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Meat Science 70 (2005) 229–240

MEAT SCIENCE

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The relationship between body dimensions of living pigs and their carcass composition

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Received 27 October 2004; received in revised form 9 January 2005; accepted 9 January 2005

Abstract

The performance of a visual image analysis (VIA) system was tested with regards to its potential to determine in vivo carcass composition and conformation, either alone, or in conjunction with other in vivo measures such as live weight and backfat depth. Pigs of both sexes of a commercial type were reared and slaughtered at weights ranging from 50 to 120 kg. Feeding was ad libitum on diets ranging from 0.14 to 0.19 kg kg^{-1} crude protein content to produce animals of a range of body condition. Two analyses were carried out: the first analysis addressed the relationship between dimensionless carcass and VIA indices; the second analysis assessed the relationship between carcass composition and VIA body shape using detrended carcass and VIA data, which were produced by removal of allometric growth trends.

A statistically significant relationship ($P < 0.05$) between in vivo VIA body size and shape and carcass muscle dimensions and composition was found for most body regions. Adjusted R^2 statistics ranged between 0.13 and 0.54 for relative fat weights and between 0.14 and 0.51 for relative lean weights. The predictive power of the regression models, indicated by R^2-like statistics for prediction, was approximately 70% of the adjusted R^2 values. The descriptive and predictive powers of the corresponding models generally strengthened if VIA indices were combined with other in vivo measurements. The relationships between in vivo and carcass measures remained statistically significant ($P < 0.05$) after removal of the growth trends, although adjusted R^2 statistics generally decreased. The predictive power of models corresponding to the detrended measures was, however, weak.

The results show in vivo VIA measurements to be useful in the estimation of muscle size, carcass conformation and composition, all of which are of significant importance to the pig production, marketing and processing industries.

Keywords: Pigs; Body shape; Visual image analysis; Conformation; Carcass composition

1. Introduction

Accurate knowledge of the changing proportions of fat and lean tissue during pig growth is essential for determining carcass quality and defining optimum nutritional needs for pig growth and environmental protection. Various digital imaging techniques such as

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doi:10.1016/j.meatsci.2005.01.010

ultrasound, computer tomography (CT) and magnetic resonance imaging (MRI) have proved useful estimates of muscle and fat contents (see for example Newcom, Bass, & Lampe, 2002 for ultrasound; Jopson, Kolstad, Sehested, & Vangen, 1995; Kolstad, 2001 for CT and Mitchell, Scholz, Wange, & Song, 2001 for MRI), although various shortcomings have been identified for each of these techniques. For example, high expense and lack of mobility have confined CT and MRI primarily to research, whereas lower accuracy in the estimates or operator dependency have put the reliability of ultrasonic measurements into question (McLaren et al., 1991; Szabo et al., 1999).

A recent research evaluated visual image analysis (VIA), which yields pig body size measures and shape indices from two-dimensional visual images of living pigs, as a potential technique for estimating fat and lean content in pig carcasses (Doeschl et al., 2004). This previous research concentrated on the question whether a statistically significant association between VIA shape indices and carcass composition measures exists and how this association differs between different pig types. The present analysis aims to explore further the potential of using VIA body size and shape indices as indicators of the proportion of lean and fat in pig carcasses. Only one pig type is considered here, but the relationship between VIA body shape and carcass composition is assessed for different body regions; this study thus aims to respond to the increasing interest of the production market in individual carcass joints. Further, if a significant association between VIA shape indices and carcass composition measures was found, VIA could be established as an alternative method for predicting proportions of lean and fat or in combination with existing methods to increase the predictive value of the carcass composition estimates. For this reason, various statistical models are considered in this study to estimate the value of VIA shape indices as indicators for carcass composition alone and in combination with existing measures (body weight and ultrasonic backfat depth) of the live animal.

Other carcass measurements considered are lipid and protein content, due to their relevance in pig growth models, plus the dimensions of various muscles, e.g. *longissimus dorsi* and *gluteobiceps*, due to the increasing interest in the shape of retail cuts in the meat industry (Brown, 2003; Tholen, Baulain, Henning, & Schellander, 2003).

2. Materials and methods

2.1. Description of the trial and derived data

A total of 144 pigs of a commercial type were housed in controlled environment facilities in six rooms. Each room was divided into two pens, each holding 12 pigs, the sexes housed separately. Pig live weight at the beginning of the trial ranged from 23 to 59 kg. Feeding was ad libitum with the feed varying in crude protein content, such that the average crude protein content of the feed presented varied from 0.140 to 0.190 kg kg^{-1} across pens.

2.1.1. Carcass measures

At slaughter, the live weight of the pigs ranged from 52 to 120 kg; the variation was due to age and dietary differences. From each pen, four pigs were randomly selected for carcass dissection, giving a total of 48 dissected carcasses. Carcass jointing and dissection followed the protocol of Brown and Wood (1979) with modifications as described by Fisher, Green, Whittemore, Wood, and Schofield (2003). Dissection of the pelvic limb and measurements of the dimensions of specific muscles were carried out for all 48 pigs (24 boars, 24 gilts); a full carcass side dissection was performed on a randomly selected subset consisting of 22 (14 boars and 8 gilts) of these 48 pigs.

The dependent variables in the determination of composition are the fat and lean tissue proportions in the dissected carcass side together with those in individual body regions (joints), namely shoulder, foreloin, flank, hindloin, belly and pelvic limb, as shown in Fig. 1. Fat tissue weight is the sum of the subcutaneous and intermuscular fat weights. For the 22 fully dissected pigs, regression equations were obtained describing the relationship between fat/lean weights in the entire carcass side and those contained in the pelvic limb. The corresponding R^2 statistics were greater than 0.93, which agrees with those reported from other studies (Evans & Kempster, 1979; Fisher et al., 2003). The regression equations for the 22 fully dissected pigs were then used predictively to estimate the lean and fat tissue weights in the entire carcass side for the remaining 26 dissected pigs, for which only the pelvic limb was dissected. For the body regions described above, the R^2 statistic in the regression models using pelvic limb tissue weights as predictors were generally less than 0.85, which was considered insufficiently strong to produce reliable estimates of lean and fat tissue weights in individual body

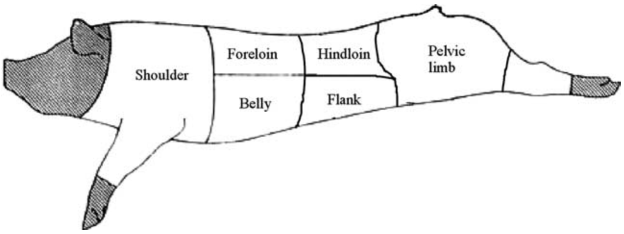

Fig. 1. Side of pig carcass showing the joints into which the carcass tissue weights were separated (apart from minor changes, the figure was originally published in Fortin et al. (1987).)

regions. Other carcass measurements considered in this study are the dimensions of the *longissimus dorsi* and *gluteobiceps* muscles (48 observations each).

For the fully dissected pigs, protein and lipid masses were calculated according to the method of Whittemore, Green, Wood, Fisher, and Schofield (2003), with the exception that here no chemical analysis of the dissected tissues was obtained. Therefore, for the lean and fat tissues, average values from the chemical analysis of the Whittemore et al. (2003) data were used to calculate protein and lipid masses: lean mass was taken to consist of 0.233 protein and 0.0414 lipid; fat mass was taken to consist of 0.107 protein and 0.601 lipid. Estimates of total body protein and lipid masses for the remaining 26 partially dissected pigs were derived in a similar way as the estimates of total carcass fat and lean weights described above, with the protein and lipid masses in the pelvic limb as predictors in the corresponding regression equations. Equations were derived separately for the two sexes.

2.1.2. Measurements of the live animals

Measurements of live weight (LW) and ultrasonic backfat depth at the P2 site (BF) were taken prior to slaughter. The animals were monitored by a visual imaging system (VIA) throughout the trial (Marchant, Schofield, & White, 1999; Schofield, Marchant, White, Brandl, & Wilson, 1999). This system provides plan view images of the pigs by video camera, from which the 11 VIA measures shown in Fig. 2 were derived. To reduce the error in the VIA measurement of pig size and shape prior to slaughter, the median for each VIA measurement over the last seven days before slaughter was used. Table 1 shows summary statistics for some of the in vivo and carcass measurements analysed.

2.1.3. Dimensionless relative measures

Dimensionless measures of relative fat and lean tissue weights, and relative protein and lipid masses, were calculated by dividing the mass concerned by the carcass side weight. Dimensionless body shape indices were calculated by dividing the linear measures L1–L6 by VIA body length L7, and the area measures A1–A3 by VIA plan area A4.

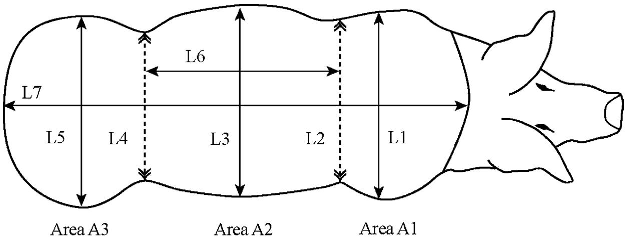

Fig. 2. Linear and area measures from the VIA system.

Table 1
Value ranges of various live and carcass measures used in this study together with their means and coefficients of variation (CV)[a]

Live or carcass measure	Value range	Mean	CV
VIA L7 (m)	0.755–0.959	0.864	5.00
VIA A4 (m^2)	0.172–0.288	0.228	11.3
Live weight at slaughter (kg)	52–120	87.5	18.4
Ultrasonic backfat depth (mm)	8.07–21.1	12.4	23.5
Carcass fat weight (kg)	4.76–27.1	13.4	38.1
Carcass muscle weight (kg)	26.7–49.1	35.6	15.0
Estimated carcass lipid (kg)	6.60–26.8	14.3	30.5
Estimated carcass protein (kg)	8.05–20.7	15.3	18.2

[a] The carcass fat and muscle weights are the sums of the fat and muscle weights in the shoulder, foreloin, belly, hindloin, flank and pelvic limb for the fully dissected pigs (22 out of 48), and the estimated weights, derived from the pelvic limb fat or muscle weights for the partially dissected pigs.

2.2. Statistical analysis

The relationship between the in vivo measures and indices and the relative carcass composition indices was assessed using multiple linear regression analysis, which was carried out with the SAS procedure PROC REG (SAS Institute Inc., 1999). Preliminary analysis screened the VIA shape indices such that only those indices that showed a significant relationship with the corresponding composition measure in the pairwise correlation matrix ($P < 0.05$) were considered in the models. There was no evidence of a nonlinear relationship or heterogeneity of the residuals.

Multiple linear regression does not automatically account for colinearity between individual shape indices or ultrasonic backfat depth and live weight. To select the most significant shape indices, a stepwise procedure with a 95% significance level in the entrance and exit criteria was used and the colinearity between the shape indices was assessed using the variance inflation factors and condition indices as diagnostic tools (Montgomery & Peck, 1992). Errors in the regression coefficients and variance inflation due to multicolinearity were minimised by including only predictors with pairwise Pearson's correlation coefficients R less than 0.5 and which resulted in variance inflation factors less than two and condition indices less than 50 in the final models.

Three linear models were used in assessing the relationship between in vivo measures and proportions of fat and lean in the entire carcasses and individual joints, as well as the estimated relative carcass lipid and protein masses. The first model (denoted hereafter model A) contained only VIA shape indices as predictors, whereas the second and third models allowed a combination of VIA shape indices with LW and ultrasonic BF, denoted models B and C, respectively. The correlation between LW and BF was too high ($R > 0.8$) for a simultaneous appearance of both variables in the stepwise regression approach.

As an indication of the predictive capability of the regression models the PRESS statistic was calculated as an approximate measure of how much variability in new observations the model might be expected to explain (Montgomery & Peck, 1992). The PRESS statistics yields an R^2-like statistic for prediction (R^2_{pred}) provided by the following formula (Montgomery & Peck, 1992):

$$R^2_{\mathrm{pred}} = 1 - \mathrm{PRESS} \,/\, \mathrm{SST},$$

where SST is the total sum of squares of the regression model.

2.2.1. Analysis of detrended data

Previous studies showed that pigs change body composition and shape during growth (Doeschl et al., 2004; Doeschl-Wilson, Whittemore, Knap, & Schofield, 2004; Fisher et al., 2003; Gu, Schinckel, & Martin, 1992; Landgraf et al., 2004). The data set analysed here includes pigs of different growth stages, due to dietary and age differences. To test whether VIA shape indices or ultrasonic backfat depth can be used to identify from a group of pigs of similar body weights those pigs with relatively fat or lean tissues, it was necessary to estimate and remove the underlying growth effects from the live and carcass composition data.

Assuming allometric growth of body components (Doeschl-Wilson et al., 2004; Fisher et al., 2003; Gu et al., 1992), the following linear equation was fitted to model the growth trends:

$$\log Y = a + b \times \log X. \tag{1}$$

Here, the VIA body length L7, the surface area A4, or the live weight were substituted as X variables, and the linear VIA size measures L1 to L6, the area measures A1 to A3, or the ultrasonic backfat depth BF were substituted as corresponding Y variables. Common slope values were used for boars and gilts unless a significant difference ($P < 0.05$) was found.

The calculated growth coefficients b were then used to derive the detrended in vivo and carcass measures,

$$\mathrm{d}\mathrm{L}i = \log \mathrm{L}i - b \times \log L7 \quad \text{for } i = 1, \ldots, 6,$$

$$\mathrm{dA}i = \log \mathrm{A}i - b \times \log \mathrm{A4} \quad \text{for } i = 1, \ldots, 3,$$

$$\mathrm{dBF} = \log \mathrm{BF} - b \times \log(\mathrm{LW}),$$

$$\mathrm{dCFW} = \log \mathrm{CFW} - b \times \log(\mathrm{CSW}),$$

$$\mathrm{dCMW} = \log \mathrm{CMW} - b \times \log(\mathrm{CSW}),$$

$$\mathrm{dLt} = \log \mathrm{Lt} - b \times \log(\mathrm{CSW}),$$

$$\mathrm{dPt} = \log \mathrm{Pt} - b \times \log(\mathrm{CSW}).$$

Here, Lt and Pt are lipid and protein weight, and CFW and CMW are the fat and muscle weights, respectively, either in the whole carcass or in any of the joints described above. CSW is the carcass side weight.

Having removed the variation due to growth, the regression analysis described above was repeated with the detrended measures to test whether VIA shape or ultrasonic backfat depth measures can identify pigs of a specified composition from a group of pigs of similar body weight.

3. Results

3.1. Predicting carcass muscle dimensions from VIA size and shape measures

Indices of the areas of the *longissimus dorsi* and *gluteobiceps* muscles were obtained from the product of the measured muscle lengths and widths. Boars had on average a larger *longissimus dorsi* muscle area, but a smaller *gluteobiceps* muscle area than gilts (Table 2), although these differences were not statistically significant ($P > 0.5$).

Table 2 shows that there was a significant association between the carcass muscle areas and both LW and VIA size measures, with R^2_{adj} ranging between 0.18 and 0.52. The relationship between the carcass muscle dimensions

Table 2
Relationship between the indices of the areas of the *longissimus dorsi* and *gluteobiceps* muscles (index = length × width) and live weight (LW) and the most strongly related VIA size measure[a]

Muscle	Sex	Predictor	Dep. mean (mm^2)	RMSE (mm^2)	R^2_{adj}	R^2_{pred}
Longissimus dorsi	Boar	LW (kg)	5870	898	0.42	0.30
	Gilt		5750	907	0.34	0.19
	Boar	L7 (mm)	5870	819	0.52	0.41
	Gilt	A3 (mm^2)	5750	1030	0.18	0.05
Gluteobiceps	Boar	LW (kg)	63,000	10,900	0.30	0.18
	Gilt		64,200	8040	0.28	0.21
	Boar	L7 (mm)	63,000	10,500	0.35	0.27
	Gilt	A3 (mm^2)	64,200	8250	0.19	0.14

[a] All of the shown relationships were statistically significant ($P < 0.05$). Statistics shown are the dependent mean (Dep. mean), the root mean square error (RMSE), and the coefficients of determination.

and the in vivo measures was generally stronger for boars than for gilts. VIA size measures were better descriptors for the muscle areas for boars, whereas LW was the better descriptor for gilts. The VIA size measure most closely related to the areas of both muscles was the body length measure L7 for boars and the pelvic limb area measure A3 for gilts.

3.2. Sex effects on carcass composition

Preliminary analysis of the relationship between the composition of carcass sides or joints and the VIA body shape indices revealed significant differences in the regression results between boars and gilts. For example, for boars no significant association between the relative total carcass fat weight and VIA shape indices could be found ($P < 0.05$), whereas the corresponding relationship was significant for gilts ($R^2_{adj} = 0.54$, coefficient of variation CV = 0.19, Table 3). Combining boars and gilts in the regression analysis resulted in a weak relationship between relative carcass fat weight and VIA body shape ($R^2_{adj} = 0.12$, CV = 0.55).

Statistical models based upon fewer than 10 observations were not considered sufficiently robust. Therefore, despite the observed sex effects in the preliminary analysis, sex was only included in those models for which there were 48 observations. These were the pelvic limb fat and muscle weights, the measured and estimated total carcass fat and muscle weights, and the estimates for body protein and lipid weights. The derived regression models were found to be robust for the available number of observations, as removal of randomly selected individual observations had no drastic impact on the regression results.

Table 3
Linear regression statistics for the proportion of fat in the whole carcass or individual joints as dependent variables and the VIA shape indices rL1–rL6 and rA1–rA3, as well as live weight (LW) and ultrasonic backfat depth (BF) as predictors[a]

Carcass component	Sex	Model	Predictors	Dep. mean	RMSE	R^2_{adj}	R^2_{pred}
Entire carcass	Boar	A	NS	0.21	NS	NS	NS
	Gilt	A	rL4	0.22	0.041	0.54	0.45
	Boar	B	LW	0.21	0.062	0.10	NS
	Gilt	B	LW + rL4	0.22	0.030	0.62	0.52
	Boar	C	BF + rL1 + rL6	0.21	0.049	0.36	NS
	Gilt	C	BF + rA2	0.22	0.029	0.66	0.55
Shoulder	Pooled	A	rL2	0.07	0.013	0.13	Ns
		B	LW	0.07	0.010	0.36	0.25
		C	BF	0.07	0.098	0.49	0.35
Foreloin	Pooled	A	rL4	0.03	0.007	0.42	0.31
		B	LW + rL2 + rA2	0.03	0.005	0.75	0.67
		C	BF + Rl4	0.03	0.004	0.84	0.81
Belly	Pooled	A	rL4	0.03	0.010	0.14	NS
		B	LW	0.03	0.009	0.32	0.18
		C	BF	0.03	0.007	0.58	0.49
Hindloin	Pooled	A	rL4	0.02	0.004	0.28	0.19
		B	LW + rA2	0.02	0.003	0.54	0.41
		C	BF	0.02	0.003	0.67	0.52
Flank	Pooled	A	rL4	0.02	0.005	0.14	NS
		B	LW	0.02	0.005	0.30	0.14
		C	BF	0.02	0.004	0.47	0.35
Pelvic limb	Boar	A	rL4	0.05	0.012	0.42	0.32
	Gilt	A	rL4	0.06	0.009	0.50	0.42
	Boar	B	Same as model A[b]				
	Gilt	B	LW + rL4	0.06	0.012	0.53	0.41
	Boar	C	BF + rL4 + rA3	0.05	0.010	0.62	0.38
	Gilt	C	BF + rL4	0.06	0.011	0.56	0.40

Three types of models are presented for each carcass component: model A used only VIA shape indices as predictors, models B and C combined shape indices with the LW and BF measurements as predictors, respectively.

[a] Statistics shown are the dependent mean (Dep. mean), the root mean square error (RMSE) and the coefficients of determination. Values are shown for boars and gilt pooled for those carcass measurements for which only 22 observations existed and for boars and gilts separately in those cases where 48 observations existed. With exception of those models denoted by NS (not significant) in the predictors, all of the shown relationships were statistically significant ($P < 0.05$).

[b] The corresponding in vivo measure LW or BF had no statistically significant contribution to the final model ($P < 0.05$), so that only VIA indices appear as predictors in the resulting model.

3.3. The relationship between carcass composition and VIA shape indices alone and in combination with other in vivo measures

A statistically significant relationship between VIA shape indices alone and carcass composition indices was found for all physical and chemical carcass components, with exception of the proportion of lean in the flank for both sexes, and for boars the relative fat weight in the entire carcass and the relative protein weight (Tables 3–5, model A). R^2_{adj} varied between 0.13 and 0.54 for relative fat weights (Table 3) and between 0.14 and 0.51 for relative lean weights (Table 4). The R^2_{adj} values for relative lipid weights were in the same range (0.33 for boars and 0.62 for gilts), but the relationships for estimated relative protein weight in the empty carcasses were much weaker (not statistically significant for boars; $R^2_{adj} = 0.12$ for gilts, see Table 5).

Those models that included live weight or ultrasonic backfat depth in addition to VIA shape indices (models B and C in Tables 3–5) had higher regression statistics for most carcass composition variables than models including VIA shape indices alone (models A in Tables 3–5). Inclusion of ultrasonic backfat depth in the linear models generally led to higher values of R^2_{adj} and R^2_{pred} and lower RMSE values than inclusion of LW. Differences between LW and ultrasonic BF as predictors were less pronounced for the relative lipid and protein weights (Table 5).

For some carcass joints, such as the shoulder or the flank, the VIA shape indices did not contribute significantly to the models B and C, whereas for relative foreloin muscle weight, only VIA indices were included. But for most carcass composition indices, a combination of VIA shape indices and LW or BF produced the linear models of best fit with R^2_{adj} statistics often more than twice those for models containing VIA shape indices alone. R^2_{adj} statistics varied between 0.30 and 0.56 for relative lean weights and between 0.36 and 0.84 for relative fat weights (Tables 3 and 4). Similar results were ob-

Table 4
Linear regression statistics for the proportion of lean in the whole carcass or individual joints as dependent variables and the VIA shape indices rL1–rL6 and rA1–rA3, as well as live weight (LW) and ultrasonic backfat depth (BF) as predictors[a]

Carcass component	Sex	Model	Model (predictors)	Dep. mean	RMSE	R^2_{adj}	R^2_{pred}
Entire carcass	Boar	A	rA1	0.60	0.043	0.24	NS
	Gilt	A	rA2	0.59	0.032	0.51	0.30
	Boar	B	LW	0.60	0.040	0.37	0.28
	Gilt	B	LW + rL4	0.59	0.031	0.56	0.49
	Boar	C	BF + rL3	0.60	0.042	0.45	0.28
	Gilt	C	BF	0.59	0.040	0.51	0.37
Shoulder	Pooled	A	rL2	0.19	0.023	0.19	0.06
		B	LW	0.19	0.021	0.34	0.22
		C	BF	0.19	0.011	0.48	0.39
Foreloin	Pooled	A	rA1 + rA2	0.01	0.006	0.21	0.04
		B	Same as model A[b]				
		C	Same as model A				
Belly	Pooled	A	rL3	0.06	0.010	0.15	NS
		B	LW + rL3	0.06	0.007	0.30	0.19
		C	BF + rL3	0.06	0.006	0.47	0.38
Hindloin	Pooled	A	rL4 + rA2	0.06	0.004	0.38	0.18
		B	LW + rA2	0.06	0.004	0.44	0.31
		C	BF	0.06	0.004	0.39	0.30
Flank	Pooled	A	NS	0.02	NS	NS	NS
		B	NS	0.02	NS	NS	NS
		C	BF	0.02	0.003	0.13	NS
Pelvic limb	Boar	A	rA3	0.20	0.019	0.14	0.01
	Gilt	A	rL4	0.20	0.020	0.29	0.17
	Boar	B	LW + rL3 + rL5	0.20	0.010	0.35	0.16
	Gilt	B	LW	0.20	0.011	0.39	0.30
	Boar	C	BF + rL5	0.20	0.010	0.40	0.19
	Gilt	C	BF	0.20	0.011	0.44	0.32

Three types of models are presented for each carcass component: model A used only VIA shape indices as predictors, models B and C combined shape indices with the LW and BF measurements as predictors, respectively.

[a] See corresponding footnote to Table 3.

[b] See footnote to Table 3.

Table 5
Linear regression statistics for the estimated proportion of lipid and protein in the whole carcass as dependent variables and the VIA shape indices rL1–rL6 and rA1–rA3, as well as live weight (LW) and ultrasonic backfat depth (BF) as predictors[a]

Carcass component	Sex	Model	Predictors	Dep. mean	RMSE	R^2_{adj}	R^2_{pred}
Lipid	Boar	A	rL4	0.48	0.054	0.33	0.20
	Gilt	A	rL4	0.45	0.046	0.62	0.55
	Boar	B	Same as model A[b]				
	Gilt	B	LW + rL4	0.45	0.043	0.67	0.58
	Boar	C	BF + rL6	0.48	0.040	0.63	0.50
	Gilt	C	BF	0.45	0.044	0.65	0.55
Protein	Boar	A	NS	0.50	NS	NS	NS
	Gilt	A	rL4	0.53	0.022	0.12	0.05
	Boar	B	LW	0.50	0.022	0.31	0.18
	Gilt	B	LW	0.53	0.019	0.32	0.19
	Boar	C	BF	0.50	0.023	0.28	0.20
	Gilt	C	BF + rL1	0.53	0.019	0.36	0.26

Three types of models are presented for each carcass component: model A used only VIA shape indices as predictors, models B and C combined shape indices with the LW and BF measurements as predictors, respectively.

[a] Statistics shown are the dependent mean (Dep. mean), the root mean square error (RMSE) and the coefficients of determination. With exception of those models denoted by NS (not significant) in the predictors, all of the shown relationships were statistically significant ($P < 0.05$).

[b] See footnote to Table 3.

tained for models with relative lipid and protein weights as dependent variables (Table 5).

Comparison of Tables 3–5 reveals that the relationship between in vivo and carcass measures was generally stronger for relative carcass fat and lipid weights than for relative carcass muscle and protein weights. Accordingly, the root mean square errors relative to the means of fat and lipid were also approximately two to three times higher than those for lean and protein, which suggests that the higher R^2 statistics may be associated with the observed higher coefficients of variation for relative fat and lipid than for relative muscle and protein weights (as can be deduced from Table 1).

For most of the carcass measures for which separate models for boars and gilts were derived, a stronger association with in vivo measures was found for gilts than for boars. This was true for all three models A, B and C corresponding to any carcass variable, but the difference between the sexes was less pronounced if BF was used as the predictor (Tables 3–5).

The R^2_{pred} for models B and C were on average 70% of the R^2_{adj} statistics, indicating moderate predictive power of the models for new observations. In contrast, for models A the difference between adjusted and predictive R^2 values was considerably larger, implying that VIA shape indices alone were less reliable predictors of carcass composition.

3.4. The relationship between carcass composition and in vivo measures after removal of growth trends

After fitting the linear models represented by Eq. (1) for estimating growth trends, no nonlinearities or heterogeneities in the residuals, or significant sex effects upon the slopes, were found. Detrending removed the variation due to growth from the shape, backfat depth and composition indices, and consequently caused a general decrease in the between-animal variation in the resulting indices. Between-animal variation in the detrended fat and lipid weights was approximately three times higher than in the detrended lean and protein weights.

As would be expected, given the smaller between-animal variation, the association between shape and composition was generally weaker in the detrended data. R^2_{adj} values for statistically significant relationships between detrended fat and muscle weights, respectively, and detrended VIA shape indices either alone (model A in Tables 6–8) or in combination with detrended BF (model B in Tables 6–8), ranged from 0.06 to 0.44 for detrended carcass fat, and between 0.06 and 0.34 for detrended carcass lean weights (Tables 6 and 7). R^2_{adj} statistics for detrended lipid and protein weights ranged from 0.22 to 0.51 and from 0.13 to 0.31, respectively (Table 8). R^2_{pred} was generally weak for the models on detrended data (<0.1 for most models), suggesting low predictive power of the derived regression models.

There was no statistically significant relationship between detrended VIA shape indices and detrended fat weights for most carcass composition variables (Table 6). Significant relationships were found only for the foreloin region (sexes pooled), and the pelvic limb and entire carcass for gilts. The detrended ultrasonic backfat depth was, however, significantly related to most carcass measures (Table 6, model B).

In contrast to the detrended fat weights, a statistically significant relationship between the detrended carcass lean weights and the detrended VIA shape indices

Table 6
Linear regression models with the detrended fat tissue weights as dependent variables and detrended VIA measures (dL1–dL6, dA1–dA3), as well as the detrended ultrasonic backfat depth (dBF) as independent variables[a]

Carcass component	Sex	Model	Predictors	Dep. mean	RMSE	R^2_{adj}
Entire carcass	Boar	A	NS	−3.76	NS	NS
	Gilt	A	dL4	−3.73	0.07	0.32
	Boar	B	dBF	−3.76	0.09	0.09
	Gilt	B	dBF + dA2	−3.73	0.07	0.44
Shoulder	Pooled	A	NS	−4.14	NS	NS
		B	dBF		0.06	0.15
Foreloin	Pooled	A	dL2 + dL3	−7.67	0.06	0.19
		B	dBF		0.06	0.37
Belly	Pooled	A	NS	−7.10	NS	NS
		B	dBF		0.11	0.31
Hindloin	Pooled	A	NS	−7.69	NS	NS
		B	dBF		0.08	0.20
Flank	Pooled	A	NS	−6.19	NS	NS
		B	dBF		0.12	0.15
Pelvic limb	Boar	A	NS	−3.30	NS	NS
	Gilt	A	dL4	−3.28	0.07	0.33
	Boar	B	dBF	−3.30	0.08	0.06
	Gilt	B	dBF + dL4	−3.28	0.07	0.39

Two types of models are presented for each carcass component: model A used only VIA shape indices as predictors, whereas model B combined shape indices with the detrended BF measurements as predictors, respectively.

[a] Statistics shown are the dependent mean (Dep. mean), the root mean square error (RMSE) and R^2_{adj}. R^2_{pred} was generally less than 0.1 and is not shown here. With exception of those models denoted by NS (not significant) in the predictors, all of the shown relationships were statistically significant ($P < 0.05$).

Table 7
Linear regression models with the detrended lean tissue weights as dependent variables and detrended VIA measures dL1–dL6, dA1–dA3, as well as the detrended ultrasonic backfat depth (dBF) as independent variables[a]

Carcass component	Sex	Model	Predictors	Dep. mean	RMSE	R^2_{adj}
Entire carcass	Boar	A	dL2 + dL5	1.04	0.021	0.27
	Gilt	A	dL4		0.024	0.13
	Boar	B	dBF + dL5		0.086	0.34
	Gilt	B	dBF		0.074	0.22
Shoulder	Pooled	A	NS	0.82	NS	NS
		B	dBF		0.032	0.16
Foreloin	Pooled	A	dA2	−0.80	0.041	0.10
		B	Same as model A[b]			
Belly	Pooled	A	NS	0.67	NS	NS
		B	dBF		0.052	0.08
Hindloin	Pooled	A	dA2	0.18	0.029	0.14
		B	Same as model A			
Flank	Pooled	A	NS	−0.80	NS	NS
		B	dBF		0.062	0.19
Pelvic limb	Boar	A	dL3 + dL5	0.06	0.026	0.33
	Gilt	A	dL4	0.06	0.026	0.08
	Boar	B	Same as model A			
	Gilt	B	dBF	0.06	0.025	0.29

Two types of models are presented for each carcass component: model A used only VIA shape indices as predictors, whereas model B combined shape indices with the detrended BF measurements as predictors, respectively.

[a] See corresponding footnote to Table 6.

[b] The index dBF had no statistically significant contribution to the final model ($P < 0.05$), so that only VIA indices appear as independent variables in the resulting model.

Table 8
Linear regression statistics for the estimated detrended lipid and protein in the whole carcass as dependent variables and the VIA shape indices dL1-dL6 and dA1-dA3, as well as the detrended ultrasonic backfat depth (dBF) as predictors[a]

Carcass component	Sex	Model	Predictors	Dep. mean	RMSE	R^2_{adj}
Lipid	Boar	A	dL3	−2.00	0.048	0.22
	Gilt	A	L4	−2.02	0.046	0.42
	Boar	B	BF + dL6	−2.00	0.040	0.46
	Gilt	B	BF + dL4	−2.02	0.042	0.51
Protein	Boar	A	dL5	0.32	0.014	0.31
	Gilt	A	Dl1 + dL6	0.29	0.015	0.13
	Boar	B	Same as model A[b]			
	Gilt	B	dBF + dL1	0.29	0.014	0.24

Two types of models are presented for each carcass component: model A used only VIA shape indices as predictors, whereas model B combined shape indices with the detrended BF measurements as predictors, respectively.

[a] Statistics shown are the dependent mean (Dep. mean), the root mean square error (RMSE) and R^2_{adj}. R^2_{pred} was generally less than 0.1 and is not shown here. All of the shown relationships were statistically significant ($P < 0.05$).

[b] See footnote to Table 7.

remained for entire carcass and half of the carcass joints. In particular, for the foreloin and hindloin (sexes pooled), and pelvic limb (for boars only), VIA shape indices were found to be better descriptors of lean content than detrended ultrasonic backfat measures, which did not enter into the final regression models (model B in Table 7). Only for the detrended lean weight in the shoulder, belly and flank, which were not significantly related to any VIA shape index, was the detrended backfat measure a better descriptor.

VIA and ultrasonic backfat were found to be useful descriptors of detrended carcass lipid and protein masses. A combination of these in vivo measures resulted generally in the model of best fit (Table 8), except for detrended protein weight for boars, for which VIA shape indices alone resulted in the best fitting statistical model.

In contrast to the relationships between in vivo indices and carcass lean, fat, lipid and protein proportions before detrending, which predominantly were stronger for gilts than for boars (Tables 3–5), only the relationship between detrended fat and lipid weights and in vivo indices remained generally stronger for gilts than for boars (Tables 6 and 8); for detrended muscle and protein weights, the opposite was true (Tables 7 and 8).

4. Discussion

The aim of this study was to assess whether VIA shape indices derived from digital images of live pigs could provide useful information about carcass composition, and in particular, how the information obtained from VIA compares to that obtained from other in vivo measures such as live weight and ultrasonic backfat depth. Multiple linear regression analysis was found to be the appropriate statistical tool for determining the existence of a statistically significant relationship between the inspected in vivo measures or indices and carcass traits and for identifying the most informative of these measures or indices. As indicated by the relatively low R^2_{pred}, especially for the models associated with detrended indices, the models presented here have more descriptive than predictive power. Reliable prediction models would not only require data from a substantially larger number of animals of different genotype, sex and weight groups, but also regression methods that focus on maximising the predictive power, such as partial least-squares regression (Brown, 1993; Tholen et al., 2003).

4.1. Sex differences in the relationship between in vivo and carcass composition indices

Sex differences in the relationship between in vivo and carcass indices were found in all models in which sex was included as factor. The differences were more pronounced in the models in which VIA shape indices only were used as independent variables (model A). Although differences in body composition between the sexes have been reported in the literature (Wagner, Schinckel, Chen, Forrest, & Coe, 1999), the mean values and variances of the composition indices were not significantly different ($P > 0.1$) between boars and gilts for any of the carcass composition indices in the present data. The same was true for the VIA shape indices. Differences between boars and gilts were thus only evident in the relationships between in vivo measures and carcass traits, but not in the measures themselves.

The VIA shape index–carcass composition relationship was consistently stronger for gilts than for boars (Tables 3–5). This consistency may be explained in part by the stronger relationship found for the pelvic limb in gilts than in boars and the use of this joint to predict the composition of other regions and the entire side, as described in Section 2.

4.2. The relationship between VIA measures and pelvic limb muscle dimensions

Although not presented here, in addition to the *longissimus dorsi* and *gluteobiceps* muscles, relationships between body dimensions and estimated muscle areas were assessed for the pelvic limb muscles *gluteus medius*, *vastus lateralis*, *semimembranosus*, *semitendinosus* and *rectus femoris*, for which 48 estimates (24 for each sex) of the areas were available. Significant relationships between the VIA body dimensions of the living pigs and muscle areas were found for all these muscles, except for the *vastus lateralis* and *rectus femoris* for gilts and the *semimembranosus* for boars. Relationships were generally stronger for boars than for gilts. Associated R^2_{adj} values ranged between 0.16 and 0.52. As was the case for the *longissimus dorsi* and *gluteobiceps*, VIA indices were generally more closely related to muscle areas than live weight or ultrasonic backfat depth. The A3 measurement was most frequently identified as the most informative measure for muscle area. Although L7 had been identified as the most informative measure for the *longissimus dorsi* and *gluteobiceps* areas for boars, A3 was found to be similarly strongly associated ($R^2_{\text{adj}} = 0.41$ and 0.30 for the two muscles respectively). These results suggest that A3 is the most informative descriptor of pelvic limb muscle areas.

4.3. Selection of the most informative VIA shape indices for estimating carcass composition

The relationship between VIA shape indices and proportions of fat and lean was stronger for the regions that were directly exposed to the camera in the visual imaging system, such as the shoulder, foreloin, hindloin and pelvic limb.

The VIA shape indices that showed the strongest correlation with the proportions of fat or lean in specific carcass joints were generally derived from measurements made in the region of the joints, suggesting that VIA body shape provides not only information about composition in the entire carcass, but also about the distribution of fat and lean in the body.

Among the VIA shape indices however, there was a propensity for rL4 to be selected as a predictor for proportions of fat and lipid in the carcass side and the joints (Table 3). This had already been noted in a previous analysis of a different trial (Doeschl et al., 2004), but had then been attributed to a higher between-animal variation in rL4 than in the other VIA shape indices. This observation did not hold for the present data set, for which the coefficient of variation for rL4, pooled over both sexes (4.53) was within the range found for the other VIA indices (3.18, rL6 to 6.12, rL2). Both studies thus suggest rL4 to be a valid indicator of carcass fat content.

No unique VIA shape measure could be identified as being the most informative for the proportion of lean or protein in the carcass side or any joint or for the detrended physical or chemical composition indices. Instead, the VIA shape indices yielding the highest coefficients of determination depended on the sex of the animal as well as on the other measures entering the models. For example, for pelvic limb lean percentage, four different VIA shape indices, rL3, rL4, rL5 and rA3, were represented in the different regression models (Table 4). Due to the strong colinearity between the shape indices, model statistics were often similar after replacing the shape index selected by the stepwise regression procedure by an index that was more representative of the body region in consideration. These results suggest that a valid insight of the relationship between VIA body shape and carcass composition could be gained from simple regression models that include only the VIA shape index that is expected to be most related to the corresponding carcass area, such as A1 or L1 for shoulder area, L2 and L3 for foreloin and belly, L4 for hindloin and flank, and A3 or L5 for the pelvic limb area.

4.4. Describing carcass composition by VIA shape indices alone or by combining them with other in vivo measures

For many carcass composition variables, a stronger relationship was found when VIA shape indices were combined with the ultrasonic backfat depth or live weight than with VIA shape indices alone (Tables 3–8). Although not presented here, similar increases in the descriptive and predictive powers of the regression models were found when ultrasonic backfat depth and live weight measures were augmented by VIA shape indices.

These results agree with those of Newcom et al. (2002), who found that ultrasonic backfat measures combined with five other in vivo ultrasound image parameters produced the most accurate prediction models for intramuscular fat content in the *longissimus dorsi*. As in the present study, ultrasonic backfat depth was identified as a more accurate predictor than live weight.

5. Implications

The present study complements a previous analysis (Doeschl et al., 2004) in which statistical relationships between VIA shape indices and physical and chemical composition in the entire carcass were established for three different pig types. The key results of the previous analysis are that the strength of the relationship between VIA shape and carcass composition and the most informative shape indices varied between the represented pig types. The present study confirmed the previously established association between VIA body shape and physical and chemical carcass composition, although the coefficients of determination (R^2_{adj} and R^2_{pred}) associated with the proportions of carcass fat, lean, lipid and protein were slightly lower than those calculated in the previous trial. This is likely due to the lower between-animal variation in the shape and carcass indices in the present trial, in which variation in these indices were primarily caused by different diets instead of different genotypes and ages. In contrast, between-animal variation and coefficients of determination in the detrended models were higher in the present trial.

The present study suggests that additional to genotype, pig sex also has a strong influence on the relationship between live and carcass measures. There is a strong indication that VIA shape indices may provide a valuable augmentation to the prevailing industry-wide measures of live weight and ultrasonic backfat depth for predicting carcass composition, and that these indices may additionally provide useful information about the distribution of lean and fat in the pig carcasses. Although the relatively small sample size available in the present study limits the derived regression models to description models, the statistical results are nevertheless encouraging for a future development of models that use VIA shape indices alone or in combination with other in vivo measures as reliable predictors for carcass muscle dimensions and composition.

Acknowledgements

This work is part of the UK LINK Sustainable Livestock Production Programme LK0614 Integrated Management Systems for Pig Nutrition Control and Pollution Reduction. The experiment was conducted at ADAS Terrington, Terrington St. Clement, Norfolk, UK, and the dissection of the carcasses was performed at the University of Bristol. The authors thank Roger White from the Silsoe Research Institute for the statistical advice. The authors also acknowledge the support of the sponsors: UK Department for Environment, Food and Rural Affairs, UK Meat and Livestock Commission and the industrial partners BOCM PAULS Ltd., Pig Improvement Company (UK) Ltd and Osborne (Europe) Ltd.

References

Brown, A. J. & Wood, J. D. (1979). Pig carcass evaluation – measurement of composition using a standardised butchery method. Meat Research Institute Memorandum, 42. Agricultural Research Council.

Brown, C. (2003). Who matters? The changing market: perspective from multiple retailers. In: J. E. Thompson, B. P. Gill, & M. A. Varley (Eds.), *The appliance of pig science* (pp. 19–22). BSAS Publication 31.

Brown, Ph. J. (1993). *Measurement, regression, and calibration.* Clarendon Press: Oxford.

Doeschl, A. B., Green, D. M., Whittemore, C. T, Schofield, C. P., Fisher, A. V., & Knap, P. W. (2004). The relationship between the body shape of living pigs and their carcass morphology and composition. *Animal Science, 79*, 73–83.

Doeschl-Wilson, A. B., Whittemore, C. T., Knap, P. W., & Schofield, C. P. (2004). Using visual image analysis to describe pig growth in terms of size and shape. *Animal Science, 79*, 415–427.

Evans, D. G., & Kempster, A. J. (1979). A comparison of different predictors of the lean content of pig carcasses. *Animal Production, 28*, 97–108.

Fisher, A. V., Green, D. M., Whittemore, C. T., Wood, J. D., & Schofield, C. P. (2003). Growth of carcass components and its relation with conformation in pigs of three types. *Meat Science, 65*, 639–650.

Fortin, A., Wood, J. D., & Whelehan, O. P. (1987). Breed and sex effects on the development, distribution of muscle, fat and bone and the partition of fat in pigs. *Journal of Agricultural Science, 108*, 141–153.

Gu, Y., Schinckel, A. P., & Martin, T. G. (1992). Growth, development, and carcass composition in five genotypes of Swine. *Journal of Animal Science, 70*, 1719–1929.

Jopson, N. B., Kolstad, K., Sehested, E., & Vangen, O. (1995). Computer tomography as an accurate and cost effective alternative to carcass dissection. *Proceedings of the Australian Association of Animal Breeding and Genetics, 11*, 635–638.

Kolstad, K. (2001). Fat deposition and distribution measured by computer tomography in three genetic groups of pigs. *Livestock Production Science, 67*, 281–292.

Landgraf, S., Susenbeth, A., Knap, P. W., Looft, H., Plastow, G., Kalm, E., & Roehe, R. (2004). Analysis of change of carcass cuts, organs, body tissues and chemical body composition during growth of pigs. *Animal Science* (submitted).

Marchant, J. A., Schofield, C. P., & White, R. P. (1999). Pig growth and conformation monitoring using image analysis. *Animal Science, 68*, 141–150.

McLaren, D. G., Novakofski, J., Parrett, D. F., Lo, L. L., Singh, S. D., Neumann, K. R., et al. (1991). A study of operator effects on ultrasonic measures of fat depth and *longissimus* muscle area in cattle, sheep and pigs. *Journal of Animal Science, 69*, 54–66.

Mitchell, A. D., Scholz, A. M., Wange, P. C., & Song, H. (2001). Body composition analysis of the pig by magnetic resonance imaging. *Journal of Animal Science, 79*, 1800–1813.

Montgomery, D. C. & Peck, E. A. (1992). *Introduction to linear regression analysis. Wiley series in probability and statistics* (2nd ed., pp. 171–172). John Wiley & Sons.

Newcom, D. W., Bass, T. J., & Lampe, E. F. (2002). Prediction of intramuscular fat percentage in life swine using real-time ultrasound. *Journal of Animal Science, 80*, 3046–3052.

SAS Institute Inc. (1999). *SAS/STAT user's guide*, version 8. Cary, NC: SAS Institute Inc..

Schofield, C. P., Marchant, J. A., White, R. P., Brandl, N., & Wilson, M. (1999). Monitoring pig growth using a prototype imagine system. *Journal of Agricultural Engineering Research, 72*, 205–210.

Szabo, C. S., Babinszky, L., Verstegen, M. W. A., Vangen, O., Jansman, A. J. M., & Kanis, E. (1999). The application of digital imaging techniques in the in vivo estimation of the body composition of pigs: a review. *Livestock Production Science, 60*(1), 1–11.

Tholen, E., Baulain, U., Henning, M. D., & Schellander, K. (2003). Comparison of different methods to assess the composition of pig bellies in progeny testing. *Journal of Animal Science, 81*, 1177–1184.

Wagner, J. R., Schinckel, A. P., Chen, W., Forrest, J. C., & Coe, B. L. (1999). Analysis of body composition changes of swine during growth and development. *Journal of Animal Science, 77*, 1442–1466.

Whittemore, C. T., Green, D. M., Wood, J. D., Fisher, A. V., & Schofield, C. P. (2003). Physical and chemical composition of the carcass of three different types of pigs grown from 25 to 115 kg live weight. *Animal Science, 77*, 235–245.