.

At 36 d of age, 72 birds [18 from each strain (A vs. B) and grower feed form (pellets vs. mash from 23-36 d) combination] were removed from their floor pens and fasted overnight in preparation for a 7-d FCR test. Half of the birds from each strain and grower feed form were switched to the alternate finisher feed form, whereas the remaining half remained on their previous feed form. Body composition was measured on 32 birds (8 from each strain and grower feed form combination). Treatments were arranged in a 2 strains, 2 grower feed form, × two finisher feed form (switched to the alternate feed form or not from 37-44 d) factorial arrangement for this trial.

Data analysis.

In both trials, data were analyzed by analysis of variance as a completely randomized design with the aforementioned factorial arrangement of treatments, with appropriate interaction terms. Significance was accepted at $P < 0.05$. Actual P values are presented where $P < 0.10$. Behaviors were averaged across all observation days and time of day to provide a summary of activity patterns, and to provide a single unit for each behavior trait that could then be used in subsequent correlation analyses. The ECV was calculated by the equation of McKinney and Teeter (2004) using the average of the starting and ending BW and the FCR while on test. Correlations were made between broiler traits (starting and ending BW, feed intake, BW gain, FCR, and ECV) and behaviors for all birds. Correlations were also made between behaviors, ECV, and total NEg and NEg per kg of diet consumed to determine if activity of broilers affects NEg.

Regression analyses were used for both trials to establish quantitative relationships among ECV, feed consumption, and behaviors.

RESULTS AND DISCUSSION

Trial 1.

As with McKinney and Teeter (2004), pelleting improved BW gain, feed intake, FCR, and subsequent ECV (Table 1) compared to feeding mash. As expected from results of Jensen et al. (1962), birds fed pellets were observed eating less often (4.25% vs. 18.81%) and resting more (62.48% vs. 47.35%) than those fed mash. The magnitude of difference between pellets and mash for eating behavior agrees well with Jensen et al. (1962), who found a three-fold difference in time spent eating between chickens fed pellets vs. mash. Strain differences were significant for BW gain and FCR, in agreement with Skinner-Noble et al. (2003b) who used the same sire lines as the current report.

When the model of McKinney and Teeter (2004) relating caloric density to BW and FCR was applied, the resulting ECV (in ME_n) of the diet was 3,028 kcal/kg for mash and 3,179 kcal/kg for pellets, resulting in an average of 3,103 kcal ME_n/kg (Table 1), closely matching the calculated ME_n of the current grower diet of 3,119 kcal ME_n/kg. Both strain and feed form impacted ECV ($P < 0.05$). Pelleting benefits, calculated as the differential ECV between pellets and mash, was 151 Kcal ME_n/kg of ration. Though the model of McKinney and Teeter (2004) used males and the current study used females, the aforementioned model appears to fit the current data. This may be due in part to the age of birds utilized in Trial 1. The model would be expected to fit less well as female birds aged, and sexual dimorphism would become a greater factor.

Birds fed pellets had greater final lean, fat gain, lean gain, and total NEg (Table 1). This agrees with the results of McKinney and Teeter (2004) which found pelleting could result in up to 187 kcal ME_n/kg of ECV over mash. Though the ECV differed ($P < 0.05$) between pellets and mash, the NEg/kg was not significant (2,107 for mash vs. 2,351 for pellets; $P = 0.0679$). However, the directional response of NEg/kg did agree with the hypothesis that pelleting increased dietary energy available for gain by increasing resting and decreasing eating behavior. The lack of significance is likely due to inadequate replication, as a model without the interaction term resulted in a greater F statistic ($P = 0.0629$). Nonetheless bird performance measured by weight gain, FCR, ECV, and NE are all correlated, where no such value is possible for strict ME_n.

Resting behavior was negatively correlated, and eating behavior was positively correlated with FCR and ECV, while NEg was correlated with resting but not eating behavior (Table 2). This is in contrast to results of Skinner-Noble et al. (2003a), who found a positive correlation between resting and FCR. A notable difference between Skinner-Noble et al. (2003a) and the current report is that a feed form treatment was applied in the current study that would be expected to have a major impact on behaviors and broiler performance, whereas Skinner-Noble et al. (2003a) used sifted pellets for all birds to reduce chance variation in feed form and based conclusions on correlation analyses in that "no treatment" experiment. McKinney and Teeter (2004) also demonstrated a relationship between increased resting behavior and increased ECV of the diet. These results also support the hypothesis that pelleting decreases energy expended in birds (Jensen et al., 1962). This energy could, therefore, be dedicated to gain.

The correlation between ECV and total NEg was 0.41, whereas the correlation between NEg per kg of diet and ECV was 0.34 (Table 2). Regressing NEg or ECV on lean and fat gain indicated that lean gain appears to be a better predictor of both FCR and ECV than fat gain, where the opposite is true for NEg.

The results of Trial 1 clearly confirm that regardless of strain, pelleting of feed resulted in increased resting behavior, decreased eating behavior, improved BW, improved BW gain, improved FCR, and increased ECV in broilers at this age. In contrast to Jensen et al. (1962), broilers in the present study were not given an adaptation period prior to FCR testing. Both feed form treatments should have been novel to the birds, as all birds had previously been fed crumbled feed, and then were switched to either pellets or mash. If pre-testing adaptation were a factor, it would be expected to manifest itself either in an initial rejection of feed or hyperphagia. Data collected within 4 h of feeding did not indicate such a rejection of feed occurred (data not shown). Additionally, the overnight fasting period utilized in the current study was designed to stimulate appetite and reduce adaptation time (Skinner-Noble et al., 2003a). The ECV was effectively modeled by the interactive model of eating and resting behavior (data not shown).

Trial 2.

Given the treatment effects observed in Trial 1 and results from Skinner-Noble et al. (2003b), the presence of grower feed form and strain by grower feed form interactions were expected and observed for BW and composition at the start of trial 2 (Table 3). These interactions were caused by a lack of grower feed form effect for Strain A, whereas strain B had greater BW and total energy when fed pellets in the grower phase. This indicates that the pretrial 2 wk of feeding the diet in pellet form resulted in a benefit for

strain B, whereas no such benefit was observed for strain A from 23-36 d. As a result, the relative position of birds on the growth curve differed at experiment initiation and would be expected to impact the results of Trial 2. This is reflected in the initial BW and composition of birds in Trial 2. These differences agreed with results of trial 1 and are consistent with previous studies (McKinney and Teeter, 2004).

The results of Trial 2 become clear when the finisher feed form is considered from the view of being switched from the grower feed form or left the same. When viewed in that context, birds that were switched to the alternate feed form consumed 50 g more feed in less than half the time of those birds that were not switched to the alternate feed form, regardless of the grower feed form (Table 3). This indicates that birds adjusted to a switch in feed form with hyperphagia. Anecdotal evidence from the authors' laboratory indicates that similar hyperphagia often occurs in response to a perceived stressor. This decreased time spent eating was then devoted to resting. This increase in resting and decrease in eating appears to be the driving factor leading to a 10 point improvement in FCR during the finisher phase. Again, this was regardless of grower feed form. When used in a regression model, the interactive effects of eating and resting effectively model ECV, with an R^2 of over 99% (Figure 1). While it may seem contrary to expectations that the coefficients of both eating and resting behavior were positive for their effect on ECV, it should be noted that feed intake increased as eating time decreased (Figure 2).

There appears to be a carry-over effect of grower feed form that affected subsequent feed intake and weight gain (Table 3). Birds fed pellets during the grower

phase appeared to have the ability to more efficiently eat feed (more feed consumed per time observed eating) than those birds fed mash during the grower phase.

Additionally, the correlation model relating broiler traits (BW and FCR) to ECV did not effectively model NEg/kg of diet in Trial 2 (Table 4). It appears that different factors influence NEg and FCR. The fact that NEg was not correlated with behavior whereas ECV was correlated with behavior suggests that given the unequal starting points, performance based ECV provides more useful information than does NEg in this trial. That ECV was affected by grower feed form, finisher feed form switch, and the grower feed form × finisher feed form interaction, whereas NEg was affected only by finisher feed form adds credence to use of ECV as a performance based response variable. A downside of the use of NEg is that it is biased favoring birds with increased fat gain, which may be undesirable in some cases.

Modeling FCR and NEg by regression analysis indicates that gain of lean is a better predictor of FCR than gain of fat, whereas the opposite is true for NEg, where gain of fat had a greater impact on NEg than gain of lean. These results agree with previous reports of selection experiments for improved FCR that report improved FCR is associated with decreased fatness (Thomas et al., 1958; Chambers and Gavora, 1982; Leenstra and Pit, 1988; Buyse et al., 1998). The decrease in fatness should contribute to decreased energetic efficiency through the course of continued selection for improved FCR. Conversely, the continued selection for improved FCR should also result in increased lean mass, if FCR is the only selection criterion.

General.

That diets differing only in feed form resulted in different broiler performance and NEg responses of broilers should not be surprising. MacLeod (2000) stated that while ME is a property of the feed, net energy is the *response of the bird to its feed*. Concomitantly, it appears appropriate because ECV represents the interfacing of bird, diet, and environment. Similarly, Skinner-Noble and Teeter (2003) reported that broilers differing in FCR expressed greater NE response than measured ME responses. The lack of difference in NEg between pellets and mash ($P = 0.0679$) in Trial 1 may be due to difficulties associated with measuring NEg, or it may be an artifact of the sample size. Skinner-Noble and Teeter (2003) reported NEg values obtained by subtracting total heat production from measured apparent ME. The current study obtained NEg by subtracting initial energy from final energy as measured by whole bird live body composition. As such, this method would have fewer sources of error than those of Skinner-Noble and Teeter (2003).

This study also points out how NEg and FCR are influenced by different factors, most notably gain of fat having a greater impact on NEg, whereas gain of lean has a greater impact on FCR and consequently ECV. This would be expected, given that each g of protein gained yields 3.03 g of lean (and thus BW) gain and 1.695 calories of energy, whereas 1 g of lipid gained yields 1 g of fat (and thus BW) gain and 9.31 calories of energy (Dixson, 2003).

While the ECV of McKinney and Teeter (2004) and NEg was well correlated (Trial 1), the correlation was not significant in Trial 2. The unequal initial BW and composition as lean and fat would be expected to influence bird maintenance energy need and may have unduly influenced NEg to the point that the current feed form effects were

masked by previous actions. Nonetheless, in both trials ECV provided a useful assessment of the relative practical value of a management-husbandry practice, as correlations between bird behavior and performance were attained. Because ECV is based on two traits (BW and FCR) that are fairly easy to measure in the field (as opposed to NEg, which is difficult to measure in the field), they can be used to place relative merit on management and husbandry practices. Ultimately the goal of animal production is efficient production of lean tissue with acceptable fatness. Whereas NEg is related to fat gain, ECV more closely expresses the relationship between the bird and its environment. If NEg were the only criterion for efficiency of production, then increased fatness would result and indeed appears that it masks husbandry relationships. Thus, ECV does appear to be a practical predictor of the effective and relative values of any management-husbandry changes that result in changes in BW and FCR. Subsequent energy utilization fate will be determined by the "ration balance", relative to the birds' potential for lean mass accretion. Those wishing to produce a specific bird composition must thereby integrate both nutrition and management.

The most striking finding of these trials is the manner in which the interactive model of eating and resting behavior effectively predicted ECV. It indeed appears that pelleting benefits broiler performance by modifying behavior patterns, notably by reducing times observed eating and increasing times observed resting. Similar relationships among eating, resting, and ECV were observed in both trials. Similarly, voracity of eating occurred in both trials indicating that increased feed intake occurred in a reduced time observed eating. Jensen et al. (1962) determined that broilers reduced eating time in response to pelleting feed. This response occurred after a week of

adaptation to the tested feed forms. The current study did not use an adaptation period, and observed more extreme modifications of behavior patterns (hyperphagia in response to changing feed form in Trial 2) than those observed by Jensen et al. (1962).

The results of these trials indicate that feed form impacts broiler performance through a reduction in activity, and that response to pelleting of feed depends on the strain of broiler utilized and their previous feed form history. Regression analysis indicated that FCR (and subsequently ECV) was best predicted by lean gain, whereas NEg was best predicted by fat gain. Results indicate that Trial 2 data were biased by unequal starting composition, where ECV resulted in greater separation of statistical effects that were not detected by NEg. The ECV appears to be an effective estimator of the caloric value of management-husbandry practices.

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Table 1. Broiler performance, energy, and behavior traits of two strains of broilers fed either pellets or mash from 23 to 30 d of age, Trial 1

			Broiler performance and energy traits[1]								
	Strain (S)	Treatment (T)	BW30	WG2330	FI2330	FCR2330	ECV	Fat gain (g)	Lean gain (g)	NE gain (kcal)	NE gain (kcal/kg diet)
Means	A	Mash	1,207	477	769	1.62	3,013	81.0	334.3	1,222	1,601
	A	Pellets	1,383	596	923	1.56	3,124	108.6	401.8	1,574	1,779
	B	Mash	1,249	523	831	1.59	3,044	120.2	353.7	1,614	1,917
	B	Pellets	1,418	637	922	1.45	3,233	145.2	409.0	1,925	2,159
			probability								
ANOVA	Source	S	NS	**	NS	*	*	**	NS	**	**
		T	**	**	**	**	**	*	**	*	0.0672
		S x T	NS	NS	NS	NS	NS	NS	NS	NS	NS
		Pooled SEM	18.75	10.28	12.81	0.017	18.07	6.77	8.11	66.55	62.94

			Behavior traits[2]								
	Strain (S)	Treatment (T)	Eat	Drink	Stand	Rest	Walk	Peck	Preen	Dust	Other
Means	A	Mash	17.37	7.13	15.09	47.13	8.72	0.89	3.04	0.55	0.07
	A	Pellets	5.03	9.87	13.59	59.02	6.08	0.78	4.77	0.98	0.00
	B	Mash	20.26	7.65	12.42	47.58	5.82	1.05	3.46	1.90	0.00
	B	Pellets	3.46	7.25	11.76	65.95	6.54	0.98	2.94	1.18	0.00
			probability								
ANOVA	Source	S	NS	NS	NS	NS	NS	NS	NS	*	NS
		T	**	NS	NS	**	NS	NS	NS	NS	NS
		S x T	0.053	0.09	NS	NS	NS	NS	0.09	NS	NS
		Pooled SEM	1.04	0.47	0.77	1.53	0.54	0.14	0.33	0.19	0.02

[1]BW23=BW at 23 d of age; BW30= BW at 30 d of age; WG2330= BW gained from 23 to 30 d of age; FI2330= feed intake from 23 to 30 d of age; FCR2330= feed conversion ratio (g feed/g gain) from 23 to 30 d of age; ECV=effective caloric value, the equivalent value of dietary ME needed to achieve the FCR and BW response observed

[2]Percent of times each bird was observed performing each behavior

NS= not significant ($P > 0.10$); **= $P < 0.01$; *= $P < 0.05$

Table 2. Correlations among traits measured[1], Trial 1

	Trait[2]											
Broiler trait[3]	Eat	Drink	Stand	Rest	Walk	Peck	Preen	Dust	Other	ECV	Lean gain	Fat gain
BW23	-0.41**	NS	NS	0.24*	NS	NS	NS	NS	NS	0.34**	0.38*	NS
BW30	-0.58**	NS	NS	0.43**	NS	NS	NS	NS	NS	0.65**	0.72**	0.35*
WG2330	-0.60**	NS	NS	0.52**	NS	NS	NS	NS	NS	0.81**	0.85**	0.55**
FI2330	-0.51**	NS	NS	0.41**	NS	NS	NS	NS	NS	0.39**	0.75**	0.52**
FI/BW23	NS	NS	NS	NS	-0.26*	NS	NS	NS	NS	NS	NS	0.31+
FCR2330	0.37**	NS	NS	-0.33**	NS	NS	NS	NS	NS	-0.93**	-0.47**	NS
ECV	-0.52**	NS	NS	0.44**	NS	NS	NS	NS	NS	--	0.63**	0.32+
NE gain (kcal)	NS	NS	-0.38*	0.40*	NS	NS	NS	NS	NS	0.41*	0.38**	0.99**
NE gain (kcal/kg)	NS	NS	-0.42*	0.38*	-0.33+	NS	NS	NS	NS	0.34*	NS	0.96**

[1]Lean gain, fat gain, and NE gain were measured on 36 birds, whereas 72 birds were measured for the remaining traits

[2]Eat=percent of times the bird was observed eating; Drink=percent of times the bird was observed drinking; Stand=percent of times the bird was observed standing; Rest=percent of times the bird was observed resting; Walk=the percent of times the bird was observed walking; Peck=percent of times the bird was observed pecking; Preen=percent of times the bird was observed preening; Dust=percent of times the bird was observed dustbathing; Other=percent of times the bird was observed performing any behavior other that the aforementioned eight behaviors; ECV=effective caloric value, the equivalent dietary ME required for the specific body weight and feed conversion response

[3]BW23=BW at 23 d of age; BW30=BW at 30 d of age; WG2330=BW gained from 23 to 30 d of age; FI2330=feed intake from 23 to 30 d of age; FI/BW23= feed consumed per unit initial BW; FCR2330=feed conversion ration (g feed/g gain) from 23 to 30 d of age; NE gain= the gain of energy (in total kcal and per kg of diet consumed) from 23 to 30 d of age

NS= not significant ($P > 0.10$); **= $P < 0.01$; *= $P < 0.05$

Table 3. Broiler performance, energy, and behavior traits of two strains of broilers fed either pellets or mash from 37 to 44 d of age, Trial 2

				Broiler and energy trait[1]								
	Strain (S)	Grower feed form (G)	Finisher feed form (F) switched?	Initial fat (g)	Initial lean (g)	Initial energy (kcal)	BW37 (g)	FI (g)	WG (g)	FCR (g)	BW44 (g)	ECV
Means	A	Mash	No	341	1,362	5,081	1,679	1,081	561	1.95	2,177	3,192
	A	Mash	Yes	305	1,421	4,823	1,764	1,110	589	1.89	2,344	3,383
	A	Pellets	Yes	308	1,417	4,849	1,772	1,171	672	1.75	2,362	3,524
	A	Pellets	No	265	1,411	4,442	1,775	1,136	597	1.92	2,371	3,378
	B	Mash	No	207	1,434	3,930	1,714	937	489	1.93	2,005	3,154
	B	Mash	Yes	243	1,319	4,105	1,649	1,015	551	1.85	2,178	3,360
	B	Pellets	Yes	383	1,547	5,726	1,966	1,237	726	1.71	2,581	3,803
	B	Pellets	No	337	1,496	5,231	1,901	1,056	579	1.84	2,426	3,535
				probability								
	ANOVA	Source	S	NS	NS	NS	NS	*	NS	NS	NS	0.09
			G	0.06	*	*	**	**	**	*	**	**
			F	NS	NS	NS	NS	**	**	*	*	**
			S x G	**	0.09	**	*	0.06	0.08	NS	**	*
			S x F	NS	NS	NS	NS	NS	NS	NS	NS	NS
			G x F	NS	NS	NS	*	NS	NS	NS	NS	NS
			S x G x F	NS	NS	NS	NS	NS	NS	NS	NS	NS
			Pooled SEM	14.70	19.61	150.18	21.56	17.39	12.80	0.022	29.54	34.55

				Behavior trait[2]							
	Strain (S)	Grower feed form (G)	Finisher feed form (F) switched?	Eat	Drink	Stand	Rest	Walk	Peck	Preen	Dust
Means	A	Mash	No	20.60	3.67	9.32	57.09	3.41	1.71	3.80	0.39
	A	Mash	Yes	10.29	6.39	11.20	62.33	3.25	0.91	5.10	0.52
	A	Pellets	Yes	4.59	6.02	10.47	69.88	3.54	1.44	3.27	0.78
	A	Pellets	No	8.49	5.67	10.01	67.35	1.89	1.06	5.30	0.24
	B	Mash	No	27.12	4.71	17.53	40.96	4.18	1.44	3.40	0.65
	B	Mash	Yes	11.38	6.15	11.37	62.08	2.87	1.83	4.19	0.13
	B	Pellets	Yes	6.54	6.28	4.58	72.13	1.57	1.05	7.72	0.13
	B	Pellets	No	13.26	4.13	8.25	65.36	1.18	1.62	5.46	0.74
				Probability							
	ANOVA	Source	S	0.09	NS	NS	NS	NS	NS	NS	NS
			G	**	NS	**	**	0.07	NS	0.09	NS
			F	**	**	NS	**	NS	NS	NS	NS
			S x G	NS	NS	**	NS	NS	NS	0.06	NS
			S x F	NS	NS	*	0.08	NS	NS	NS	0.07
			G x F	0.07	NS	NS	NS	NS	NS	NS	NS
			S x G x F	NS	NS	NS	NS	NS	NS	NS	NS
			Pooled SEM	1.30	0.31	0.77	1.72	0.37	0.18	0.39	0.12

[1]BW37=BW at 37 d of age; BW44= BW at 44 d of age; FI3744= feed intake from 37 to 44 d of age
[2]Percent of times each bird was observed performing each behavior
NS= not significant ($P > 0.10$); **= $P < 0.01$; *= $P < 0.05$

Table 4. Correlations among traits measured[1], Trial 2

Trait[3]	Trait[2]											
	Eat	Drink	Stand	Rest	Walk	Peck	Preen	Dust	ECV	Lean gain	Fat gain	NE gain (kcal/kg)
BW37	-0.36**	NS	NS	0.35**	-0.33**	NS	0.34**	NS	0.55**	0.32+	NS	NS
BW44	-0.44**	NS	0.44*	0.44**	-0.31**	NS	0.37**	NS	0.79**	0.68**	0.42*	NS
WG3744	-0.46**	NS	0.30*	0.44**	NS	NS	0.34**	NS	0.80**	0.83**	0.42*	NS
FI3744	-0.47**	NS	-0.27*	0.42**	NS	NS	0.35**	NS	0.53**	0.75**	0.34+	NS
FCR3744	0.21+	NS	0.24*	-0.24*	NS	NS	NS	NS	-0.78**	-0.49*	NS	NS
FI/BW37	NS	NS	NS	NS	NS	NS	NS	NS	--	0.73**	NS	NS
ECV	-0.41**	NS	-0.28*	0.43**	-0.21+	NS	0.34**	NS	--	0.58*	0.38+	NS
NE gain (kcal)	NS	NS	NS	NS	NS	NS	NS	NS	0.47*	0.31+	0.98**	0.90**
NE gain (kcal/kg)	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	0.94**	--

[1]Lean gain, fat gain, and NE gain were measured on 32 birds, whereas 72 birds were measured for the remaining traits

[2]Eat= percent of times each bird was observed eating; Drink=percent of times each bird was observed drinking; Stand=percent of times each bird was observed standing; Rest=percent of times each bird was observed resting; Walk=percent of times each bird was observed walking; Peck=percent of times each bird was observed pecking; Preen=percent of times each bird was observed preening; Dust=percent of times each bird was observed dustbathing; ECV=effective caloric value, the equivalent dietary ME required for the specific body weight and feed conversion response

[3]BW37=BW at 37 d of age; BW44=BW at 44 d of age; WG3744=BW gained from 37 to 44 d of age; FI3744=feed intake from 37 to 44 d of age; FCR3744=feed conversion ratio (FI3744/WG3744); FI/BW37= feed consumed per unit starting BW

NS= not significant ($P > 0.10$); **= $P < 0.01$; *= $P < 0.05$; + = $P < 0.10$

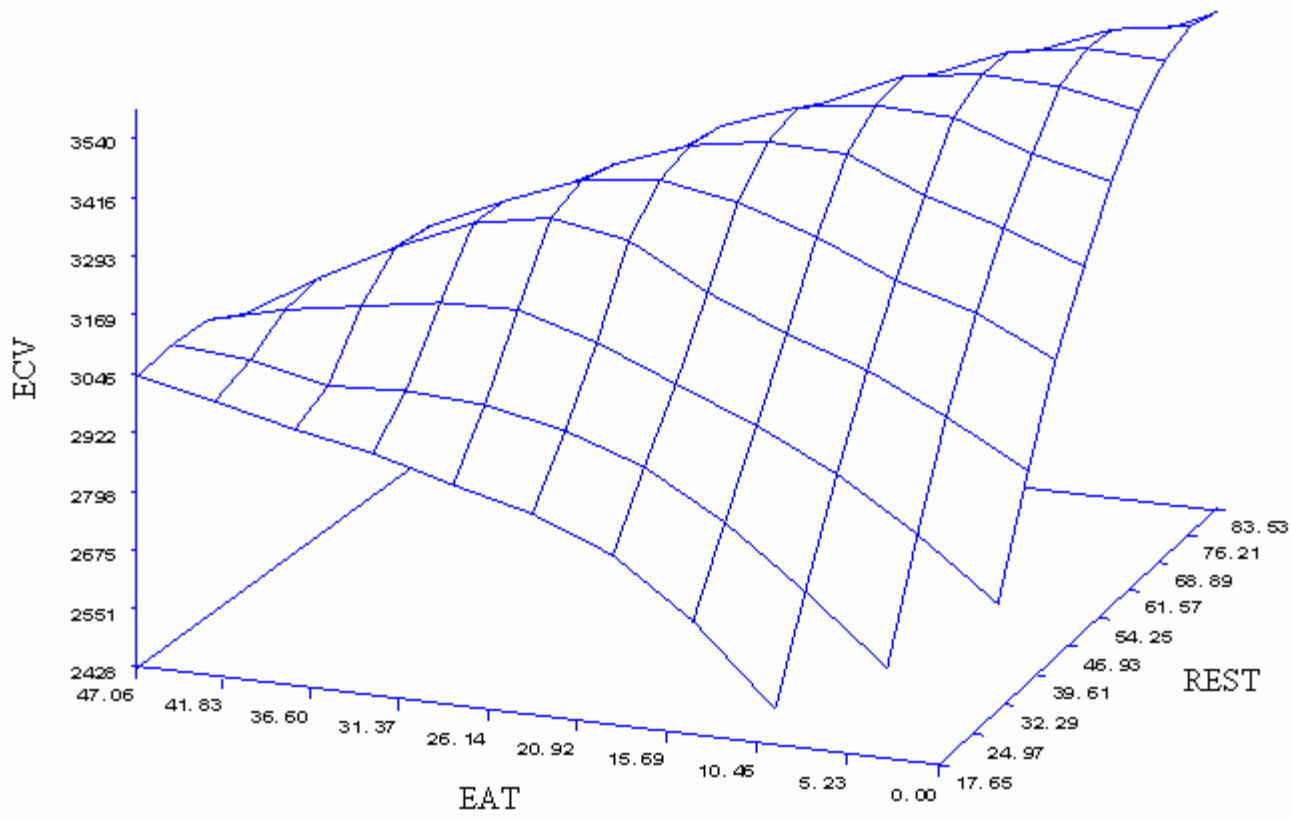

Figure 1. The interactive relationship among percent time eating (EAT), percent time resting (REST), and effective caloric value (ECV; kcal ME_n/kg) predicted by the equation
ECV=EAT x 119.65 + REST x 88.65 – EAT2 x 1.30 - REST2 x 0.60 – EAT x REST x 1.71 ($R^2 = 0.9948$), Trial 2.

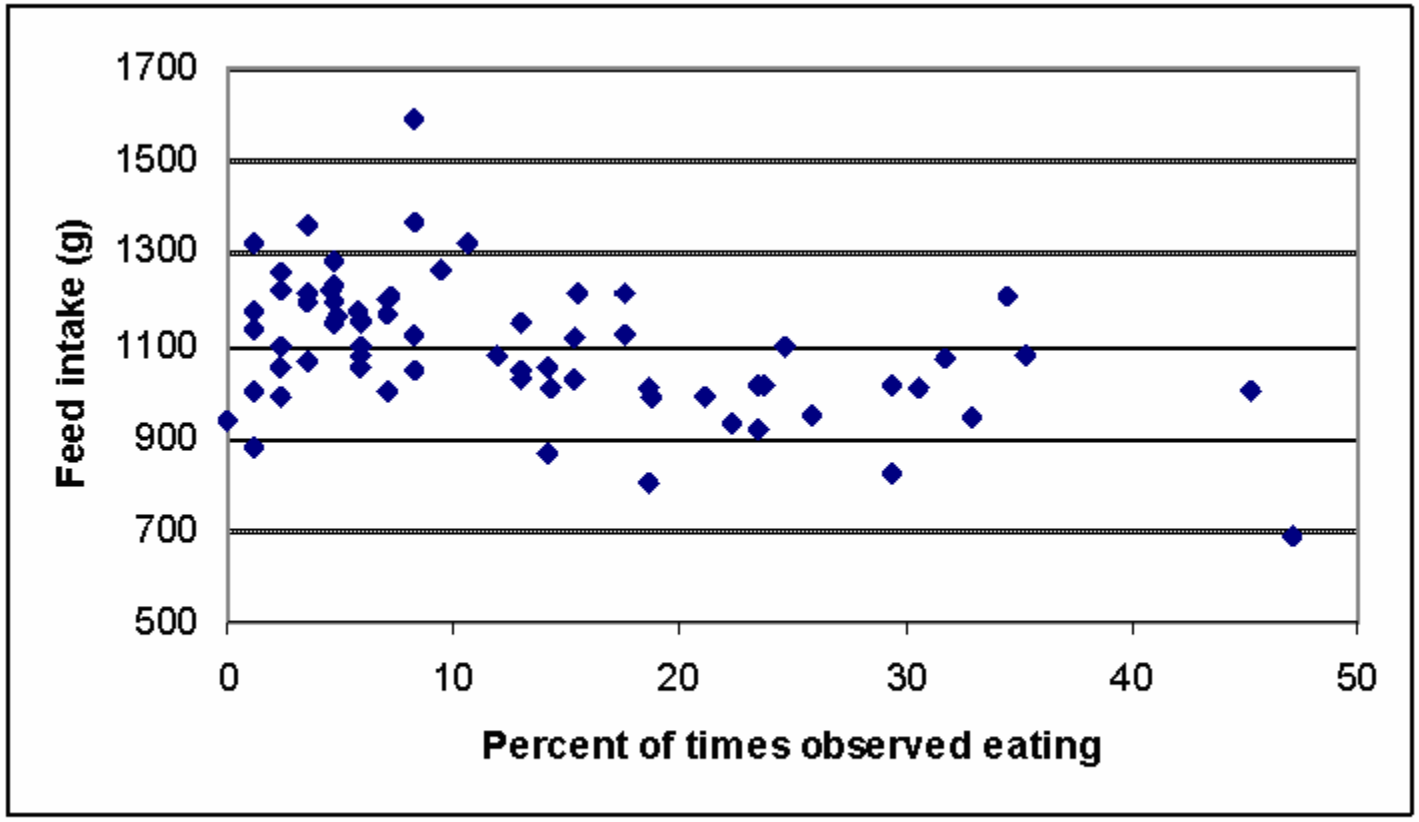

Figure 2. Relationship between feed intake and percent of time birds were observed eating.

CHAPTER VI

Predicting Effective Caloric Value of Nonnutritive Factors: IV. Nutrient to calorie ratios as influenced by pelleting

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Abbreviation Key: ECV = effective caloric value; BWG = body weight gain; FCR = feed conversion ratio; M = mash; C = mash steam pelleted and crumbled; P = mash steam pelleted and sifted; PD = protein deposition; LD = lipid deposition; $kLys_{PD}$ = efficiency of dietary lysine for protein deposition; kRE = apparent energetic efficiency

ABSTRACT

Three experiments of similar design were conducted to first, evaluate dietary lysine in ratio with effective caloric value (ECV) altered either through the addition of soybean oil or by feed form, and second, to develop mathematical models that describe lysine requirement based on body composition. Studies utilized male and female broilers over age intervals ranging from 1 to 10 (Experiment 1), 19 to 29 (Experiment 2), and 45 to 55 (Experiment 3) days. Treatments evaluated were structured as 4 suboptimal dietary lysine levels by 2 (Experiment 1) or 3 (Experiments 2 and 3) ECV treatments. ECV treatments examined were: 1) unprocessed mash (M), 2) M plus 187 kcal ME_n/kg of soybean oil (M187), and 3) M steam pelleted (P). No significant sex × treatment interactions were detected therefore sex effects were combined. In all experiments, increasing dietary lysine level resulted in greater feed intake, weight gain, protein and lipid tissue gain, and feed efficiency. No significant dietary ECV effects were detected in Experiments 1 and 2. However, overall in Experiment 2 results suggest that calories provided in the diet can be replaced on a one-to-one basis by calories spared through reduced activity. In Experiment 3, P fed birds had higher feed intake, weight gain, protein and lipid gain, and feed efficiency compared to M187. Responses to P and M187 were equal when lysine intake was used as a covariate in the model. Regression models were successful in inter-relating body composition with lysine need. Models indicated that current recommendations for dietary lysine fail to sufficiently meet lysine requirement for the fist 10 d of age. Afterwards, recommended dietary lysine levels exceed requirements particularly towards the end of the growth curve.

(Key words: broilers, pelleting, lysine, effective caloric value)

INTRODUCTION

Intrinsic factors determine a broiler's overall capacity to synthesize and accumulate muscle (Lawrence and Fowler, 1997). However, whether or not the inherent upper limit is realized largely depends on the dietary supply of essential amino acids, as well as energy, as protein accretion is energetically costly (4 to 7 moles of ATP per peptide bond formed; Bequette, 2003). As maximum meat yield at optimal efficiency is a principle goal, nutritionist's routinely tweak nutrient to calorie ratios in an attempt to provide an ideally balanced ration.

In practical corn-soybean meal based broiler diets, methionine is considered first limiting followed by lysine, arginine, valine, and threonine (Han et al., 1992). However, lysine is the amino acid to which all others are proportionally related (i.e. ideal protein concept; Baker and Han, 1994; Baker, 1997). Additionally, lysine is generally expressed in ratio to energy, as dietary caloric density largely regulates voluntary feed intake (Leeson et al., 1996; McKinney and Teeter, 2004). Lysine is largely viewed as a pivotal nutrient because lysine has no major precursor role, and there has been extensive work to quantify digestible lysine need in broilers reared under a wide range of dietary and environmental circumstances (Han and Baker, 1993; Emmert and Baker, 1997).

In addition to pelleting, numerous other nonnutritive factors encountered in broiler production such as stocking density (Cravener et al., 1992; Puron et al., 1997), lighting program (Buyse et al., 1996; Ingram et al., 2000), ventilation (Lott et al., 1998), and feed processing techniques (i.e., pelleting; Acar et al., 1991; Schiedeler, 1995; Moritz et al., 2001) are well documented to impact body weight (BW) and feed conversion ratio (FCR). If the paradigm is accepted that these responses are consequences of managerial-

husbandry decisions that either “take away” or “add to” energy provided by the diet, then nonnutritive entities of broiler production need to be considered as variables directly influencing the ration formula.

Therefore, the following experiments were conducted to evaluate the efficacy of expressing lysine in ratio with calories added to the diet in two ways. 1) by increasing ME through substrate addition, or 2) through reduced activity energy expenditure by differing broiler management circumstances. Secondly, data will be utilized to develop a model that enables lysine requirement to be inter-related with body composition.

MATERIALS AND METHODS

General Information

In a related experiment that was directed at evaluating the ECV of pelleting under conditions mimicking those found commercially, male and female broilers (Cobb 500) were obtained from a commercial hatchery following sexing and vaccination for Marek’s disease. The chicks were wing-banded and allotted by sex to floor pens (3.5 × 2.0 m) with used litter top-dressed with fresh wood shavings. The lighting program followed was 23L:1D and the stocking density was 45 birds per pen. Birds were reared with ad libitum access to feed and water on starter (0-18 d), grower (18-35 d), and finisher (35-60 d) diets (Table 1) formulated to meet or exceed nutrient recommendations of the Cobb Broiler Nutrition Guide (2003). Treatments during the starter phase were: 1) unprocessed mash (M) and 2) M steam pelleted and crumbled (C). Treatments for the grower and finisher phases were: 1) M; 2) M plus soybean oil (187 kcals ME_n / kg diet; M187); and 3) M steam pelleted and sifted (P). Pens assigned to C in the starter phase were randomly

re-assigned to either M187 or P in the grower and finisher phases. At the outset of this experiment, 25 wing-bands from each pen were randomly selected. Spray paint was applied to the wing bows of the birds with pre-selected wing-bands so that those birds could be easily identified for use in the experiments reported herein.

The aim of the experiments described herein was also to evaluate dietary ECV, namely the efficacy of expressing dietary nutrients in ratio to ECV. Experiments were of similar design and utilized male and female broilers (obtained from the aforementioned bird population) over age intervals ranging from 1 to 10 (Experiment 1; EXP1), 19 to 29 (Experiment 2; EXP2), and 45 to 55 (Experiment 3; EXP3) days. During the test periods, the birds were housed individually in floor pens (46 x 60 x 60 cm) equipped with a stainless steel feeder, a nipple drinker, and fresh wood-shavings. Feed and water were provided for ad libitum consumption and the same lighting program stated previously was followed. The general treatment structure for the three experiments was four dietary lysine levels and 2 (M and M187; Experiment1) or 3 (M, M187, and P; Experiments 2 and 3) ECV treatments in a factorial arrangement. Note, dietary ECV treatments formerly assigned were maintained in these experiments. Body weight gain (BWG), feed intake (FI), and whole-body protein (PD) and lipid (LD) deposition were quantified in each assay. Further, digestible lysine (LI) and metabolizable energy (MEI) intake, feed conversion ratio (FCR), apparent efficiency of energy retention (retained energy/energy intake; kRE), and the efficiency of lysine for whole-body protein deposition (protein gain/lysine intake; $kLys_{PD}$) were calculated.

To obtain whole-body PD and LD, initial and final body composition was determined using dual-energy x-ray absorptiometry (DXA) as described by McKinney et al. (2005).

In brief, birds were fasted (8 h), anesthetized (Skinner-Noble et al., 2005), and scanned 4 consecutive times in the prone position. Equations developed by McKinney et al. (2005) were used to adjust DXA measurements to match what would otherwise have been obtained by proximate analysis (AOAC, 1990). As a check of DXA results, the summation of the adjusted bird protein, water, lipid, and ash were compared with the gravimetric weight. Body weight calculated from adjust DXA measurements not within ± 5% of the respective gravimetric weight were excluded and the accepted scans for each bird were combined for analysis.

Diets

The preparation of the experimental diets involved several steps. First, for each experiment, a basal diet (Table 2) was formulated to 105% of recommended nutrient concentrations (Cobb Broiler Nutrition Guide, 2003), with the exception of lysine. Second, four premixes with graded levels of lysine were formulated to be iso-caloric, iso-nitrogenous and equal in Na^+ and Cl^- ions, utilizing L-lysine-HCL, NaCL, $NaHCO_3$, glutamic acid, corn starch, and Solka-Floc®. Four additional premixes were formulated in the same manner with the exception that the energy level was increased by adding soybean oil at the expense of Solka-Floc®. The experimental diets were then prepared by mixing proportions of the basal diet (95%) and the premixes (5%). In Experiments 2 and 3, half of the diets of the base energy level were steam conditioned and pelleted.

Experimental design

All dietary lysine levels examined were deficient relative to that recommended (Cobb Broiler Nutrition Guide, 2003). Not focusing replication around the zone where

responses to lysine plateau allowed a wider range of lysine levels to be evaluated. In addition, this approach ensured response linearity, which enables the lysine requirement to be projected based on slope analysis. Experiment 1 had a 2 × 4 factorial arrangement of dietary treatments. Diets of four lysine levels (3.9, 5.2, 6.5, and 7.8 g/kg) were fed as: 1) M (3,053 kcal ME_n / kg diet) and 2) M187 (3240 kcal ME_n / kg diet). Experiments 2 and 3 had a 3 × 4 factorial arrangement of dietary treatments. Dietary lysine levels in Experiments 2 and 3 were: 3.5, 4.8, 6.1, and 7.4, and 3.0, 4.3, 5.6, and 6.9 g/kg, respectively. In Experiment 2, each of the lysine levels were fed as: 1) M (3,131 kcal ME_n / kg diet); 2) M187 (3,318 kcal ME_n / kg diet); and 3) P (3,131 kcal ME_n / kg diet). In Experiment 3, each of the lysine levels were fed as: 1) M (3,174 kcal ME_n / kg diet); 2) M187 (3,361 kcal ME_n / kg diet); and 3) P (3,174 kcal ME_n / kg diet).

Data Analysis

Bird served as the experimental unit and the experiments were analyzed as a completely randomized design. Data were analyzed using General Linear Models of SAS (2000), with probability values of $P < 0.05$ considered significant. When a significant F-statistic was detected, least square means were used for treatment comparisons. Orthogonal polynomial contrasts were used to test for linear and curvilinear responses with respect to lysine level.

Modeling procedures were based on forward stepwise regression (Neter et al., 1990). Factors were added to the regression model until three conditions were met: 1) adding factors to the model did not result in a substantial (R^2 improvement < 2 %) increase in the

model R^2; 2) all factors in the model were significant at $P < 0.10$; and 3) the resulting model matched known properties of the independent variables.

RESULTS AND DISCUSSION

No significant sex × lysine treatment interactions were detected in any of the experiments. This was expected as prior research with both swine (Susenbeth, 1995) and poultry (Han and Baker, 1993) have shown no sex differences when diets of sub-optimal lysine content were fed. Limited data is available as to differences between male and female responses to pelleting. However, it has been suggested (Nir and Hillel, 1995) that females are slightly less responsive to pellets. However, similar observations were obtained from two independent studies, one utilizing males (McKinney and Teeter, 2004), the other females (Skinner-Noble et al., 2005), as to the activity calories spared due to pelleting. In the present study no sex × ECV treatment interactions were detected indicating that males and females response similarly to pelleting. As no significant sex × dietary treatment interactions were detected sex effects were combined (Table 3, 4, and 5).

No significant ECV × lysine level interactions were detected for FI, LI, or MEI. Overall, there was a tendency for feed consumption to increase in a linear manner ($P < 0.09$) as dietary lysine level was increased. Observations that a bird's appetite increases to a point as dietary lysine is increased are well documented throughout the literature (Tesseraud et al. 1992; Edwards et al., 1999; Fatufe et al., 2004). Lysine fed in excess of need has the opposite effect. Dietary ECV did not influence feed consumption in EXP1 or EX2. However in EXP3, birds provided pellets consumed more ($P < 0.05$) feed,

lysine, and energy compared to those fed M187, which appeared to have a depressed appetite. It is generally accepted that voluntary intake is largely controlled by energy consumption (Leeson et al. 1996; McKinney and Teeter, 2004). However, birds fed P consumed more energy overall compared to the M187 fed group. This would suggest that calories spared by reduced activity are not perceived in a manner that would regulate consumption.

No ECV × dietary lysine level interactions were detected for BWG, PD, or LD in EXP 2 and EXP 3. A significant interaction was observed in EXP1. Birds fed the lowest lysine level and M had significantly higher ($P < 0.05$) BWG, PD, and LD compared to birds fed the same lysine level and M187. Then as the dietary lysine levels increased, M187 fed birds surpassed those receiving M. It should be noted that birds on the low lysine M187 treatment did not consume feed well. Either birds on this treatment did not adapt to the experimental cages or as Jensen (1965) reported, the supplemental dietary energy resulted in an energy-lysine imbalance. Unfortunately, birds of this age are unable to consume whole pellets so Jensen's (1965) hypothesis that pelleting exacerbates a deficiency could not be evaluated.

In EXP2 and EXP3, BWG, PD and LD increased (EXP2; linearly $P < 0.05$) as more dietary lysine was provided. Based on the work of Urdaneta-Rincon and Leeson (2004) this is a result of increased tissue synthesis rather than a reduction in tissue degradation. Similarly, Tesseraud et al. (1992) demonstrated that both fractional synthesis and degradation of protein increases with lysine consumption, only fractional synthesis occurs at a higher level. In EXP3, P resulted in significantly more PD and LD compared to M187 and M birds. This may be partially attributed to the greater lysine consumption

of birds fed P. However, when lysine consumption was included in the model as a covariate, a significant F-statistic for ECV was obtained. Means separation revealed the P still yielded higher PD. Additionally, though not statistically different, it should be noted that in EXP2, treatment P and M187 were virtually the same with respect to BWG, PD, and LD, and had similar lysine intakes.

In general FCR and kRE were improved and $kLys_{PD}$ reduced as dietary lysine was increased. Regarding the latter, several reports have suggested that the efficiency of lysine utilization declines with increased LI (Batterham et al., 1990; Gahl et al., 1991; Fatufe et al., 2004). In contrast, Möhn et al. (2000) reported that lysine utilization did not decline with increasing LI. It ultimately may depend on the manner in which lysine efficiency is quantified (Lys/Lys verses Lys/Prot). There is still discussion as to the composition of protein under conditions of sub-optimal lysine. For example, Skan and Noy (2004, 2005) contend that the lysine content of chicken tissue remains constant when dietary lysine is deficient. Conversely, Edwards et al. (1999) and Fatufe et al. (2004) contend that during lysine deficiency the lysine content of the tissue proportionally decreases. Nonetheless, lysine content of tissues was not evaluated in this study and $kLys_{PD}$ is expressed as lysine consumed per unit protein gain. This is an apparent estimation and subject to error if the lysine content of the animal actually changes (i.e., increase collagen vs. breast tissue).

Indeed, the results of this experiment were somewhat variable. This may have resulted from 1) birds individually housed; 2) lack of appropriate replication; 3) birds in EXP2 not having an adaptation period to pellets; or 4) an inadequate experimental period. However, overall the data suggests that calories provided in the diet can be replaced by

calories spared through reduced activity. Additionally, there was a general lack of interaction between energy (provided in either form) and lysine. Moreover, results give support to the importance of considering broiler management in establishing nutrient to energy ratios.

An objective of this study was to develop a mathematical model that inter-relates broiler lysine requirement with the body composition for the entire growth curve. As P was not included as a treatment in EXP1, data for the entire growth curve was unavailable. Therefore, P was excluded from the data set for modeling purposes. Numerous variables expressed both as measured and per unit metabolic body size ($BW^{0.67}$) evaluated in the development of this model. The parameters which yielded the best model for predicting daily total (TL, g) and digestible lysine (DL, g) consumption were 1) dietary :ME_n:Lysine ratio (EL; g/kcal); 2) mean PD (g) and 3) daily PD (g). The resulting equations were:

(Eq. 1) TL = 0.46335 – (0.00007321 × EL) + (0.00121× mean PD) + (0.04227× daily PD); (R^2 = 91.6%)

(Eq. 2) DL = 0.41308 – (0.00005846 × EL) + (0.00110 × mean PD) + (0.03878× daily PD);(R^2 = 91.0%)

To evaluate the estimated daily total and digestible lysine requirement, as it compares to current recommendations (Cobb Vantress, 2003), data provided from the field (Wiernusz, 2005) were applied to the equations.

Results from these equations are illustrated in Figure 1. Based on these estimations, current recommendations do not sufficiently supply the broiler with the required amount of lysine for the first 10 days of age. After that, lysine is fed in excess particularly towards the end of the growth curve. Indeed, nutritionist's build buffers into the ration formula to protect against, for example, feed mixing mistakes, but is possible with these equations to quantify that allowance.

Potentially, information obtained from these equations could be used to modify the existing ideal protein model. Furthermore, it may be possible to integrate these equations into a more mechanistic approach whereby producers could specify, for example, desired bird composition, total days available for production, and rearing conditions, and these models would provide dietary provisions necessary to achieve that target.

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Table1. Composition of diets used to rear broilers to the ages evaluated in Experiments 1, 2, and 3

	Age interval, d and Treatments[1,2]				
	0 to 18	18 to 35		35 to 60	
Ingredient, %	M and P	M and P	M187	M and P	M187
Corn	58.12	64.89	60.73	68.72	64.31
Soybean meal (48% CP)	32.66	24.59	25.61	22.76	23.63
Soybean oil	2.90	2.93	6.4	3.32	6.89
Poultry by-product meal	1.50	3.00	3.00	0.50	0.50
Monocalcium phosphate	1.36	1.05	0.94	1.20	1.21
Limestone	1.32	1.04	0.94	1.08	1.07
NaCl	0.34	0.29	0.32	0.34	0.35
$NaHCO_3$	0.25	0.32	0.27	0.30	0.28
Vitamin premix[3]	0.28	0.24	0.24	0.25	0.25
Trace mineral premix[4]	0.09	0.09	0.09	0.09	0.09
Selenium premix	0.04	0.04	0.04	0.04	0.04
$CuSO_4$	0.002	0.002	0.002	0.002	0.002
Choline chloride	0.001	–	–	–	–
DL-Methionine	0.22	0.22	0.19	0.12	0.12
Lysine	0.076	0.157	0.10	0.10	0.08
Arginine	0.03	0.05	0.03	0.05	0.03
Threonine	0.03	0.05	0.02	0.05	0.04
AmeriBond 2x	0.75	1.00	1.00	1.00	1.00
Coccidiostat	0.05	0.05	0.05	0.08	0.08
Ethoxyquin	0.012	0.012	0.012	0.012	0.012
Calculated Analysis					
ME_n (kcal / kg)	3,053	3,131	3,318	3,174	3,361
CP, %	22.1	19.8	19.8	17.5	17.5
Arg	1.49	1.30	1.30	1.16	1.16
Lys	1.26	1.14	1.14	0.96	0.96
Met	0.55	0.52	0.52	0.42	0.42
TSAA	0.94	0.88	0.88	0.76	0.76
Ca	0.90	0.80	0.80	0.72	0.72
P, available	0.44	0.40	0.40	0.37	0.37

[1]Treatments: M = mash; M187 = M plus soybean oil (187 kcal ME_n/kg); P = M steam pelleted and sifted.
[2]From 0 to 18 days, P was crumbled.
[3]Supplied per kilogram of diet: vitamin A, 10,141 IU (retinyl acetate); cholecalciferol, 3,086 IU; vitamin E, 23.92 IU (dl-α-tocopheryl acetate); menadione, 2.87 mg; thiamine, 2.20 mg; riboflavin, 7.72 mg; niacin, 60.30 mg; d-pantothenic acid, 12.46 mg; pyridoxine, 3.75 mg; vitamin B_{12}, 0.017 mg; folic acid, 1.066 mg; d-biotin, 0.127 mg.
[4]Supplied per kilogram of diet: Ca,160 mg; Zn, 100 mg; Mn, 120 mg; Fe,75 mg; Cu, 10 mg; I, 2.5 mg.

Table 2. Basal diets used in Experiments 1, 2, and 3

	Experiment		
Ingredient	1	2	3
Corn	62.0	70.2	76.2
Corn gluten meal	15.0	13.9	11.4
Wheat bran	5.6	2.1	–
Soybean oil	3.2	3.0	3.0
Poultry by-product meal	1.58	1.28	1.22
Soybean meal	1.58	1.26	0.53
Mono-calcium phosphate	1.56	1.46	1.34
Limestone	1.54	1.39	1.22
Corn Starch	1.26	–	–
Potassium sulfate	1.26	0.87	0.95
Arginine	0.99	0.81	0.71
Pellet binder	0.79	1.05	1.05
$NaHCO_3$	0.72	0.62	0.54
Vitamin premix[1]	0.68	0.27	0.28
Isoleucine	0.33	0.23	0.18
Serine	0.33	–	–
Threonine	0.29	0.23	0.23
Glycine	0.29	0.13	0.29
Valine	0.28	0.18	0.18
Histidine	0.22	0.15	0.07
Methionine	0.21	0.18	0.09
Tryptophan	0.13	0.11	0.09
Trace mineral premix[2]	0.095	0.095	0.100
Coccidiostat	0.053	0.079	0.079
Selenium premix	0.011	0.021	0.028
Ethoxyquin	0.013	0.013	0.013
$CuSO_4$	0.002	0.002	0.002
Choline chloride	–	0.116	0.026
NaCl	–	0.105	0.175
Calculated Analysis			
ME_n (kcal / kg)	3,214	3,296	3,341
CP, %	22.01	19.93	17.68
Arg[3]	1.44	1.25	1.11
Lys[3]	0.39	0.35	0.30
Met[3]	0.55	0.50	0.41
TSAA[3]	0.84	0.78	0.69
Ca	0.95	0.84	0.76
P, available	0.46	0.42	0.39

[1]Supplied per kilogram of diet: vitamin A, 10,141 IU (retinyl acetate); cholecalciferol, 3,086 IU; vitamin E, 23.92 IU (dl-α-tocopheryl acetate); menadione, 2.87 mg; thiamine, 2.20 mg; riboflavin, 7.72 mg; niacin, 60.30 mg; d-pantothenic acid, 12.46 mg; pyridoxine, 3.75 mg; vitamin B_{12}, 0.017 mg; folic acid, 1.066 mg; d-biotin, 0.127 mg.
[2]Supplied per kilogram of diet: Ca,160 mg; Zn, 100 mg; Mn, 120 mg; Fe,75 mg; Cu, 10 mg; I, 2.5 mg.
[3]True digestible basis according to the listing of Ajinomoto Heartland, Incorporated (2001).

Table 3. Broiler growth performance and whole body protein and lipid deposition and retention efficiencies as influenced by dietary treatment, Experiment 1

Dietary treatment[1]		Intake			Deposition[3]			Efficiency		
ECV	Lys[2], %	Diet	Lys[2]	ME_n	BWG	Protein	Lipid	FCR[4]	$kLys_{PD}$[5]	kER[6]
Interactive effect means		(g)		(kcal)	(g)			(g/g)		(%)
M	0.39	146	0.57	446	50^{c}	4.7^{c}	0.1^{d}	3.00	9.7	7.1
M	0.52	144	0.75	439	57^{c}	6.0^{c}	0.7^{cd}	2.60	12.7	14.9
M	0.65	162	1.05	494	83^{b}	9.7^{bc}	2.7^{bc}	1.88	9.7	15.8
M	0.78	187	1.46	571	88^{b}	10.3^{b}	3.3^{b}	2.17	7.4	15.9
M187	0.39	86	0.33	278	36^{d}	1.5^{d}	-1.8^{e}	2.42	4.4	-4.4
M187	0.52	155	0.81	503	61^{c}	5.8^{c}	0.7^{cd}	2.58	8.2	8.5
M187	0.65	211	1.45	685	95^{b}	12.4^{b}	4.4^{b}	2.32	8.2	13.6
M187	0.78	270	2.11	875	127^{a}	18.4^{a}	7.9^{a}	2.15	9.0	20.4
Main effect means										
M		160	0.95	487	70	7.7	1.7	2.41	9.9	13.4
M187		181	1.17	585	80	9.5	2.8	2.37	7.4	9.5
	0.39	116^{c}	0.45^{d}	362^{b}	43^{d}	3.1^{c}	-0.8^{d}	2.71	7.1	1.4^{b}
	0.52	150^{bc}	0.78^{c}	471^{b}	59^{c}	5.9^{b}	0.7^{c}	2.59	10.4	11.7^{a}
	0.65	186^{abc}	1.24^{b}	589^{ab}	89^{c}	11.0^{a}	3.6^{b}	2.10	8.9	14.7^{a}
	0.78	229^{a}	1.78^{a}	723^{a}	108^{a}	14.3^{a}	5.6^{a}	2.16	8.2	18.2^{a}
Source of variation		Probability								
ECV		0.9702	0.4464	0.6470	0.3624	0.5660	0.5766	0.6577	0.2092	0.1273
Lys		0.0074	< 0.0001	0.0054	< 0.0001	< 0.0001	< 0.0001	0.6762	0.7577	0.0127
Linear		0.0809	0.0009	0.0701	< 0.0001	< 0.0001	< 0.0001	0.4186	0.6832	0.0512
Quadratic		0.9534	0.6284	0.9599	0.2036	0.3029	0.3040	0.7327	0.4593	0.4328
ECV × Lys		0.1373	0.0708	0.1057	0.0027	0.0018	0.002	0.8854	0.7913	0.4929
Pooled SEM		10.87	0.55	33.60	2.12	0.43	0.25	0.21	1.28	1.82

[a- e]Means within a column with different superscripts differ ($P < 0.05$).

[1]M = unprocessed mash; M187 = M plus soybean oil (187 kcal ME_n/kg diet).

[2]Expressed as true digestible lysine based on the listing of Ajinomoto Heartland, Incorporated (2001).

[3]Initial body composition determined by whole bird chemical analysis; final body compositions were based on dual energy x-ray absorptiometry measurements adjusted as described by Mckinney et al. (2005).

[4]Feed conversion ratio (FCR) = feed consumption / body weight gain.

[5]Efficiency of dietary lysine for protein deposition ($kLys_{PD}$) = protein deposition/lysine consumption.

[6]Efficiency of energy retention (kER) = ((protein deposition × 5.65 + lipid deposition × 9.31)/Energy (ME_n basis) consumption) × 100.

Table 4. Broiler growth performance and whole body protein and lipid deposition and retention efficiencies as influenced by dietary treatment, Experiment 2

Dietary treatment[1]		Intake			Deposition[3]			Retention		
ECV	Lys[2], %	Diet	Lys[2]	ME_n	BWG	Protein	Lipid	FCR[4]	$kLys_{PD}$[5]	kER[6]
Interactive effect means		(g)		(kcal)	(g)			(g/g)		(%)
M	0.35	490	1.71	1,533	135	22	16	3.64	12.9	17.7
M	0.48	668	3.21	2,091	244	41	31	2.84	12.7	24.7
M	0.61	718	4.38	2,248	318	56	43	2.30	12.8	31.8
M	0.74	819	6.06	2,565	376	65	51	2.21	10.6	32.4
M187	0.35	648	2.27	2,149	209	34	26	3.23	14.4	19.3
M187	0.48	574	2.75	1,904	229	38	29	2.53	14.6	26.8
M187	0.61	735	4.48	2,439	342	59	47	2.17	13.0	31.1
M187	0.74	815	6.03	2,704	396	70	57	2.07	11.5	34.1
P	0.35	700	2.45	2,191	273	46	36	2.83	18.7	27.2
P	0.48	594	2.85	1,860	226	38	30	2.65	13.4	26.2
P	0.61	712	4.34	2,228	285	49	38	2.53	11.4	28.2
P	0.74	863	6.13	2,703	398	68	54	2.20	10.9	32.0
Main effect means										
M		674	3.84	2,109	268	46	35	2.75	12.2	26.7
M187		693	3.88	2,299	294	50	40	2.50	13.4	27.8
P		717	3.94	2,246	295	50	39	2.55	13.6	28.4
	0.35	612[c]	2.14[d]	1,958[c]	205[c]	34[c]	26[c]	3.23[a]	15.3[a]	21.4[c]
	0.48	612[c]	2.94[c]	1,952[c]	233[c]	39[c]	30[c]	2.67[b]	13.6[ab]	25.9[b]
	0.61	721[b]	4.40[b]	2,305[b]	315[b]	55[b]	42[b]	2.33[c]	12.4[bc]	30.4[a]
	0.74	832[a]	6.07[a]	2,657[a]	390[a]	68[a]	54[a]	2.16[c]	11.0[c]	32.8[a]
Source of variation		Probability								
ECV		0.8513	0.9775	0.7756	0.8037	0.8685	0.767	0.3575	0.5164	0.8149
Lys		0.0006	< 0.0001	0.0006	< 0.0001	< 0.0001	< 0.0001	< 0.0001	0.0005	< 0.0001
Linear		0.0856	< 0.0001	0.0875	0.0017	0.001	0.0029	< 0.0001	0.0182	0.0002
Quadratic		0.2670	0.2748	0.2577	0.2988	0.2787	0.3096	0.4576	0.7612	0.9861
ECV × Lys		0.655	0.9431	0.6659	0.4284	0.4726	0.4835	0.3927	0.1839	0.2115
Pooled SEM		19.29	0.12	61.72	10.24	1.87	1.64	0.06	0.37	0.69

[a- d]Means within a column with different superscripts differ ($P < 0.05$).

[1]M = unprocessed mash; M187 = M plus soybean oil (187 kcal ME_n/kg diet); P = M steam pelleted and sifted.

[2]Expressed as true digestible lysine based on the listing of Ajinomoto Heartland, Incorporated (2001).

[3]Based on dual energy x-ray absorptiometry measurements adjusted as described by Mckinney et al. (2005).

[4]Feed conversion ratio (FCR) = feed consumption / body weight gain.

[5]Efficiency of dietary lysine for protein deposition ($kLys_{PD}$) = protein deposition/lysine consumption.

[6]Efficiency of energy retention (kER) = ((protein deposition × 5.65 + lipid deposition × 9.31)/Energy (ME_n basis) consumption) × 100.

Table 5. Broiler growth performance and whole body protein and lipid deposition and retention efficiencies as influenced by dietary treatment, Experiment 3

Dietary treatment[1]		Intake			Deposition[3]			Retention		
ECV	Lys[2], %	Diet	Lys[2]	ME_n	BWG	Protein	Lipid	FCR[4]	$kLys_{PD}$[5]	kER[6]
Interactive effect means		(g)		(kcal)	(g)			(g/g)		(%)
M	0.30	1,412	4.24	4,482	245	40.5	50.5	5.86	9.6^{bc}	15.6
M	0.43	1,515	6.51	4,809	306	55.5	75.7	5.21	8.8^{bc}	21.8
M	0.56	1,520	8.51	4,824	351	60.3	80.0	4.54	7.1^{bc}	22.5
M	0.69	1,663	11.48	5,279	395	59.5	81.0	4.51	5.1^{c}	20.2
M187	0.30	1,233	3.70	4,144	222	39.6	52.0	5.55	10.7^{bc}	17.1
M187	0.43	1,137	4.89	3,820	321	49.2	69.0	4.13	10.3^{bc}	24.5
M187	0.56	1,445	8.09	4,857	353	58.6	76.3	4.69	7.0^{bc}	20.6
M187	0.69	1,505	10.39	5,059	524	79.0	111.0	2.96	7.8^{bc}	29.7
P	0.30	1,079	3.24	3,426	322	69.1	91.4	3.34	22.9^{a}	39.1
P	0.43	1,557	6.69	4,940	423	74.4	102.7	3.75	11.0^{b}	27.6
P	0.56	2,230	12.49	7,078	570	102.9	142.7	4.09	8.2^{bc}	26.7
P	0.69	2,086	14.40	6,622	680	104.6	161.9	3.38	7.1^{bc}	30.8
Main effect means										
M		1,528^{b}	7.68^{ab}	4,849^{ab}	324^{b}	54.0^{b}	71.8^{b}	5.03^{a}	7.6^{b}	20.0^{b}
M187		1,330^{b}	6.77^{b}	4,470^{b}	355^{ab}	56.6^{b}	77.1^{b}	4.34^{ab}	8.9^{b}	23.0^{b}
P		1,738^{a}	9.20^{a}	5,517^{a}	499^{a}	87.8^{a}	124.7^{a}	3.64^{b}	12.3^{a}	31.0^{a}
	0.30	1,241^{c}	3.72^{d}	4,017^{c}	263^{b}	49.7^{b}	64.7^{b}	4.92	14.4^{a}	23.9
	0.43	1,403^{bc}	6.03^{c}	4,523^{bc}	350^{b}	59.7^{ab}	82.5^{ab}	4.37	10.0^{b}	24.6
	0.56	1,732^{ab}	9.70^{b}	5,587^{ab}	425^{ab}	73.9^{ab}	99.6^{ab}	4.44	7.4^{bc}	23.3
	0.69	1,752^{a}	12.09^{a}	5,653^{a}	533^{a}	81.0^{a}	118.0^{a}	3.62	6.7^{c}	26.9
Source of variation		Probability								
ECV		0.0072	0.0043	0.0295	0.0226	0.0046	0.0029	0.0358	0.0036	0.0076
Lys		0.0027	< 0.0001	0.0027	0.0071	0.0691	0.0320	0.2847	< 0.0001	0.8227
Linear		0.0111	< 0.0001	0.0112	0.0868	0.0992	0.1228	0.4948	0.0002	0.8793
Quadratic		0.5779	0.4541	0.5636	0.9370	0.8593	0.9862	0.5843	0.5276	0.7763
ECV × Lys		0.1938	0.3146	0.2039	0.9201	0.9398	0.9004	0.5828	0.0094	0.2783
Pooled SEM		52.07	0.31	166.73	26.34	4.10	6.36	0.20	0.48	1.28

[a- d]Means within a column with different superscripts differ ($P < 0.05$).

[1]M = unprocessed mash; M187 = M plus soybean oil (187 kcal ME_n/kg diet); P = M steam pelleted and sifted.

[2]Expressed as true digestible lysine based on the listing of Ajinomoto Heartland, Incorporated (2001).

[3]Based on dual energy x-ray absorptiometry measurements adjusted as described by Mckinney et al. (2005).

[4]Feed conversion ratio (FCR) = feed consumption / body weight gain.

[5]Efficiency of dietary lysine for protein deposition ($kLys_{PD}$) = protein deposition/lysine consumption.

[6]Efficiency of energy retention (kER) = ((protein deposition × 5.65 + lipid deposition × 9.31)/Energy (ME_n basis) consumption) × 100.

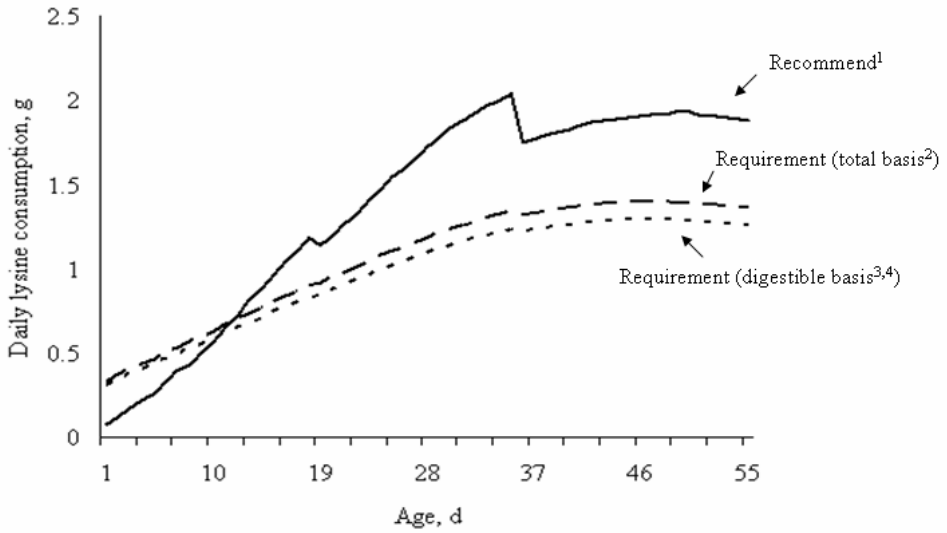

Figure 1. Recommended and predicted total and digestible daily lysine requirement of male and female broilers

[1]Cobb Broiler Nutrition Guide (2003).

[2]Total daily lysine requirement = $0.46335 - 7.321e^{-5} \times$ ME (kcal kg^{-1}) lysine (g) ratio $+ 1.21e^{-3} \times$ mean daily whole body protein $+ 4.227e^{-2} \times$ daily whole body gain.

[3]Digestible daily lysine requirement = $0.41308 - 5.846e^{-5} \times$ ME (kcal kg^{-1}) lysine (g) ratio $+ 1.1e^{-3} \times$ mean daily whole body protein $+ 3.387e^{-2} \times$ daily whole body gain.

[4]Digestibility coefficients reported by Ajinomoto Heartland, Incorporated (2001).

CHAPTER VII

A Novel Approach for Determining the Efficiencies of Metabolizable Energy Utilization for Protein and Lipid Tissue Accretion in Broilers

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RUNNING TITLE: Research Note

Abbreviation Key: MEI = intake of metabolizable energy; MEm = intake of metabolizable energy for maintenance; RE = metabolizable energy retained in body tissue; ERP = metabolizable energy retained as protein; ERL = metabolizable energy retained as lipid; k_p = efficiency of energy utilization for protein tissue retention; k_f = efficiency of energy utilization for lipid tissue retention

ABSTRACT

Data from two 10 d experiments utilizing 15 and 34 d old Cobb 500 male broilers were conducted, pooled and used to model metabolizable energy (ME) need for maintenance, and tissue accretion. Methodologies used to estimate energetic efficiency of energy consumed above maintenance for protein (k_p) and lipid (k_f) tissue accretion were tested and a novel method developed. The maintenance energy requirement, expressed per unit metabolic body size, was independent of bird age and was determined as 114 kcal/ kg $BW^{0.67}$. Values determined using regression analyses were 0.75 and 0.86 for k_p and k_f, respectively. Regression analysis separating retained energy into energy retained as protein and lipid tissue has been criticized due to the colinearity between protein and lipid tissue accretion. To circumvent this, a novel methodology was developed as follows: first a matrix of biologically possible k_p and k_f values is created followed by its application to predict ME intake above maintenance. The k_p k_f combination enabling ME intake computation with zero error was accepted. Between the two methods, values for k_f were in close agreement (0.86 verses 0.88). While the regression analysis estimated k_p as 0.75 vs. 0.61 for the novel approach. Utilizing resulting k_p and k_f values, coupled with protein and lipid accretion to estimate ME intake above maintenance, indicated less error for the novel approach. Based upon the regression overestimate it was thereby concluded that the method discrepancy was a result of muticollinearity between the predictor variables in the regression model. Further, the proposed methodology for calculating k_p and k_f appears to provide more accurate estimates.

(Key words: broiler, maintenance energy, energetic efficiency, body composition)

INTRODUCTION

Intrinsically, there is a caloric cost associated with the accretion of lean and lipid tissue. These costs are reflected in the overall heat production of an animal and are accounted for when a diet's energy value is expressed as net energy. Though net energy fully accounts for energetic inefficiencies, a net energy system has been difficult to establish due to the complexity of its accurate measure and practical application. Conversely, metabolizable energy can be rapidly and precisely determined (Sibbald 1976; McNab and Blair, 1988), and therefore remains the standard measure for evaluating dietary energy in poultry diets. As such, efforts have been directed towards quantifying the metabolizable energy required for maintenance and the efficiency of metabolizable energy utilization for broiler tissue accretion (Leclercq and Saadoun, 1982; Boekholt et al. 1994).

The simplest approach for assessing the efficiency of metabolizable energy utilization for tissue accretion is by partitioning metabolizable energy intake into energy utilized for maintenance and that retained as tissue. This is accomplished by regressing retained energy on metabolizable energy consumption. In this instance, the slope parameter estimate yields the efficiency of metabolizable energy for tissue accretion and the residual energy (intercept) indicates the energy needed for maintenance (DeGroote, 1974). However, this approach is not descriptive as to the type of tissue accreted and thus differences in efficiencies of energy utilization associated with protein and lipid tissue are ignored.

In an effort to separate the energetic efficiencies associated with the production of protein and lipid tissue, Kielanowski (1965) proposed subdividing metabolizable energy

intake as follows: MEI = ME_m + ($1/k_p$ × RPE) + ($1/k_f$ × RLE), where: MEI = metabolizable energy intake, ME_m = metabolizable energy required for maintenance, RPE = energy retained as protein, RLE = energy retained as fat, k_p = efficiency of energy utilization for protein, and k_f = efficiency of energy utilization for fat. Through regression analysis values for ME_m, k_p, and k_f can be attained. This approach however, has received criticism due to the autocorrelation among the predictor variables (Emmans, 1994; Noblet et al., 1999), and its inability for separating metabolizable energy into contributing dietary substrates (Noblet et al., 1993). Further, any approach to estimating the efficiency of energy utilization for tissue accretion requires a sound understanding of energy required for maintenance. Errors or assumptions made relative to the maintenance energy requirement carries-over resulting in an over or under estimation of energy available for gain and ultimately false estimates for the metabolic costs of tissue accretion.

The objective of the following chapter is first directed at quantifying metabolizable energy required for maintenance and production in broilers, and second, to examine potential errors associated with the method proposed by Kielanowski (1965) for separating the energetic efficiencies associated with the production of protein and lipid tissue and its associated criticisms.

MATERIALS AND METHODS

Data Source

Data analyzed in this report were obtained from two experiments of the same design that were conducted in an effort to quantify differences in the energetic efficiency of

dietary protein, starch, and fat (unpublished). Diets were formulated to represent ranges of nutrients typically fed to broilers in the United States. Both studies utilized Cobb 500 male broilers that were obtained from a commercial hatchery. Birds were reared in floor pens equipped with two cylinder-shaped gravity feeders, nipple drinkers, and used litter (wood shavings) that was top-dressed with fresh litter. Stocking density in the floor pens was 40 birds per pen providing 0.03 m^3 of floor space per bird and ad libitum access to a commercial diet and water was provided. On 15 (Experiment 1) and 34 (Experiment 2) days of age, 90 broilers were randomly selected from the floor pens and individually housed in cages. Cages were elevated (1.2 m) and constructed of plastic-coated-wire (46 x 60 x 60 cm) equipped with a small plastic trough feeder and a nipple drinker. For a 6 day period, the birds were fed 1 of 15 dietary treatments (Table 3) twice per day (0900 and 2100 h) so as to provide 50, 100, or 150% of the estimated maintenance energy requirement (Leclercq and Saadoun, 1982).

Preparation of the experimental diets involved several steps. First, for each experiment, three basal diets (Table 1) were formulated to either: 97.5, 100, or 102.5% the dietary crude protein recommended by the NRC (1994) and 3,050 kcal ME/kg diet. Amino acids were balanced in proportion to lysine in accordance to minimum amino acid ratios of the ideal protein concept (Baker and Han, 1994; Baker, 1997). Secondly, either corn starch or corn oil was added in place of areaneous flour to increase the dietary caloric density to either 0, 3,200, or 3,350 kcal ME/kg diet.

Initial and final body composition was determined using dual-energy x-ray absorptiometry (DEXA) as described by McKinney et al. (2005). In brief, birds were fasted (8 h), anesthetized (Skinner-Noble et al., 2005), and scanned 4 consecutive times

in the prone position. Equations developed by McKinney et al. (2005) were used to adjust DEXA measurements to match what would otherwise have been obtained by proximate analysis (AOAC, 1990). As a check of DXA results, the summation of the adjusted bird protein, water, lipid, and ash were compared with the gravimetric weight. Body weight calculated from adjust DXA measurements not within ± 5% of the respective gravimetric weight were excluded and the accepted scans for each bird were combined for analysis.

Calculations and Data Analysis

Variables used in the analysis were calculated as: mean metabolic body size (MBW) = ((final body weight + initial body weight)/2) to the exponent of 0.67; energy retained as lipid (RLE) = change in body lipid (kg) × 9,310 kcal; energy retained as protein (RPE) change in body protein (kg) × 5,650 kcal; and retained energy = RPE + RLE. All data presented herein are expressed per unit MBW. Maintenance energy requirement and the efficiency of metabolizable energy intake (MEI) for protein (k_p) and lipid (k_f) tissue accretion were estimated according to the following regression models:

(1) $ME_m = a + b \times RE$

(2) $MEI = ME_m + (1/k_p) \times RPE + (1/k_f) \times RLE$

RESULTS AND DISCUSSION

When the data were expressed on a per MBW basis, no differences were detected between Experiments 1 and 2, therefore data of the two experiments were combined and are presented in Table 4 and Figure 1.

Maintenance Energy Requirement

Metabolizable energy required for maintenance was estimated in three ways (Table 5). In the first approach, all of the data were used in developing the regression equation (Table 5; equation 1). This approach requires the assumption that RE responses are linear as MEI increases. This was tested using a polynomial regression model (MEI = a + b × RE + c × RE^2). In this instance, the quadratic parameter estimate was not significant (P = 0.60), which would indicate that this assumption is true. However, if a slight change in the slope of the line below verses above maintenance does exist, as has been proposed (NRC, 1994), then the maintenance energy requirement (intercept) would be overestimated. Therefore, the second and third approaches in estimating maintenance energy requirement were to subdivide the data into regions (Figure 1). Comparison of the resultant regression equations (Table 5) indicate that the slope of the line does change slightly as MEI increases above the maintenance energy requirement. All of the estimates for maintenance energy requirement were in close agreement with previously reported values (Leclercq and Saadoun, 1982; Robbins, and Ballew, 1984; Pinchasov and Galili, 1990; Sakomura, 2004).

Estimates for the Efficiency of Energy Utilization for Protein and Lipid Tissue Retention

The regression model where RE was subdivided into RPE and RLE (Table 6) resulted in k_p and k_f estimates of 0.75 and 0.86, respectively. The k_f estimate was similar to that reported by Leclercq and Saadoun (1982; 0.87), Boekholt et al. (1994; 0.86), Pullar and Webster (1977; 0.74), and van Milgen and Noblet (1999; 0.92). The value determined for k_p appeared to be overestimated compared to previously reported estimates (Leclercq and Saadoun, 1982; k_p = 0.4; Boekholt et al., 1994; k_p = 0.66; Pullar and Webster, 1977;

k_p = 0.45). Note however, that considerable variability exists among the proposed values. This variation has been attributed to the autocorrelation that exists among the variables in the model (Emmans, 1994; Noblet et al., 1999). It appears however, that the variability is not necessarily due to autocorrelation, but rather the collinearity between RPE and RLE (Figure 2).

Multicollinearity is a term that denotes correlation among variables in the regression model (Neter et al., 1990). Multicollinearity is not necessarily problematic if the goal of the model is predicting the independent variable. However, as the goal is to obtain k_p and k_f through regression analysis, interpreting the parameter coefficients becomes difficult if not impossible when multicollinearity exists among the dependent variables. In general correlation coefficients of 0.70 or higher establish that significant multicollinearity exists (Leahy, 2000).

In order to avoid the variability associated with the interpretation of the parameter estimates when multicollinearity exists, a different approach is suggested for obtaining k_p and k_f values (Appendix). Consider a data set (EnergyforGain) that includes the following variables MEI, ME_m, RPE, and RLE. Based on this data set, a new data set (Matrix) can be created. In that data set, a matrix of biologically possible k_p and k_f values can be generated (use caution in generating this k_p and k_f matrix: if the matrix becomes to large then the SAS output will cease). Using the matrix data set, a new data set (kpkf) can be created. Next, by subtracting ME_m from MEI the following equation can be derived: $ME_{forgain} = RPE/k_p + RLE/k_f$. The program will examine every combination of k_p and k_f in the equation and thus enable the identification of a k_p and k_f combination that yields the actually MEI value, as illustrated in Figure 3.

This approach was utilized to calculate k_p and k_f with the same data as used in the regression models. The results of calculating kp and kf in this manner are shown in Figure 4. The combination of k_p and k_f that resulted in predicting $ME_{forgain}$ with zero error was 0.61 and 0.88, respectively. The value obtained for k_f using this methodology is in close agreement with that obtained from regression analysis. However, it appears that the value for k_p obtained by regression was overestimated. This is presumably due to the high level (0.93) of correlation that exists between RPE and RLE.

In conclusion, the proposed method for obtaining k_p and k_f gave values that are in close agreement with previously reported constants. With this approach, however, the problems associated with interpreting parameter coefficients when multicollinearity exists are avoided.

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Table 1. Composition of the basal diets used for Experiments 1 and 2

	Age interval, d					
	15 – 21			34 – 40		
Ingredient, %	B1	B2	B3	B1	B2	B3
Corn	40.21	35.36	31.02	51.18	46.33	41.46
Soybean meal, 48% CP	29.24	31.12	32.02	19.44	21.3	23.14
Arenaceous flour	10.09	10.09	10.09	10.26	10.26	10.26
Corn oil	8.57	8.66	8.56	6.55	6.63	6.73
Wheat	4.50	4.5	4.5	4.49	4.49	4.49
Corn gluten meal	2.61	5.78	9.42	3.9	7.06	10.11
Dicalcium phosphorus	1.86	1.83	1.82	1.38	1.36	1.33
Limestone	1.44	1.45	1.46	1.52	1.53	1.53
Salt	0.52	0.52	0.52	0.38	0.38	0.38
Vitamin premix[1]	0.31	0.31	0.31	0.31	0.31	0.31
Lysine HCL	0.16	0.07	—	0.24	0.14	0.05
DL-Methionine	0.12	0.02	—	0.04	—	—
Choline chloride	0.12	0.11	0.11	0.04	0.04	0.04
Trace mineral premix[2]	0.07	0.07	0.07	0.07	0.07	0.07
Threonine	0.06	—	—	0.06	—	—
Salinomycin	0.05	0.05	0.05	0.05	0.05	0.05
Avizyme 1502	0.05	0.05	0.05	0.05	0.05	0.05
Selenium premix	0.02	0.02	0.01	0.02	0.02	0.01
Tryptophan	—	—	—	0.01	—	—

[1]Supplied per kilogram of diet: vitamin A, 10,141 IU (retinyl acetate); cholecalciferol, 3,086 IU; vitamin E, 23.92 IU (dl-α-tocopheryl acetate); menadione, 2.87 mg; thiamine, 2.20 mg; riboflavin, 7.72 mg; niacin, 60.30 mg; d-pantothenic acid, 12.46 mg; pyridoxine, 3.75 mg; vitamin B_{12}, 0.017 mg; folic acid, 1.066 mg; d-biotin, 0.127 mg.
[2]Supplied per kilogram of diet: Ca,160 mg; Zn, 100 mg; Mn, 120 mg; Fe,75 mg; Cu, 10 mg; I, 2.5 mg.

Table 2. Chemical composition of the basal diets used for Experiments 1 and 2

	Age interval, d					
	15 – 21			34 – 40		
Calculated composition	B1	B2	B3	B1	B2	B3
ME, kcal/kg	3,050	3,050	3,050	3,050	3,050	3,050
	%					
Crude protein	20.50	23.00	25.50	17.50	20.00	22.50
Ether extract	10.48	10.48	10.32	8.83	8.83	8.08
Crude fiber	2.19	2.20	2.18	2.07	2.07	2.08
Starch	30.26	27.55	25.17	36.89	34.18	31.46
Calcium	1.00	1.00	1.00	0.90	0.90	0.90
NonPhytate Phosphorus	0.45	0.45	0.45	0.35	0.35	0.35
Sodium	0.20	0.20	0.20	0.15	0.15	0.15
Potassium	0.73	0.76	0.78	0.57	0.60	0.64
Chloride	0.38	0.35	0.34	0.30	0.28	0.26
True digestible amino acids[1]						
Arginine	1.24	1.36	1.45	0.97	1.09	1.19
Histidine	0.49	0.54	0.59	0.41	0.46	0.51
Isoleucine	0.80	0.92	1.02	0.66	0.77	0.87
Leucine	1.74	2.10	2.49	1.64	2.00	2.35
Lysine[2]	1.07	1.07	1.07	0.89	0.89	0.89
Methionine	0.44	0.40	0.43	0.34	0.35	0.40
Methionine + Cystine	0.77	0.78	0.84	0.64	0.69	0.78
Phenylalanine	0.95	1.11	1.27	0.83	0.98	1.12
Threonine	0.72	0.74	0.82	0.61	0.63	0.71
Tryptophan	0.17	0.19	0.21	0.15	0.15	0.17
Valine	0.85	0.97	1.09	0.73	0.84	0.95

[1]Based on digestibility coefficients reported by Ajinomoto Heartland, Incorporated (2001).
[1]Includes amino acids from intact protein and crystalline sources, which were assumed 100% digestible.
[2]Diets were formulated relative to lysine in accordance with the ideal protein concept (Baker and Han, 1994; Baker, 1997).

Table 3. General outline of treatment combinations in Experiments 1 and 2

Diet	Basal	Crude protein, %[1]	Supplemental energy, kcal ME/kg	Supplemental energy source[2]
A	B1	(2.5)	0	AF
B	B1	(2.5)	150	CS
C	B1	(2.5)	150	CO
D	B1	(2.5)	300	CS
E	B1	(2.5)	300	CO
F	B2	0	0	AF
G	B2	0	150	CS
H	B2	0	150	CO
I	B2	0	300	CS
J	B2	0	300	CO
K	B3	2.5	0	AF
L	B3	2.5	150	CS
M	B3	2.5	150	CO
N	B3	2.5	300	CS
O	B3	2.5	300	CO

[1]Deviation from dietary crude protein levels recommended by the National Research Council for Poultry (1994).

[1]Parentheses denote a negative value.

[2]AF = arenaceous flour; CS = corn starch; CO = corn oil.

Table 4. Data utilized for estimating kp and kf values (data from Experiments 1 and 2 were pooled)

Variable[2], kcal/$BW^{0.67}$ and feed restriction[3]	Dietary treatments[1]														
	B1					B2					B3				
	AF	CS		CO		AF	CS		CO		AF	CS		CO	
	0	150	300	150	300	0	150	300	150	300	0	150	300	150	300
TMEI															
50	56.8	59.0	63.2	58.7	61.7	56.4	59.1	62.0	58.6	61.2	56.8	60.0	62.5	58.2	62.6
100	108.6	114.8	112.7	112.1	120.7	110.1	112.6	117.0	114.5	117.5	106.8	110.1	118.0	112.6	117.9
150	158.8	164.6	162.3	165.3	169.3	158.8	164.7	174.2	163.0	171.8	159.3	161.2	171.5	163.3	176.3
BMEI															
50	56.8	56.3	57.5	55.9	56.2	56.4	56.3	56.4	55.8	55.7	56.8	57.2	56.9	55.4	57.0
100	108.6	109.4	102.6	106.9	109.9	110.1	107.4	106.5	109.2	107.0	106.8	104.9	107.4	107.3	107.3
150	158.8	156.9	147.7	157.5	154.1	158.8	157.0	158.6	155.4	156.4	159.3	153.6	156.2	155.6	160.5
SMEI															
50	–	2.8	5.7	2.8	5.5	–	2.8	5.6	2.7	5.5	–	2.8	5.6	2.7	5.6
100	–	5.4	10.1	5.3	10.8	–	5.3	10.5	5.4	10.5	–	5.2	10.6	5.3	10.6
150	–	7.7	14.5	7.7	15.2	–	7.7	15.6	7.6	15.4	–	7.6	15.4	7.7	15.8
RPE															
50	(25.1)	(7.1)	(18.1)	(16.8)	(20.0)	(23.1)	(18.3)	(19.7)	(18.8)	(19.1)	(21.1)	(17.6)	(21.3)	(21.0)	(19.7)
100	(1.0)	(0.9)	(2.2)	3.4	(0.9)	0.9	2.3	2.4	(1.5)	(0.1)	(0.4)	2.2	(1.4)	2.6	0.7
150	11.7	9.2	13.7	15.1	16.1	14.7	11.8	17.9	17.5	20.1	18.6	21.1	27.2	21.2	20.9
RLE															
50	(32.8)	(16.9)	(18.9)	(23.3)	(27.3)	(29.3)	(33.8)	(26.2)	(26.9)	(26.4)	(29.3)	(27.3)	(36.7)	(24.2)	(29.1)
100	(4.4)	(12.8)	(2.4)	2.8	(7.1)	(5.3)	(0.9)	0.3	(7.7)	2.7	(2.8)	2.3	(5.6)	0.0	(1.3)
150	13.4	10.0	14.2	17.1	17.6	17.0	12.5	26.3	18.9	19.9	24.2	22.0	30.1	22.9	30.5
TRE															
50	(57.8)	(24.0)	(37.0)	(40.1)	(47.3)	(52.4)	(52.0)	(45.9)	(45.7)	(45.5)	(50.5)	(44.9)	(58.0)	(45.2)	(48.8)
100	(5.3)	(13.7)	(4.6)	6.2	(8.0)	(4.4)	1.4	2.7	(9.2)	2.7	(3.2)	4.5	(7.0)	2.6	(0.6)
150	25.1	19.2	27.9	32.2	33.7	31.7	24.4	44.2	36.4	40.0	42.9	43.1	57.3	44.1	51.4

[1]Refer to Table 3 for dietary treatment structure.
[2]Variables: TMEI = total metabolizable energy intake; BMEI = metabolizable energy intake supplied by basal diet; SMEI = metabolizable energy intake supplied by supplement; RPE = energy retained as protein; RLE = energy retained as lipid; TRE = total retained energy.
[3]Percent of proposed maintenance energy requirement (Leclercq and Saadoun, 1982).

Table 5. Linear regression equations for determining maintenance energy requirement

		MEI = a + (1/k_g) × RE[1]		
Equation	Region[2]	a	1/k_g	R^2
1	1 & 2	118.46151**	1.9787**	0.958
2	1	114.94056**	1.11644**	0.972
3	2	119.81672**	1.15217**	0.968

**P < 0.001.

[1]MEI = metabolizable energy intake (kcal/kg $BW^{0.67}$); RE = retained energy (kcal/kg $BW^{0.67}$); a = intercept; b = parameter coefficient.

[2]Denote the data used in regression analysis, refer to Figure 1.

Table 6. Results of regression analysis to determine the efficiencies of energy utilization for protein and lipid retention[1]

MEI = intercept + $(1/k_p) \times$ RPE + $(1/k_f) \times$ RLE[2]		
Intercept	$1/k_p$	$1/k_f$
116.93674**	1.32438	1.16356
	$k_p = 0.75$	$k_f = 0.86$

**P < 0.001.

[1]All birds used in analysis were in positive energy balance

[2]MEI = metabolizable energy intake; REP = energy retained as protein; REL = energy retained as lipid; k_p = efficiency of energy utilization for protein retention; k_f = efficiency of energy utilization for lipid retention.

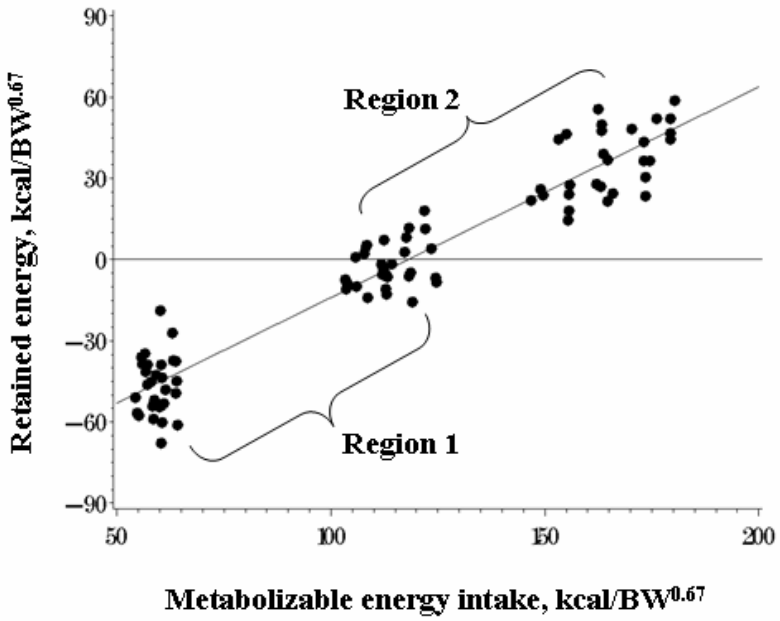

Figure 1. Relationship between metabolizable energy intake (MEI) and energy retention (RE) in broilers

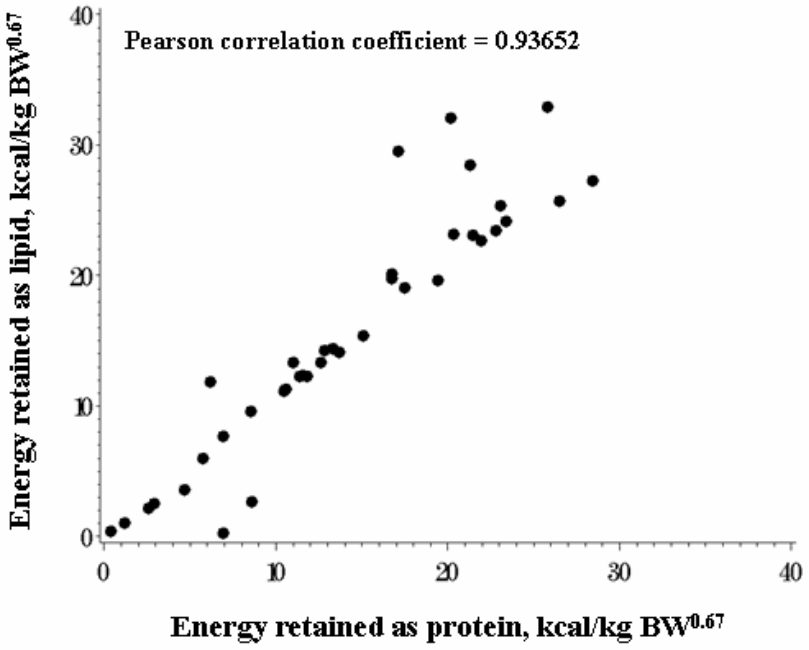

Figure 2. Relationship between energy retain as protein and lipid

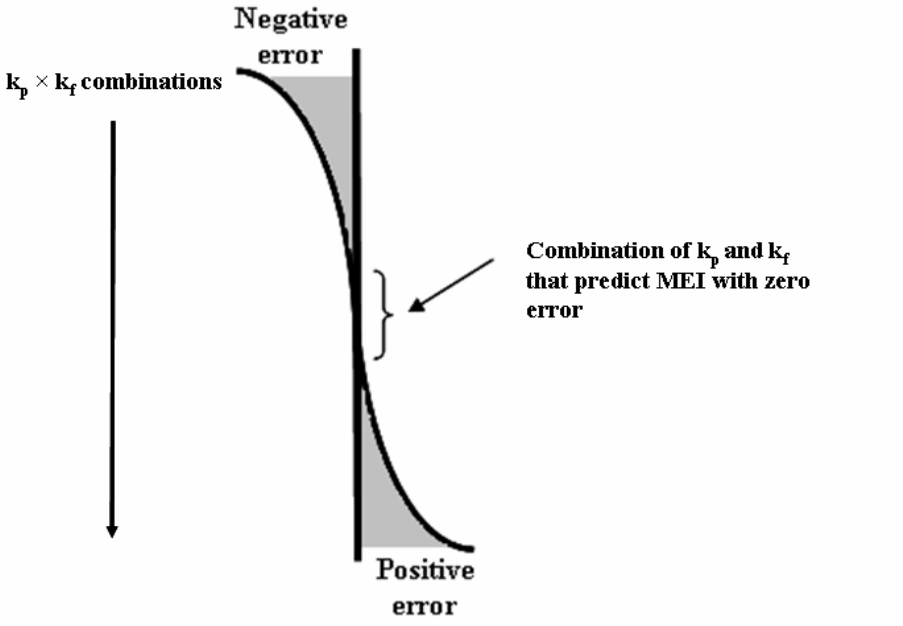

Figure 3. Illustration of predicting metabolizable energy intake (MEI) using a matrix of efficiencies of energy utilization for protein (k_p) and lipid (k_f) tissue retention

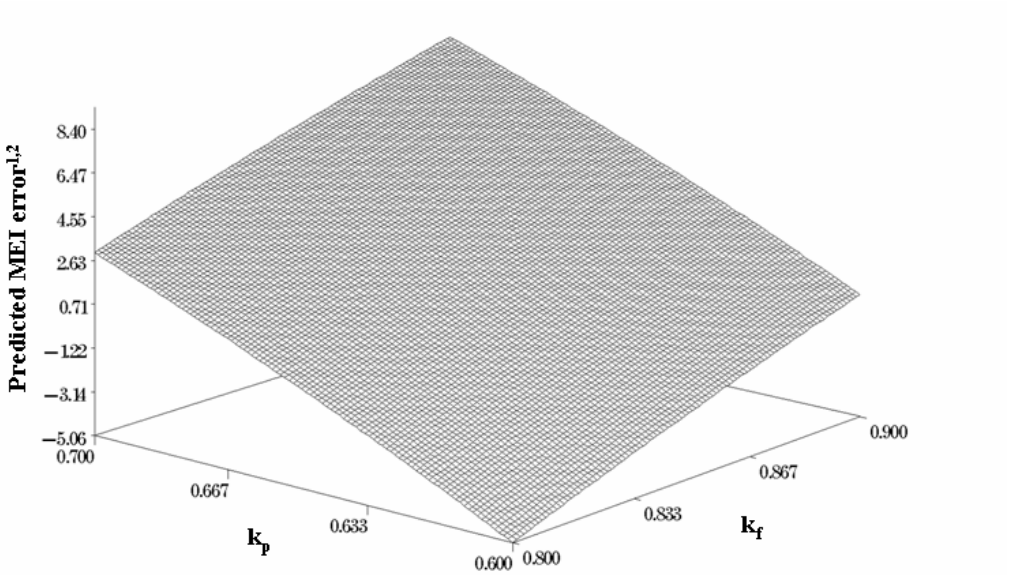

Figure 4. Utilizing a matrix of k_p and k_f values to predict MEI[2]

[1]Predicted MEI = (RPE/k_p) + (RLE/k_f); where MEI = metabolizable energy intake; RPE = energy retained as protein; RLE = energy retained as lipid; k_p = efficiency of energy utilization for protein retention, and k_f = efficiency of energy utilization for lipid retention.
[2]Predicted MEI error = ((MEI – Predicted MEI)/MEI) × 100.

APPENDIX

CHAPTER VII

```
data Matrix; set EnergyforGain;
do kp = 0.1 to 1 by 0.01;
do kf = 0.1 to 1 by 0.01;
output;
end;
end;
run;
```

```
data kpkf; set Matrix;
PredMEforGain = ERP/kp + ERF/kf ;
Error = ((MEforGain – PredMEforGain)/MEforGain)*100;
proc sort data=kpkf; by Error;
run;
proc print data=kpkf;
run;
```

VITA

LELAND JAMES MCKINNEY

Candidate for the degree of

Doctor of Philosophy

Thesis: BROILER GROWTH MODELS DYNAMICALLY INTERFACING METABOLIC EFFICIENCY WITH THE PRODUCTION ENVIRONMENT

Major Field: Animal Nutrition

Biographical:

Personal Data: Born in Wellington, Kansas, February 4, 1975, the son of David and Linda McKinney.

Education: Graduated from Manhattan High School, Manhattan, Kansas, in May 1993; received Bachelor of Science degree in Feed Science from Kansas State University, Manhattan, Kansas, in May 1998; received Master of Science degree from the Department of Grain Science, Kansas State University, Manhattan, Kansas, in 2000; completed requirements for the Doctor of Philosophy degree from Oklahoma State University, Stillwater, Oklahoma, in May 2005.

Professional Experience:

Graduate Research Assistant; Oklahoma State University	2000 – 2005
Graduate Teaching and Research Assistant; Kansas State University	1998 – 2000
Internship; XIT Feeders, Continental Grain Co., Dalhart, TX	summer 1997
Student employee; Feed Manufacturing Center; Kansas State University	1996 – 1998
Self employed; Stocker cattle and cow-calf management	1990 – 1998

Professional Organizations: Poultry Science Association

Name: Leland James McKinney Date of Degree: May, 2005

Institution: Oklahoma State University Location: Stillwater, Oklahoma

Title of Study: BROILER GROWTH MODELS DYNAMICALLY INTERFACING METABOLIC EFFICIENCY WITH THE PRODUCTION ENVIRONMENT

Pages in Study: 149 Candidate for the Degree of Doctor of Philosophy

Major Field: Animal Nutrition

Scope and Method of Study: Experiments were conducted with broilers (Cobbs 500) to: 1) validate dual energy x-ray absorptiometry (DEXA) as a method for quantifying body composition; 2) establish a methodology for predicting effective caloric value (ECV) and quantify the ECV attributable to pellet quality (PQ); and 3) Test and or refine methodologies used to estimate energetic efficiency of energy consumed above maintenance for protein (k_p) and lipid (k_f) tissue accretion.

Findings and Conclusions: DEXA measurements applied to developed regression equations successfully inter-related DEXA measurements with body compositions obtained by proximate analysis. Thus, DEXA was validated as a method for quantifying body composition in poultry. Regression equations developed provide a method for estimating ECV of nonnutritive factors that impact body weight and or feed conversion ratio. Use of this methodology suggests that pelleting contributes 187 kcal ECV to the diet at 100% PQ and that the ECV declines curvilinearly as PQ falls. Further, application reveals potential for creation of formulation "dead zones" whereby dietary changes to enhance caloric density may be offset due to reduced ECV. Regression analysis separating retained energy into energy retained as protein and lipid tissue overestimate values for k_p and k_f. These overestimations were attributed to the colinearity between protein and lipid tissue accretion. To circumvent this, a novel methodology was developed as follows: first a matrix of biologically possible k_p and k_f values is created, followed by its application to predict ME intake above maintenance. This proposed methodology for calculating k_p and k_f appears to provide more accurate estimates.

ADVISER'S APPROVAL: Robert Teeter