Modeling chemical and physical body composition of the growing pig

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ABSTRACT: In pig growth models, masses of body lipid (L) and body protein (P) are key state variables that can be related quantitatively to chemical and physical body composition for predicting growth response and carcass characteristics. The main chemical constituents in the empty body weight (EBW) are water (Wa), L, P, and ash. Within pig genotypes, Wa is independent of L and closely related to P (e.g., Wa = a × P^b). The scaling parameter (b) is remarkably constant across pig types, at about 0.855, and represents changes in distribution of P with increasing EBW and differences in Wa-to-P ratios among body pools. The parameter "a" ranges between 4.90 and 5.62 and seems to vary with pig genotype. The ash-to-P ratio, about 0.20, has little significance on estimates of EBW. Gut fill, the difference between live body weight (LBW) and EBW, ranges between 0.03 and 0.10 of LBW; it varies with LBW, feeding level, diet characteristics, and time off-feed. The distribution of P and L over the main physical body components (dissectible muscle and fat, viscera, blood, bone, integument) varies considerably among groups of pigs and appears influenced by EBW, pig genotype, feeding level, diet characteristics, and possibly thermal environment and health status. Except for extreme pig genotypes, the distribution of lean over the main carcass cuts is relatively constant; however, little is known about the observed variation in the distribution of L over body fat depots. Representing dynamic effects of animal and external factors on sizes of physical body components is an apparent weakness in pig growth models, further complicated by inconsistencies in defining some of the physical body components, and dissectible lean tissue in particular. Improved accuracy in representing physical body composition will provide more insight on manipulation of carcass value and efficiencies of converting diet nutrients into pork products.

Key Words: Body Composition, Chemical Composition, Growth Models, Physical Properties, Pigs

 J. Anim. Sci. 81(E. Suppl. 2):E159–E165

Introduction

The essence of pork production is the efficient conversion of nutrients supplied by a range of feedstuffs into high-quality pork products (Pond and Maner, 1984). This conversion encompasses relationships between nutrient intake and chemical body composition, and between chemical and physical body composition of growing pigs (Walstra, 1980). The amount of muscle tissue and its distribution are the main determinants of the amount and quality of pork that can be derived from the pig's carcass. Largely because of concerns about human health and sensory evaluation of fresh pork products, the distribution and fatty acid composition of fat tissue in the pig's body should be considered as well. Moreover, because visceral organs contribute to the inefficiency of converting dietary nutrients into pork products (de Lange et al., 2001), careful consideration should be given to nutrient needs of visceral organs in the pig.

The relationships between nutrient intake and chemical and physical body composition are affected by a range of factors associated with nutrition, pig genotype, environment, and stage of maturity. In order to identify practical means to manipulate pork quality and production efficiencies, an understanding of these relationships is required. This can be achieved by representing them causally and mathematically using a pig growth model.

Body protein mass (**P**) and body lipid mass (**L**) are key state variables in pig growth models. For predicting growth responses and carcass characteristics, P and L must be related quantitatively to chemical and physical body composition.

In this review, the mathematical representation of chemical and physical body composition of the growing pig is addressed. Main concepts are discussed and areas where further information is required are identified. Potential impacts of the pig's social and thermal

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Received August 8, 2002.
Accepted February 6, 2003.

Table 1. Chemical composition (%) of the empty body of pigs at various BW[a]

Component	Birth	7 kg of BW	25 kg of BW	Market weight (approx. 110 kg of BW; extremes)	
				Fat pigs	Lean pigs
Water	77	66	69	48	64
Protein	18	16	16	14	18
Lipid	2	15	12	35	15
Ash	3	3	3	3	3

[a]Derived from McMeekan (1940), Richmond and Berg (1971a,b), de Greef et al. (1994), Whittemore (1993), Bikker et al. (1995; 1996a,b), and Coudenys (1998).

environment and disease status on body composition are not addressed.

Chemical Body Composition: Prediction of Body Water and Ash Content

The four main chemical constituents in the pigs' empty body weight (**EBW**) are water (**Wa**), P, L, and ash (Table 1). The pig's body contains only minor amounts of carbohydrates (small stores of glycogen stores in the liver and muscle). For estimates of the whole-body mineral composition, the reader is referred to ARC (1981), Rymarz (1986), Hendriks and Moughan (1993), and Mahan and Shields (1998).

Given the high Wa content in the pig's body, an accurate prediction of Wa from P and L is critical for an accurate prediction of EBW. Water is closely associated with protein present in lean tissue and visceral organs. Given this association, Wa can be predicted from P with a reasonable accuracy, using allometric relationships that require only two parameters: Wa (kg) = a × P (kg)^b (Figure 1). Since the parameters a and b are determined statistically, care should be taken when estimating these parameters: if data covering only a limited range in Wa and P values are used, then different combinations of the two parameters may yield similar statistical fits (e.g., Emmans and Kyriazakis, 1995; Schinckel and de Lange, 1996). The scaling parameter (b) is remarkably constant across studies and pig types, at about 0.855 (ARC, 1981; de Greef, 1995; Emmans and Kyriazakis, 1995; Coudenys, 1998; Weis, 2001), and represents changes in distribution of P over various body pools with increasing EBW and differences in Wa to P ratios among these pools. Moreover, the observation that the ratio of Wa to $P^{0.855}$ is not influenced by BW and energy intake level, or by feed intake-induced variation in L to P ratios, provides further support to this rather simple and empirical approach to estimating Wa (de Greef, 1995; Weis, 2001). Maintaining the scaling parameter constant allows for a more robust and routine estimation of the parameter a, which varies between about 4.90 and 5.62 for different pig genotypes (ARC, 1981; de Greef, 1995; Emmans and Kyriazakis, 1995; Coudenys, 1998; Weis, 2001), and seems positively related to P at maturity (Emmans and Kyriazakis, 1995) or the genetically determined maximum body protein deposition rate (**PD_{max}**).

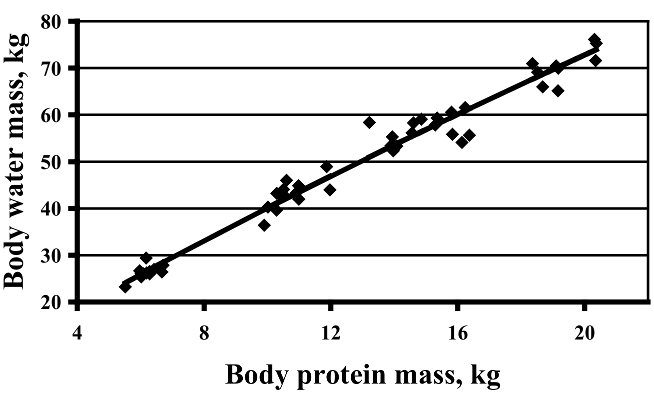

Figure 1. Relationship between body water mass and body protein mass in intact male Yorkshire pigs (Weis, 2001). Pigs varied in BW between 50 and 125 kg and were exposed to four energy intake levels ($Y = 5.5513\ X^{0.8592}$; n = 50, $r^2 = 0.8912$).

A more mechanistic approach to estimating Wa is undertaken via a dynamic representation of the distribution of P over the various body tissues and the Wa-to-P ratios in these body tissues. For example, in castrated male purebred Yorkshire pigs, Coudenys (1998) observed a Wa-to-P ratio of 4.52 in visceral organs, whereas BW did not influence this ratio. In that study, a gradual decline in Wa-to-P ratio was observed in the dissected loin, from 4.45 at 25 kg BW to 3.43 at 125 kg BW. Both the gradual decrease in the contribution of visceral organs to BW and the reduced Wa-to-P ratio in dissected lean contribute to the reduction in whole-body Wa-to-P ratio with increasing BW. This mechanistic approach to representing Wa requires, however, an accurate representation of sizes of each of the body tissues and of the Wa-to-P relationship in each tissue in different groups of pigs.

Ash can be predicted from P with reasonable accuracy: Ash (kg) = c × P (kg), with c varying between 0.186 and 0.210 (ARC, 1981; Moughan et al., 1990; Hendriks and Moughan, 1993; de Greef, 1995; Whittemore, 1983), reflecting the close association between bone tissue, which contains most of the body ash, and lean tissue. The observed variability in this parameter has little impact on prediction of BW and carcass characteristics.

Given the associations between P, Wa, and ash, most of the variation in chemical body composition between different groups of pigs can be attributed to variation in L content (Table 1).

Physical Body Composition

Gut fill (**GF**) represents the difference between EBW and live body weight (**LBW**) and is often assumed to

Table 2. Effect of diet ingredient composition and feeding level on gut fill, % of live body weight (LBW), in pigs at 110 kg of LBW[a]

Diet ingredient composition	Gut fill, % of LBW
Cornstarch and casein	
Fed ad libitum	2.42
Corn and soybean meal	
Fed ad libitum	3.00
Barley and canola meal	
Fed ad libitum (3.5 kg/d)	4.67
Fed restricted at 2 kg/d	3.26

[a]Derived from McNeilage (1999); feeding strategies were implemented 12 d before slaughter; 12 h pre-slaughter feed withdrawal.

represent a constant 5% of LBW (ARC, 1981; Stranks et al., 1988). However, findings such as those reported by Whittemore et al. (1988) and Lorschy et al. (1997) indicate that GF represents close to 9% and 4.5% of LBW in pigs at 20 kg and 100 kg LBW, respectively. Based on these two studies, GF can be predicted from LBW: GF (kg) = 0.277 × LBW (kg)$^{0.612}$. Other factors that influence GF are feeding level, diet characteristics (Table 2) and time off-feed (Stranks et al., 1988). Intake of fiber is likely to mediate feed intake and diet composition effects on GF (Whittemore, 1993).

The main tissues in the EBW of growing pigs are muscle (edible lean tissue), fat, visceral organs, bones, blood, and skin. As indicated in Table 3, physical body composition varies considerably between pig genotypes. The other tissues, including nervous, lymphatic, and vascular tissues, contribute less than 10% to empty body weight in growing pigs.

In market weight pigs, between 45 and 60% of the whole-body P is present in lean tissue, whereas approximately 15% of P is present in visceral organs (Rook et al., 1987; de Greef et al., 1994; Bikker et al., 1995, 1996a,b; Coudenys, 1998). Body fat tissues can be divided into three main categories: fat associated with muscles (intra- and intermuscular fat; intramuscular fat is also referred to as *marbling*), subcutaneous fat, and abdominal fat. Subcutaneous, abdominal, and most of the intermuscular fat constitute dissectible fat, in which approximately 70% of whole-body L is present (Rook et al., 1987; de Greef et al., 1994; Bikker et al., 1995, 1996a,b; de Greef, 1995).

Table 3. Physical composition (%) of the empty body of growing pigs of different genotype[a]

	Tissue				
Sex/Genotype	Muscle	Visceral organs[b]	Fat tissue	Bone	Skin
Male					
Synthetic Line	51.1	15.4	12.4	8.7	3.4
Pietrain	54.2	12.8	14.0	7.5	3.0
Large White	43.8	17.6	15.5	8.7	4.2
Female					
Large White	45.2	16.0	17.1	8.2	3.6
Castrates					
Large White	43.3	16.4	17.9	8.4	3.6
Meishan	27.8	16.7	28.1	7.2	7.4

[a]Adjusted to a mean empty body weight of 47.2 kg; derived from Quiniou and Noblet (1995).
[b]Includes hair and blood.

For a detailed discussion about the structure and significance of the other tissues in swine, including bone, skin, and hair; nervous, lymphatic, and vascular tissue; and blood and reproductive organs, the reader is referred elsewhere (Swatland, 1994; de Lange et al., 2001). Obviously, these tissues have important functions in the pig's body. However, these tissues represent only a small proportion of LBW. As a result, growth of these tissues has only minor impact on the prediction of physical body composition.

Prediction of Carcass Weight and Carcass Lean Content

Carcass generally constitutes LBW minus the gut fill, blood, visceral organs (including reproductive organs), hair, and the outer skin layer. Depending on the processing method, carcass may or may not include head, feet, tail, skin, kidneys, and leaf fat (Rook et al., 1987; NPPC, 1991; Swatland, 1994; OPCAP, 1996; Hicks et al., 1998). According to Whittemore and Fawcett (1974) and Whittemore (1993), the carcass weight-to-EBW ratio, also referred to as *carcass dressing percentage* (**%Carc**), increases with body lipid content: %Carc (%) = 66 + 0.09 × LBW (kg) + 0.12 × P2 back fat thickness (mm). This relationship may be valid in a large population of pigs but is not consistent with the observed inverse relationship between energy intake and carcass dressing percentage within populations of pigs (Bikker et al., 1996 a,b; Coudenys, 1998). Moreover, variability in visceral organ mass is not considered in this mathematical equation.

Within carcass processing methods, variability in %Carc can be attributed largely to variation in visceral organ mass and GF. Some of the factors that are known to influence visceral organ size are BW, feeding level, diet composition, and pig genotype (Koong et al., 1983; Bikker et al., 1996a; Quiniou and Noblet, 1995; Coudenys, 1998; Nyachoti, 1998). As illustrated in Figure 2 visceral organ mass, as a fraction of BW, is inversely related to BW. The scaling parameter of the allometric relationship between visceral organ mass and BW (approximately 0.45) appears to reflect both changes in feed intake and maintenance energy requirements with increasing BW (van Milgen and Noblet, 2003). Not only does feed intake stimulate visceral organ growth (Figure 2), it also alters the distribution of whole-body P between visceral organs and dissected lean tissue and the composition of dissected lean (Table 4). Among the visceral organs, mass of the gastrointestinal tract is most sensitive to diet characteristics, and to diet fiber levels in particular

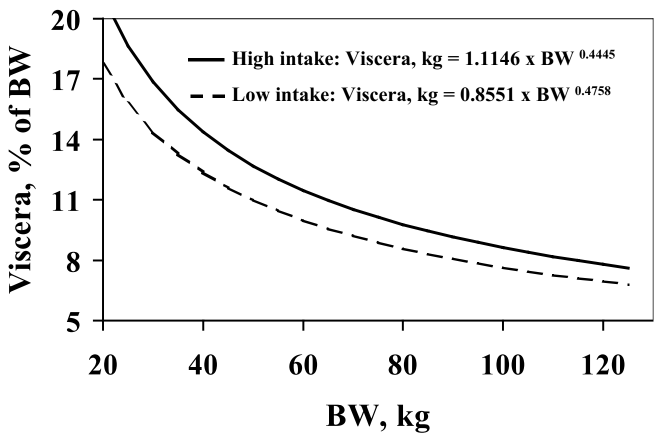

Figure 2. Relationship between visceral organ mass (Viscera) and BW in castrated male Yorkshire pigs exposed to two energy intake levels (Coudenys, 1998). Pigs varied in BW between 25 and 125 kg and were exposed to close to ad libitum (high intake) or high intake minus 35% (low intake) feeding levels (n = 32, r^2 = 0.793).

(Table 5). The aspects of dietary fiber that mediate these responses must still be clarified (Jørgensen et al., 1985; de Lange and Fuller, 2000). Given the pig genotype effects on visceral organ mass (Table 3), it is difficult to establish robust mathematical relationships to represent the effects of BW, feeding level, diet characteristics, pig genotype, and possibly health status on visceral organ mass in the growing pig.

The definition of lean tissue and methods used to estimate body lean tissue content might differ between packing plants, pig breeding organizations, and research institutions (Rook et al., 1987; NPPC, 1991; Swatland, 1994; Bikker et al., 1996a,b; OPCAP, 1996; Hicks et al., 1998). The latter should be considered carefully when interpreting physical body composition data and when predicting carcass lean tissue content. Carcass lean tissue content (**%Lean**) can be predicted from EBW and L: %Lean = 100 × (0.711 − L / EBW) (TMV, 1994). However, this equation does not reflect variability in the distribution of body tissues, P, and L between the carcass and viscera, nor does it reflect variation in the distribution of P and L within in the carcass (Tables 3, 4, and 5). A more accurate approach is first to predict carcass weight and to then predict %Lean in the carcass from carcass weight and carcass L and P content (Quiniou and Noblet, 1995). This approach will, however, not eliminate some the pig genotype biases in the prediction of %Lean (Wagner, 1992; Gu et al., 1992a; Hicks et al., 1998).

Table 4. Distribution of total body protein in lean tissue and visceral organs in pigs at approximately 85 kg body weight and fed at two levels of energy intake[a]

	Feeding level, × maintenance	
Distribution	2.2	3.7
Percentage of empty body weight present in:		
Lean tissue	51.9	44.4
Visceral organs	14.4	17.0
Percentage of whole body protein present in:		
Lean tissue	57.6	52.4
Visceral organs	12.5	16.0
Composition of dissected lean tissue, %		
Protein	20.2	19.1
Lipid	7.9	10.3

[a]Derived from Bikker et al. (1996a,b).

Table 5. Effect of additional dietary fiber intake on gastrointestinal tract mass (g/kg)

	Diet		
Reference	Control	+ Fiber	% Change
Pond et al. (1988)[a]	20.9	26.6	+27
Anugwa et al. (1989)[b]	25.5	29.9	+14
Jørgenson et al. (1996)[c]	31.7	43.6	+38
Nyachoti (1998)[d]	40.0	51.4	+28
Pluske et al. (1998)[e]	17.9	23.1	+29
McNeilage (1999)[f]	33.2	37.1	+12

[a]Diet contained 80% additional alfalfa meal.
[b]Diet contained 40% additional alfalfa meal.
[c]Diet contained 5.9 vs 26.8% total fiber; added fiber from barley, peas, and pectin.
[d]Diet contained casein-cornstarch vs barley-canola meal; excluding stomach in 25-kg pigs.
[e]Diet contained 5% added guar gum and 7% added resistant starch; weight of hindgut only.
[f]Diet contained casein-cornstarch vs barley-canola meal; implemented 12 d before slaughter.

Even though the amount of lean tissue in the carcass of market weight pigs varies considerably across groups of pigs, the distribution of lean tissue among the primal cuts is rather constant (Richmond and Berg, 1971a,b; Gu et al., 1992a,b; OPCAP, 1996; Coudenys, 1998). Generally, approximately 25, 29, 14, 11, and 13% of lean tissue in the pig's body is present in the loin, ham, Boston butt, picnic, and belly, respectively (Gu et al., 1992b). The remainder represents muscles that are present in the neck, head, and lower parts of the legs. Only in Pietrain pigs does the lean tissue distribution differ substantially from that in other main pig genotypes. Due to double muscling in the loin and hind limb, a larger proportion of total body lean tissue mass is present in the loin and ham primal cuts in this pig genotype (Swatland, 1994).

In carcass grading schemes, %Lean is generally estimated from physical measures of body fatness, such as P2 backfat thickness. This is largely because %Lean is inversely related to body fatness, body fatness is more variable than body leanness, and body fatness can be estimated easily from back fat measurements (e.g., Rook et al., 1987; Whittemore, 1993). Even when measures of body fatness are combined with measures of carcass lean content, such as backfat depth and loin eye area, the estimation of carcass lean content is

Table 6. Distribution of body lipid and fat tissue content in selected line of pigs[a]

	Pig type/line[b]		Pig type/line[c]
Item	Control	Selected	LW
Body protein mass, kg	13.30		14.3
Body lipid mass, kg	18.9	16.2 (−14%)	28.2
Body fat tissue mass, kg			
Total	18.2	15.8 (−13%)	
Subcutaneous	12.1		17.08
Intermuscular	3.81	3.62 (−5%)	9.74
P2 backfat thickness, mm	19	14 (−26%)	22
P2/L ratio	1.01	0.86 (−15%)	0.78

[a]Rook et al. (1987).
[b]Large white entire male pigs (control) were compared to pigs that were selected against back fat thickness (selected); values in brackets represent change due to genetic selection.
[c]Large White × Landrace pigs (male, female, and castrated male).

generally more sensitive to the measure of body fatness (Rook et al., 1987; NPPC, 1991; OPCAP, 1996; Schinckel et al., 1996). Substantial genotype and sex biases can exist when estimating %Lean from simple carcass measurements (Rook et al., 1987; Wagner, 1992; Wagner et al., 1999; OPCAP, 1996; Hicks et al., 1998). In the practical application of pig growth models, it is thus more important to predict accurately the estimated %Lean than the actual %Lean. This may be achieved by modeling the physical body measurements that are used to estimate %Lean and then using the prediction equations to estimate %Lean according to the various carcass-grading schemes. This implies that body fat distribution should be considered carefully for the prediction of %Lean.

Both the body fat tissue distribution (Jones et al., 1980; Rook et al., 1987; OPCAP, 1996) and total body fat tissue content vary considerably between groups of pigs (de Greef et al., 1994; Bikker et al., 1995, 1996a,b; Gu et al., 1992b; Thomke et al., 1995). For example, there are clear differences between pig genotypes in the intramuscular fat content—it is generally higher in Duroc pigs than in Landrace or Yorkshire pigs—even though differences in subcutaneous and abdominal fat content between pigs of different genotypes may be small (OPCAP, 1996). According to Rook et al. (1987), the distribution of fat tissues in the pig's body can be altered rather easily through genetic selection (Table 6). These data suggest that by selecting against backfat thickness, L and fat tissue content and, in particular, P2 backfat thickness can be reduced, altering the relationship between L and P2 backfat. It is of interest to note that the total amount of subcutaneous fat tissue is not altered significantly in this study, suggesting a substantial redistribution of subcutaneous fat tissue due to selection against backfat thickness. Variation in energy intake is an important determinant of variation in body fat distribution, as well total content, within pig genotypes (Campbell et al., 1985; Campbell and Taverner, 1988; de Greef et al., 1994; Bikker et al., 1995, 1996a,b; Quiniou et al., 1995, 1996a,b; Coudenys, 1998). Given the large variability in body fat tissue distribution between groups of pigs and the many influencing factors, it is difficult to predict this distribution accurately for individual groups of pigs. To evaluate body fat tissue distribution and to model %Lean, it is suggested that the relationships between chemical body composition, %Lean and physical body measurements—those that are used to estimate %Lean in carcass grading systems—should be established in a representative subsample of pigs for each of the main pig genotypes.

Implications

In pig growth models, body composition is generally predicted from masses of body lipid and protein. Close attention should be paid to the relationship between body water mass and protein, which is remarkably constant across body weights and feeding regimens, but varies with pig genotype. The distribution of protein and lipid over the main physical body components (dissectible muscle and fat tissue, viscera, blood, bone, integument) varies considerably among groups of pigs and seems influenced by BW, pig genotype, feeding regimens, thermal environment, and health status. The dynamic representation of physical body components is an apparent weakness in pig growth models. This is further complicated by inconsistencies in defining physical body components, and dissectible lean tissue in particular. Improved accuracy in representing physical body composition will provide more insight on manipulation of carcass value and efficiencies of converting diet nutrients into pork products.

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