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Dual X-ray absorptiometry accurately predicts carcass composition from live sheep and chemical composition of live and dead sheep

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Abstract

Fifty merino wethers (liveweight range from 44 to 81 kg, average of 58.6 kg) were lot fed for 42 d and scanned through a dual X-ray absorptiometry (DXA) as both a live animal and whole carcass (carcass weight range from 15 to 32 kg, average of 22.9 kg) producing measures of total tissue, lean, fat and bone content. The carcasses were subsequently boned out into saleable cuts and the weights and yield of boned out muscle, fat and bone recorded. The relationship between chemical lean (protein + water) was highly correlated with DXA carcass lean ($r^2 = 0.90$, RSD = 0.674 kg) and moderately with DXA live lean ($r^2 = 0.72$, RSD = 1.05 kg). The relationship between the chemical fat was moderately correlated with DXA carcass fat ($r^2 = 0.86$, RSD = 0.42 kg) and DXA live fat ($r^2 = 0.70$, RSD = 0.71 kg). DXA carcass and live animal bone was not well correlated with chemical ash (both $r^2 = 0.38$, RSD = 0.3). DXA carcass lean was moderately well predicted from DXA live lean with the inclusion of bodyweight in the regression ($r^2 = 0.82$, RSD = 0.87 kg). DXA carcass fat was well predicted from DXA live fat ($r^2 = 0.86$, RSD = 0.54 kg). DXA carcass lean and DXA carcass fat with the inclusion of carcass weight in the regression significantly predicted boned out muscle ($r^2 = 0.97$, RSD = 0.32 kg) and fat weight, respectively ($r^2 = 0.92$, RSD = 0.34 kg). The use of DXA live lean and DXA live fat with the inclusion of bodyweight to predict boned out muscle ($r^2 = 0.83$, RSD = 0.75 kg) and fat ($r^2 = 0.86$, RSD = 0.46 kg) weight, respectively, was moderate. The use of DXA carcass and live lean and fat to predict boned out muscle and fat yield was not correlated as weight. The future for the DXA will exist in the determination of body composition in live animals and carcasses in research experiments but there is potential for the DXA to be used as an online carcass grading system.

Keywords; Lambs; Body composition; Carcass composition; Dual energy X-ray absorptiometry

Introduction

The relative proportions of muscle, fat and bone in live sheep and sheep carcasses are key traits used for selecting animals and valuing carcasses. Increasing the proportion of muscle and reducing fatness of slaughter sheep is important to meet abattoir requirements for processing efficiency and consumer demand for a leaner product. An accurate determination of muscle and fat proportion has historically involved either dissection of carcasses into their components or grinding carcasses and determining the components chemically. These methods require the destruction of the animal or carcasses and are time consuming and expensive. Recent research has focused on a variety of technologies designed to obtain more accurate measurement of the composition of the animal or carcass. A variety of techniques have been used, including ultrasound (Wilson, 1992), computer tomography (Young et al., 1996), electrical conductivity, NIR, X-ray and video imaging (Hopkins, Safari, Thompson, & Smith, 2004), however, all have proved either time consuming or expensive. Access to accurate, fast and cheap methodologies for estimating body composition will be of value to the sheep industry.

Dual energy X-ray absorptiometry (DXA) is a method to measure composition which has potential for use in the sheep industry. DXA uses differential attenuation of low and high-energy X-rays by bone, lean and fat tissues to estimate body composition (Kelly et al., 1998 and Nord et al., 2000). DXA uses low radiation levels (0.01–0.10 mSv per scan) and is an attractive method for measuring human body composition (Lukaski, Marchello, Hall, Schafer, & Siders, 1999). More recently, DXA has been used to assess the composition of live pigs and pig carcasses (Suster, 2003, Suster et al., 2000 and Suster et al., 2003), beef cuts (Mitchell, Solomon, & Rumsey, 1997) and lamb carcasses and primals (Diaz et al., 2004, Dunshea et al., 2007, Mercier et al., 2006 and Rozeboom et al., 1998). Of the studies conducted with sheep carcasses, all have shown that the DXA can predict half or whole carcass composition with accuracy. The prediction accuracy of body composition assessment of live sheep using DXA has not previously been tested.

This study firstly evaluated the potential for the DXA to predict carcass composition from a live animal DXA scan. In addition the potential for the DXA to accurately predict the lean fat and bone content of not only a whole lamb carcass but also in a live sheep compared to chemical analysis determined by mincing was assessed. Finally the potential for DXA to predict boned out muscle, fat and bone weight and muscle, fat and bone yield for a carcass and live animal was evaluated.

Materials and methods

The 50 sheep used were part of a more extensive Meat and Livestock Australia (MLA) funded project which aimed to generate a lean meat yield data set from 400 Merino sheep with extremes in estimated breeding values also called ASBVs. Animal ethics approval for this experiment was obtained from the Murdoch University Animal Ethics committee.

Experimental protocol

The 50 wethers were located at a feedlot in Katanning, Western Australia for days 1–30 (liveweight range from 44 to 81 kg, average of 58.6 kg). On day 31 the sheep were fasted off feed for 24 h and water for 12 h prior to administration of anaesthesia and scanning by a DXA. On day 32 the sheep were scanned by the DXA and upon recovery from anaesthesia were given access to feed and water before rejoining flock that day. At 8 am on day 42 the sheep began a 24 h feed and water fasting and at 2 pm were transported to a commercial slaughterhouse and slaughtered on day 43 at 7 am. The carcasses were scanned through the DXA on day 44 (carcass weight range from 15 to 32 kg, average of 22.9 kg). The carcasses were then transported to a commercial boning room for dissection into saleable cuts and all parts minced frozen, later.

Feeding and management regime

Sheep were fed 'EasyOne' pellets (a commercially available pellet manufactured by Milne Feeds, Perth Western Australia). These pellets have been formulated to enable no introduction period and no requirement for an additional fibre source. The pellets were fed adlib in self-feeders and on a dry matter basis contained 14.5% crude protein, 11.0 MJ/kg metabolisable energy and 20% crude fibre. They also contained lasolocid acid (Bovatec®).

Administration of anaesthesia prior to DXA scanning

Sheep were yarded into 'emptying out' pens in the animal house for fasting off both feed and water, 24 h prior to anaesthesia and DXA scanning. Prior to being DXA scanned sheep were lightly anaesthetised with halothane (Rhodia Halothane, 250 ml bottle, Merial Pharmaceuticals, Parramatta, Australia) to prevent them from moving as this would decrease the quality of the image produced. Medical grade nitrous oxide gas was used conjunctively as it decreased the anaesthetic requirements of halothane and had a slight stimulatory effect on cardiovascular function (Greene, 1994). The halothane vaporiser was adjusted to deliver 5% halothane, 1.5 l/min oxygen and 0.75 l/min nitrous oxide. Sheep were restrained in a laparoscopy cradle during the introduction of anaesthesia and initial recovery to prevent injury to themselves or staff.

DXA scanning

The live sheep and carcasses were scanned using a Norland XR-26 Fan Beam X-ray Whole Body Densitometer (DXA) (Inderlec, Sydney, Australia). The sheep and carcasses were positioned on the DXA table in sternal recumbency with forelimbs flexed and extended caudally, and the hindquarters flexed and level with body. The laser line level was set to obtain a pilot scan that included the thoracic inlet and as much of the body as possible.

Calibration of the unit was performed with the Step Phantom (supplied by Norland) once every week. The data from the step phantom calibration scan was automatically stored on the hard drive, and used during the whole body analysis, to ensure accurate fat/lean composition results. Spine calibration scans, using Spine Phantom (supplied by Norland) were performed daily to minimise baseline drift and ensure accurate bone mineral content measurement. Measurements made by DXA included total tissue mass, lean tissue mass, fat tissue mass and bone mineral mass in grams (subsequently referred to as DXA live/carcass lean, fat or bone mass). The whole body scan mode was used for all animals and carcasses and scan times were ~2 min depending on the length of the carcass. Regional analysis was not performed in the DXA software, instead the entire DXA live animal or carcass image was placed in the left arm region of the regional grid.

Bone-out procedure

The bone-out component of this experiment was carried out in the Butchery Laboratory at the Regency College of Technical and Further Education in Adelaide, South Australia and all procedures are described in the VIAscan Lamb Manual Revision August 2005 (Anon, 2005b).

The body was initially broken down into the forequarter, saddle and legs with a bandsaw before being further processed into the following saleable cuts as defined in the AUSMEAT Handbook for Australian Meat (Anon, 2005a). From the forequarter: eye of shoulder, boneless shoulder, neck meat and tipped foreshank. From the saddle: eye of short loin, tenderloin butt off, boneless flap and eye of rack. From the legs: leg (chump on), topside, round silverside, rump, butt tenderloin and shank.

Cutting templates were used to ensure consistency between butchers.

The weight of all saleable cuts was combined and this was described as the boned out muscle weight.

The weight of all the boned out fat and bone was also weighed. The lean meat yield of the carcass

represents the boned out muscle weight divided by the weight of the cold carcass weight immediately prior to boning. The fat and bone yield was also determined by dividing the boned out fat/bone weight by cold carcass weight prior to boning.

Mincing procedure

Following the commercial bone-out into saleable cuts, the total carcass material for each sheep was frozen and shipped back to Murdoch University. The samples remained frozen for 10 d and the entire body components (including all trim) were minced frozen to minimise moisture loss using a commercial mincer (Nolex B55 grinder, MBL, Perth, Australia). The carcass parts were initially put through a coarse die mincing plate. This was done to break down the bone sections into smaller sections. They were subsequently passed twice through a fine die to further reduce particle size. Before each mincing the mince was manually mixed to ensure homogeneity. Any fluid loss was collected and re-incorporated evenly into the mince. Sub-samples of the mince were taken for chemical analysis of dry matter, fat, protein and ash.

Chemical analysis

Dry matter content was measured by weight loss after 24 h drying at 102 °C, and water content was calculated by difference. Ash was determined by residual weight following combustion of oven dry samples for 6 h at 650 °C in a muffle furnace. Additional samples were freeze-dried before chemical lipid and protein analyses by a commercial laboratory (Microserve Laboratory Pty. Ltd., East Perth, Australia). Freeze-dried samples were analysed for lipid content by soxhlet extraction with diethyl ether (Atkinson, Fowler, Garton, & Lough, 1972) and protein by the Kjeldahl method. This method predicts the protein content by determination of the nitrogen content and multiplying it by a factor of 6.25 on the assumption that protein contains 16% nitrogen (AOAC, 1990).

A 50 g sub-sample from each of the m. semimembranosus, m. semitendinosus, m. longissimus dorsi and m. infraspinatus was taken in addition to one of the flaps for the determination of intramuscular fat. These samples were taken following the commercial bone-out and prior to mincing. The intention was to process these samples for all chemical constituents (fat, protein and ash) thus enabling back correction of the final carcass chemical composition. These samples were lost in transit and thus not included in the determination of total chemical protein, fat and ash.

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Statistical analysis

Comparisons between live and carcass DXA imaging and the chemical analysis, between the live and carcass DXA images and DXA with boned out muscle weight and yield were all undertaken using a general linear regression model with Genstat. The prediction accuracy of the models generated is expressed with an r^2 , residual standard deviation (RSD) and F values.

Sire identification number was used as a random effect in both models. Non-significant terms ($P > 0.05$) were sequentially deleted from the models and in all cases the raw data was assessed to ensure that the responses were not driven by outliers.

Results

Correlation between chemical composition with DXA determined lean, fat and bone of the whole carcass and live animal

The relationship between chemical protein + water and DXA carcass lean was correlated (Table 1 and Fig. 1), with an r^2 of 0.9. While it would be more meaningful to relate DXA lean mass to muscle mass, the strong correlation between the DXA lean mass and chemical lean indicates the two are related. Comparing chemical protein and DXA lean mass was less correlated but still a moderate relationship (r^2 of 0.87). The relationship between the DXA carcass fat was highly correlated with that measured by chemical analysis (r^2 of 0.86) (Table 1 and Fig. 1). This result could have been further improved if the samples lost were included in the chemical analysis.

DXA live lean and chemical protein + water was also moderately related with an r^2 of 0.72 (Table 1 and Fig. 2). In addition, the DXA live fat is a moderate predictor of chemical fat with an r^2 of 0.7 (Table 1 and Fig. 2). The prediction accuracy for lean and fat is clearly better for a carcass with a

lower RSD of 0.64 kg compared to 1.05 kg for the live animal for lean and 0.42 kg compared to 0.71 kg for the fat.

Summation of the DXA measurements of total fat, lean and bone content yields a figure that should be equivalent to total body mass. DXA total tissue mass measurements were highly correlated between carcass total tissue mass and carcass weight and also between live animal total tissue mass and bodyweight at time of scanning (Table 1).

There was no clear relationship between DXA bone and chemical ash content for either the whole carcass or live animal (r^2 of 0.39) (Table 1, and Fig. 1 and Fig. 2).

Estimating DXA carcass lean, fat and bone from DXA live lean, fat and bone

Carcass DXA composition can be predicted from live animal DXA (Table 2 and Fig. 3). DXA carcass lean was moderately well predicted from DXA live lean (r^2 of 0.73) and the regression improved with the inclusion of bodyweight (r^2 of 0.82). DXA carcass fat was well predicted from the comparison with DXA live fat (r^2 of 0.86) and not improved with the addition of bodyweight to regression (r^2 of 0.86). DXA carcass bone was well predicted from DXA live bone (r^2 of 0.93).

Accuracy of live and carcass DXA to predict boned out meat, fat trim and bone weight and yield at a commercial bone-out

DXA carcass lean significantly predicted boned out muscle weight with a high r^2 of 0.93 (Table 3 and Fig. 4). The regression was improved if carcass weight was included (r^2 of 0.97). The use DXA live lean to predict boned out muscle weight was not as significant (r^2 of 0.64) but also improved with inclusion of body weight to the regression model (r^2 of 0.83). The use of DXA carcass fat to predict

boned out fat weight was also a significant relationship (r^2 of 0.87) and again improved with the inclusion of carcass weight (r^2 of 0.92) (Table 3 and Fig. 5). DXA live fat was also moderately related to boned out fat weight (r^2 of 0.71) and the regression further improved with the inclusion of body weight (r^2 of 0.86). The use of DXA carcass bone to predict boned out bone weight was significant (r^2 of 0.86) and improved with the inclusion of carcass and body weight (r^2 of 0.88) (Table 3).

The use of DXA% carcass lean and fat to predict boned out muscle and fat yield was moderately correlated (r^2 of 0.64 and 0.76, respectively) (Table 4 and Fig. 5). The use of DXA% live lean and carcass lean was poorly correlated with muscle (r^2 of 0.61 and 0.42, respectively). The prediction of fat yield from DXA% carcass fat and DXA% live fat were moderately well predicted and improved with the inclusion of body and carcass weight (r^2 of 0.65 and 0.81, respectively) (Table 4 and Fig. 5). The use of DXA% carcass and live bone to predict bone yield was poor (Table 4). The reduced accuracy to predict yield over weight could be attributable to the confounding effects of the inclusion of carcass weight in the yield calculation.

Discussion

This study has shown that the DXA is an accurate tool to measure carcass composition in both live animals and carcasses. DXA carcass lean and fat was moderately well predicted from DXA live lean and fat. The opportunity to define the carcass composition of a live animal is essential for research into compositional changes due to physiological status and genetic selection.

Chemical compositional analysis is the standard for the measurement of body composition in a carcass or live animal. Tissue weights determined by DXA from scans of the live animal and carcass were compared with weights of chemically-determined lean tissue. The lean mass in a carcass is predominantly muscle whereas in the live animal lean mass is the sum of muscle, organs, blood and

stomach contents, much of which is removed at slaughter to result in a carcass. The correlation between LL and chemlean (r^2 of 0.72) would then be expected to be lower than between CL and chemlean (r^2 of 0.90). The removal of fat deposits such as omental and kidney fat at slaughter also results in a higher correlation between DXA CF and chemfat (r^2 of 0.86) compared to DXA LF which was less correlated with chemfat (r^2 of 0.70). This high correlation between DXA lean/fat mass and chemical lean/fat mass indicates that DXA very accurately predicts muscle and fat weight in a carcass as also shown by lower RSDs.

There was no clear relationship between DXA bone and chemical ash. This can be expected as chemical ash is dispersed in the chemical lean following mincing and may be confounded within the lean component. Furthermore, the inclusion of non-osseous minerals such as cartilage were included in the measure of chemical ash thus making it an imperfect correlate of bone as ash in part also reflects changes in muscle and fat (Dunshea et al., 2007).

Other studies have also shown a high level of prediction accuracy using the DXA on sheep (Clarke et al., 1999, Dunshea et al., 2007 and Ponnampalam et al., 2007) with the highest accuracy being for fat. In this study the highest predictive accuracy was shown for lean tissue.

In all these studies however, very specific prediction equations were used which were highly specific to breed (Merino) and weight ranges used and consequently the predictive models may not transport well to other breeds or greater weight ranges.

Commonly used industry methods to predict lean meat yield include the VIAscan which has been shown to predict lean meat yield with a r^2 of 0.52 (Hopkins et al., 2004). The predictive approach

using a regression of the fat depth at GR site (tissue depth over the 12th rib), eye muscle area and hot carcass weight yielded a moderate relationship against % lean content with an r^2 of 0.51 (Hopkins, Ponnampalam, & Warner, 2008). Therefore, the DXA could be used to predict boned out meat weight and yield with higher accuracy than other methods due to its ability to quantitatively measure tissues and its reduced reliance on predictive association.

The high accuracy of the DXA to predict boned out muscle weight indicates that DXA may provide important compositional information for valuable wholesale cuts thus allowing a more detailed evaluation of carcass and cut yield and market value. Similar results were observed by Clarke et al. (1999) who investigated the use of the DXA to obtain compositional information from the leg cut. The results obtained from a dissection of the leg compared to the DXA measurements for lean, fat and bone were highly correlated.

Despite the positive results for the DXA to estimate boned out muscle weight it is difficult to predict whether the DXA will be used as an online carcass grading tool due to the current incompatibility of the long scanning time and chain speed of the abattoir. A cross-sectional scanning approach may be required to enable DXA to become an online grading system. Recent studies with pork have shown that the composition of a cross-section of a carcass taken with the DXA, rather than scanning the whole carcass correlated well with the composition of the entire carcass (Mitchell et al., 2003 and Mitchell et al., 1997). A single cross-section slice from the ham region (equivalent in sheep to the region from the anterior tip of the aitch bone to the hock) predicted the fat and lean in the half carcass with an r^2 of 0.81. This was improved with the inclusion of further sections to the analysis. The DXA instrument used in the study by Mitchell et al. (2003) utilised the pencil-beam X-ray technology, scanning at cross-sectional intervals of 9.6 mm at a scan speed of 7.68 cm/s. Typically DXA instruments scan at rates of 4–16 cm/s. With these units the subject remains stationary and the scan speed is determined by the simultaneous motor-driven movement of the X-ray source and

detector. By comparison, the chain speed of a modern slaughter facility is approximately 16.6 cm/s. Newer DXA instruments utilise a wide-angle or fanbeam technology that will scan wider sections. Comparative studies indicate that the pencil and wide-angle beam are comparable for measuring soft tissue composition (Nord et al., 2000).The achievement of scan times the same as chain speed could be achieved by allowing more X-ray scatter, higher levels of irradiation and a single not multiple scan types. However, the single scan slice may not be sufficient for a range of genotypes so instead may be three scans could be performed along the carcass and the data collected into a single point and calibration curves could be used to predict carcass composition.

There may also be the possibility of using DXA to assist in generating accurate coordinates for robotic or mechanical boning thus underpinning an automated boning chain. The best scenario would be to set up two DXAs to provide an overhead and side-on scan that could be then integrated into a three-dimensional build-up of the carcass. This approach, with appropriate modeling, could provide accurate positioning of bone to be incorporated into a robotic boning system. Additional applications include the potential to evaluate tenderness as recent findings demonstrate that the DXA was moderately correlated to shear force with an r^2 of 0.69 (Kroger, Bartle, West, Purchas, & Devine, 2006).

Conclusions

DXA is an accurate tool to measure carcass composition in both live animals and carcasses. The potential to scan live animals and gain an accurate estimate of both carcass composition and boned out muscle weights was identified as a clear benefit. This will enable researchers to better understand the interactions between genetics and environment and the influences they exert on carcass

composition. Genetic selection programs may benefit from scanning sheep of high genetic worth through the DXA to improve their rate of genetic gain.

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Table 1. Models for the prediction of chemically-determined lean, fat and bone mass (kg) for live animal and whole carcasses from dual energy X-ray absorptiometry (DXA) determined lean, fat, bone and total mass

Predictors	Best prediction model (values in parentheses are standard errors)	r^2	RSD	F value	Regression significance
<i>Chemlean</i>					
Live animal	(LL mean \pm SEM = 39.9 \pm 0.87 kg) 1.99 (\pm 1.1) + 0.29 (\pm 0.02) * LL	0.72	1.05	106.3	**
Whole carcass	(CL mean \pm SEM = 15.4 \pm 0.2 kg) 0.66 (\pm 0.7) + 0.853 (\pm 0.04) * CL	0.90	0.64	365	**
<i>Chemfat</i>					
Live animal	(LF mean \pm SEM = 5.37 \pm 0.4 kg) -2.52 (\pm 0.23) + 0.37 (\pm 0.04) * LF	0.70	0.71	86.4	**
Whole carcass	(Mean \pm SEM = 5.14 \pm 0.2 kg) -0.46 (\pm 0.2) + 0.78 (\pm 0.04) * CF	0.86	0.42	279.2	**
<i>Chemash</i>					
Live animal	(LB mean \pm SEM = 1.19 \pm 0.03 kg) -0.1 (\pm 0.26) + 1.17 (\pm 0.21) * LB	0.38	0.3	29.8	**
Whole carcass	(Mean \pm SEM = 1.08 \pm 0.02 kg) -0.23 (\pm 0.27) + 1.48 (\pm 0.25) * CB	0.39	0.29	31.9	**
<i>BWT/CWT</i>					
Live animal (BWT)	(LT mean \pm SEM = 46.3 \pm 1.1 kg) 0.29 (\pm 2.46) + 0.001 (\pm 0.00005) * LT	0.90	2.7	411.5	**
Whole carcass (CWT)	(CT mean \pm SEM = 21.8 \pm 0.5 kg) -0.72 (\pm 0.21) + 0.001 (\pm 0.00009) * CT	0.99	0.17	10954	**

** $P < 0.001$; chemlean, chemical lean (protein + water); chemfat, chemical fat; chemash, chemical ash, BWT, body weight at scanning; CWT, carcass weight at scanning; LF, DXA determined live fat; CF, DXA determined carcass fat; LL, DXA determined live lean; CL, DXA determined carcass lean; LB, DXA determined live bone; CB, DXA determined carcass bone; LT, DXA determined live total; CT, DXA determined carcass total.

Table 2. Models for the prediction of dual energy X-ray absorptiometry (DXA) determined carcass lean, fat and bone mass from DXA measurements on the live animal for lean, fat and bone mass

Predictors	Best prediction model (values in parentheses are standard errors)	r^2	RSD	F value	Regression significance
<i>DXA carcass lean (CL)</i>					
1	3.13 (± 1.1) + 0.30 (± 0.028) * LL	0.73	1.1	118.1	**
2	0.47 (± 1.1) + 0.12 (± 0.04) * LL + 0.17 (± 0.03) * BWT	0.82	0.87	97.2	**
3	2.1 (± 1.13) + 0.30 (± 0.03) * LL + 0.2 (± 0.06) * LF	0.78	1.02	76.2	**
4	0.55 (± 1.2) + 0.2090 (± 0.05) * LL + 0.0874 (± 0.07) * LF + 0.102 (± 0.04) * BWT	0.81	0.95	56.8	**
<i>DXA carcass fat (CF)</i>					
1	2.49 (± 0.18) + 0.52 (± 0.03) * LF	0.86	0.54	258.1	**
2	-0.068 (± 0.62) + 0.41 (± 0.035) * LF + 0.052 (± 0.01) * BWT	0.86	0.51	134.1	**
<i>DXA carcass bone (CB)</i>					
1	0.099 (± 0.03) + 0.82 (± 0.03) * LB	0.93	0.04	384.9	**
2	0.02 (± 0.05) + 0.71 (± 0.05) * LB + 0.004 (± 0.001) * BWT	0.94	0.04	360.2	**
<i>DXA carcass total (CT)</i>					
1	1.63 (± 1.22) + 0.43 (± 0.02) * LT	0.86	1.25	283.8	**

** $P < 0.001$; LL, live lean mass; BWT, body weight on day of scanning; LF, live fat mass; LB, live bone mass; LT, live total.

Table 3. Models for the prediction of boned out muscle, fat or bone weight using lean, fat and bone mass from dual energy X-ray absorptiometry (DXA) from the carcass and live animal

Predictors	Best prediction model (values in parentheses are standard errors)	r ²	RSD	F value	Regression significance
<i>Boned out muscle weight (saleable meat weight)</i>					
1	0.1 (±0.5) + 0.76 (±0.03) * CL	0.93	0.47	568.3	**
2	0.19 (±0.34) + 0.4 (±0.06) * CL + 0.23 (±0.04) * CWT	0.97	0.32	623.9	**
3	2.18 (±1.0) + 0.24 (±0.02) * LL	0.64	1.09	80.8	**
4	-0.48 (±0.8) + 0.03 (±0.03) * LL + 0.18 (±0.02) * BWT	0.83	0.75	109.1	**
<i>Boned out fat weight</i>					
1	-0.59 (±0.2) + 0.77 (±0.04) * CF	0.87	0.37	388.2	**
2	-1.5 (±0.4) + 0.64 (±0.05) * CF + 0.06 (±0.02) * CWT	0.92	0.34	230.2	**
3	1.32 (±0.2) + 0.43 (±0.04) LF	0.71	0.74	107.1	**
4	-0.712 (±0.9) + 0.35 (±0.05) * LF + 0.042 (±0.017) * BWT	0.86	0.46	136.8	**
<i>Boned out bone weight</i>					
1	0.92 (±0.3) + 5.17 (±0.3) * CB	0.86	0.34	307.4	**
2	0.87 (±0.3) + 3.4 (±0.61) * CB + 0.08 (±0.02) * CWT	0.88	0.31	188.3	**
3	1.43 (±0.35) + 4.3 (±0.3) * LB	0.82	0.39	220.1	**
4	0.59 (±0.4) + 2.9 (±0.45) * LB + 0.04 (±0.01) * BWT	0.86	0.36	134.6	**

**P < 0.001; CL, carcass lean mass; CWT, carcass weight; CF, carcass fat mass; CB, carcass bone mass; LL, live lean mass; BWT, body weight on day of scanning; LF, live fat mass; LB, live bone mass.

Table 4. Models for the prediction of yield percentage using lean, fat and bone mass from dual energy X-ray absorptiometry (DXA) from the carcass and live animal

Predictors	Best prediction model (values in parentheses are standard errors)	r^2	RSD	F value	Regression significance
<i>Muscle yield (%)</i>					
1	21.6 (± 3.5) + 0.45 (± 0.05) * CL%	0.64	1.53	85.3	**
2	25.8 (± 4.78) + 0.42 (± 0.05) * CL% - 0.82 (± 0.06) * CWT	0.65	1.52	44.5	**
3	24.5 (± 0.09) + 0.34 (± 0.05) * LL%	0.42	1.98	33.8	**
4	29.2 (± 6.4) + 0.32 (± 0.06) * LL% - 0.05 (± 0.03) * BWT	0.43	1.97	17.9	**
<i>Fat yield (%)</i>					
1	-1.4 (± 1.1) + 0.6 (± 0.04) * CF%	0.76	2.69	52.5	**
2	-4.8 (± 1.36) + 0.55 (± 0.04) * CF% + 0.21 (± 0.06) * CWT	0.81	2.69	26.8	**
3	7.52 (± 0.7) + 0.49 (± 0.05) LF%	0.61	1.96	73.1	**
4	2.7 (± 1.92) + 0.5 (± 0.05) * LF% + 0.08 (± 0.033) * BWT	0.72	1.68	54.4	**
<i>Bone yield (%)</i>					
1	8.7 (± 3.1) + 4.2 (± 0.3) * CB%	0.49	1.59	47.6	**
2	16.6 (± 3.5) + 3.6 (± 0.58) * CB% - 0.2 (± 0.05) * CWT	0.59	1.42	36.1	**
3	28.1 (± 3.6) + 0.5 (± 1.4) * LB%	na	2.09	0.13	ns
4	35.9 (± 3.9) + 0.2 (± 1.3) * LB% - 0.1 (± 0.03) * BWT	0.14	1.89	4.8	ns

**P < 0.001; CL%, carcass lean percentage; LL%, live lean percentage; CF%, carcass fat percentage; LF%, live fat percentage; CB%, carcass bone percentage; LB%, live fat percentage; LL%, live lean percentage; CWT, carcass weight; BWT, body weight at scanning.

Fig. 1. Relationships between the dual energy X-ray absorptiometry (DXA) derived lean, fat and bone tissue mass and chemically-determined protein + water, lipid and ash content in the whole carcass. A regression fit, the 95% confidence interval (dashed line) and the 95% prediction interval (solid line on outskirts of data) has also been included.

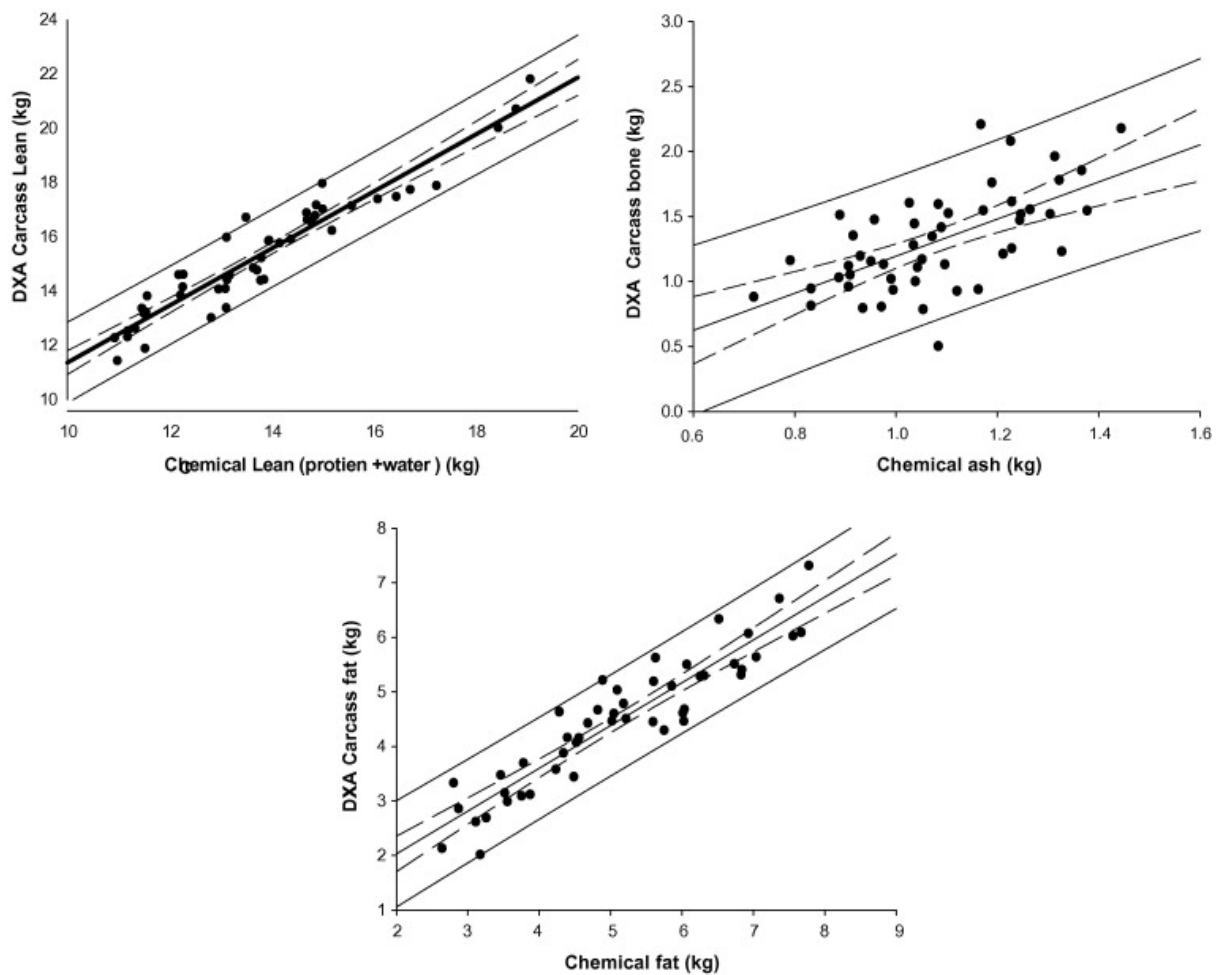


Fig. 2. Relationships between the dual energy X-ray absorptiometry (DXA) derived lean, fat and bone tissue mass and chemically-determined protein + water, lipid and ash content in the live animal. A regression fit, the 95% confidence interval (dashed line) and the 95% prediction interval line (solid line on outskirts of data) has also been included.

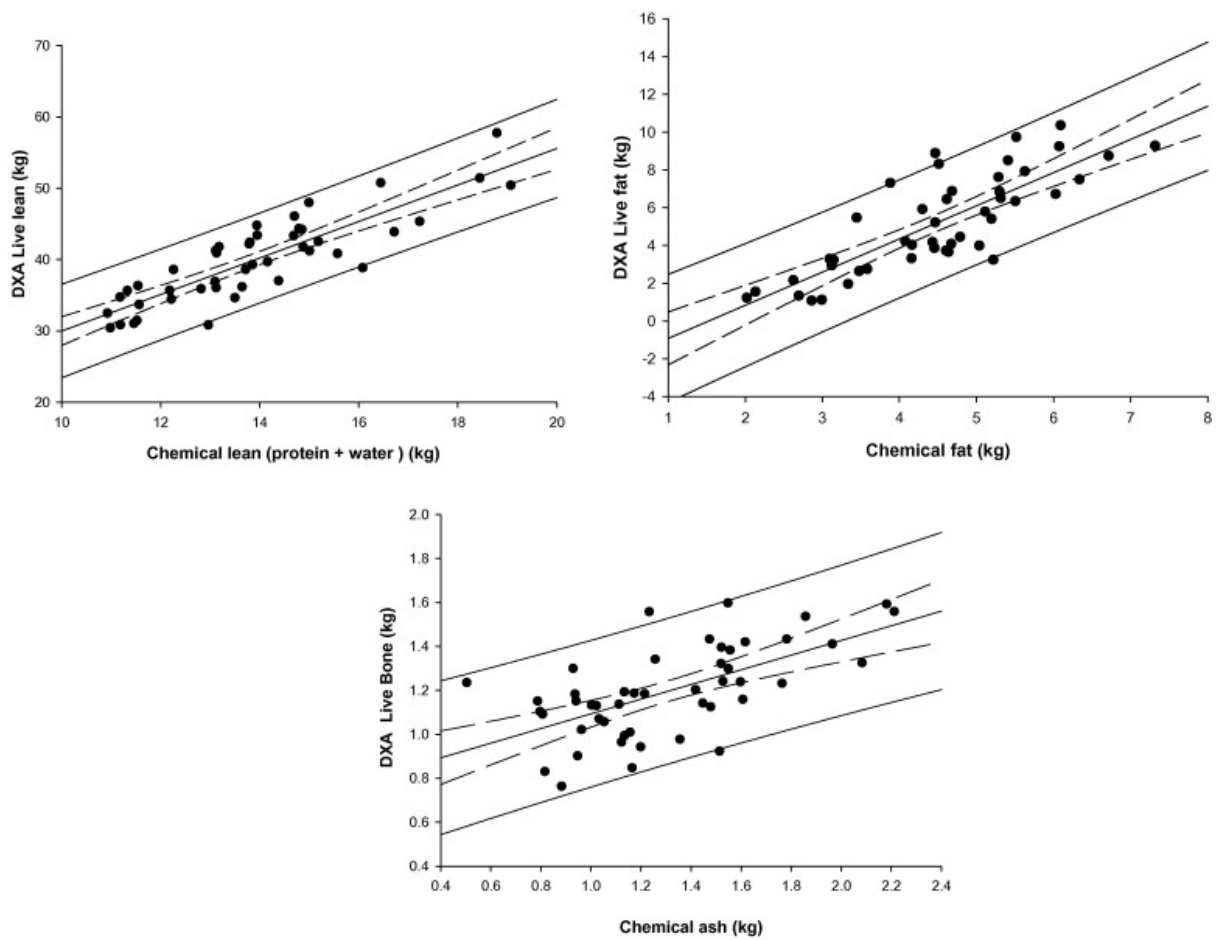


Fig. 3. Relationships between the dual energy X-ray absorptiometry (DXA) derived lean, fat and bone tissue mass in the whole carcass and the dual energy X-ray absorptiometry (DXA) derived lean, fat and bone tissue mass in the live animal. A regression fit, the 95% confidence interval (dashed line) and the 95% prediction interval line (solid line on outskirts of data) has also been included.

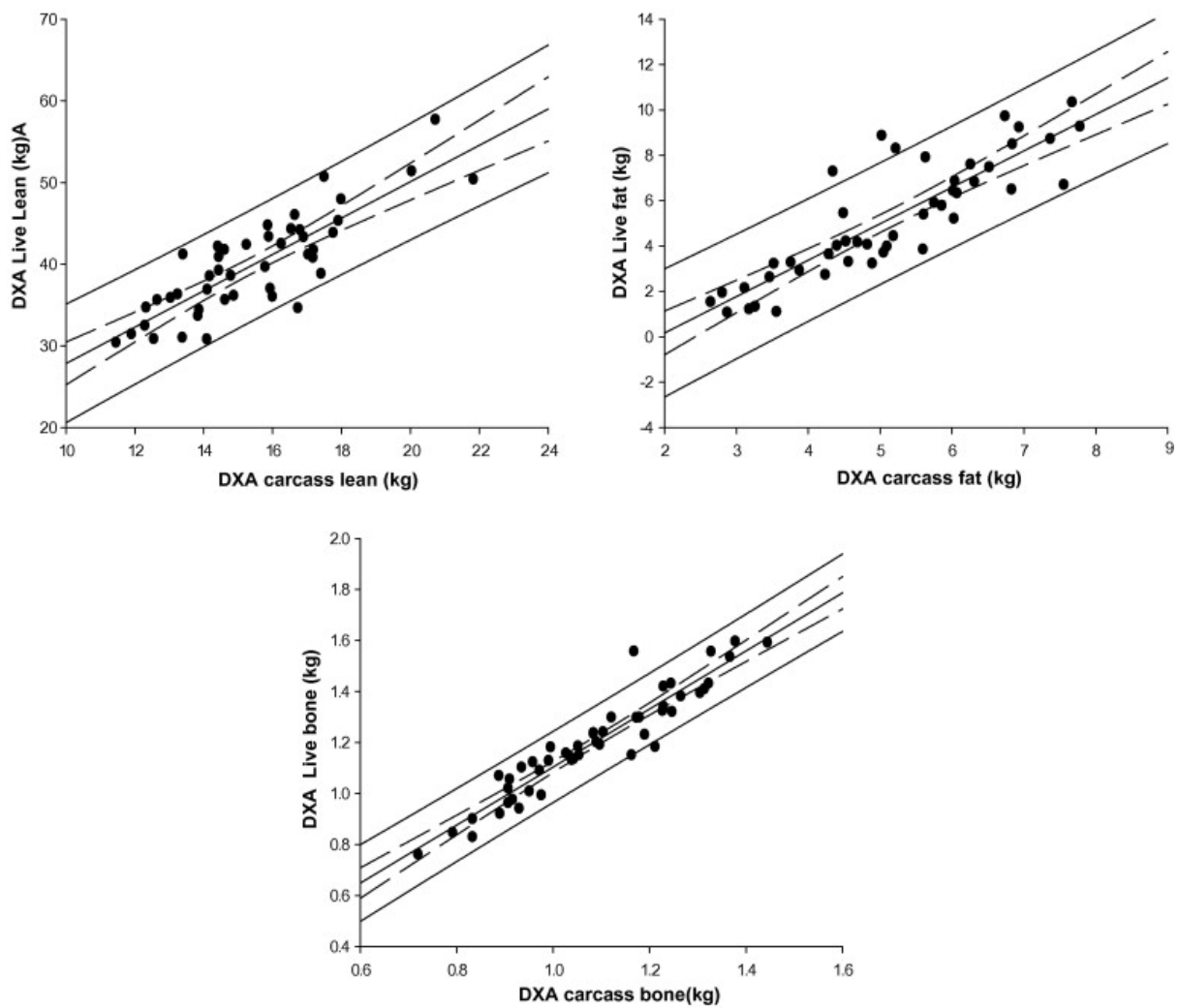


Fig. 4. Relationships between (A and B) the dual energy X-ray absorptiometry (DXA) derived lean tissue mass in the whole carcass and live animal vs. the boned out muscle weight (kg) and (C and D) the dual energy X-ray absorptiometry (DXA) derived percentage lean tissue mass in the whole carcass and live animal vs. the percentage muscle yield. A regression fit, the 95% confidence interval (dashed line) and the 95% prediction interval line (solid line on outskirts of data) have also been included.

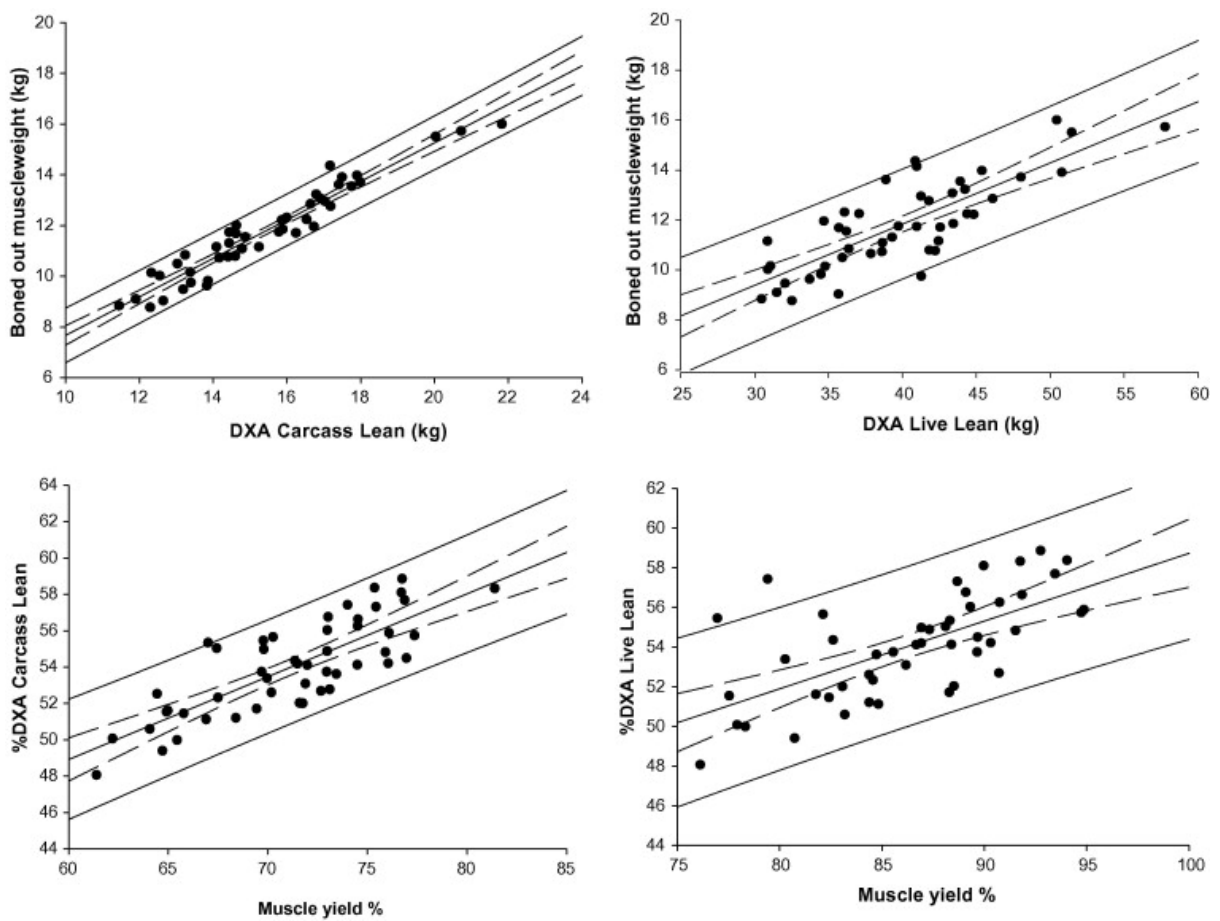


Fig. 5. Relationships between (A and B) the dual energy X-ray absorptiometry (DXA) derived fat mass in the whole carcass and live animal vs. the boned out fat weight (kg) and (C and D) the dual energy X-ray absorptiometry (DXA) derived percentage fat mass in the whole carcass and live animal vs. the percentage fat yield. A regression fit, the 95% confidence interval (dashed line) and the 95% prediction interval line (solid line on outskirts of data) have also been included.

