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The use of dual-energy X-ray absorptiometry to estimate the dissected composition of lamb carcasses

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Abstract

A total of 140 male and female Dorset and Suffolk lambs were slaughtered according to four live weight classes (36–39 kg, 41–44 kg, 46–49 kg and 51–54 kg). Total tissue, fat and lean masses, and bone mineral content measured by dual-energy X-ray absorptiometry (DXA) were used to predict dissected tissue weights. The DXA total weights accurately predict half-carcasses and primal cuts weights (shoulder, leg, loin and flank) ($R^2 > 0.99$, CVe < 1.3%). The prediction of the half-carcass dissected fat percentage is weaker ($R^2 = 0.77$, CVe = 10.4%). Fatness prediction accuracy is equivalent for the shoulder, leg and loin (R^2 between 0.68 and 0.78, CVe between 10% and 13%). The R^2 obtained when predicting dissected lean content from DXA variables is 0.93 for the half-carcass and higher than 0.83 for all cuts other than flank (CVe are between 3.5% and 6.5%, except for the flank, which is 9.1%). The prediction of bone weight using the bone mineral content is not very accurate for the half-carcass, shoulder and leg (R^2: 0.48, 0.47 and 0.43; CVe: 10.2%, 12.0% and 11.6%, respectively). The situation improves, however, for the loin ($R^2 = 0.70$, CVe = 10.7%). In conclusion, DXA is an effective technology for predicting total weight and the amount of lean and fat in lamb carcasses and their primal cuts.

Keywords: Lambs; Carcass composition; Dissection; Dual energy X-ray absorptiometry

1. Introduction

For many years, consumers have associated animal fat with the upsurge in coronary heart diseases. In order to reduce their consumption of fat, consumers are now looking for leaner cuts of meat. With the goal of meeting consumers' demand and improving the quality of the carcass marketed, a number of studies have been conducted to characterize carcass composition and assessing the impact of different means of reducing carcass fatness (genetics, nutrition, management, etc.) in sheep and in other meat-producing animals. However, the methods traditionally used to assess carcass composition, such as carcass dissection or chemical analyses, are time-consuming, expensive and subject to biases resulting from the dexterity and fatigue of the butchers (Argüello, Capote, Ginés, & Lòpez, 2001; Daumas, 1999). New technologies are now available, including bioimpedance analysis (BIA; Mazess, Barden, Bisek, & Hanson, 1990), total body electrical conductivity (TOBEC; Roubenoff, Kehayias, Dawson-Huges, & Heymsfield, 1993), magnetic resonance imaging (MRI; Mazess et al., 1990), X-ray computed tomography (Brienne, Denoyelle, Baussart, & Daudin, 2001) and dual-photon absorptiometry (DPA; Brienne et al., 2001). Another such method, called dual-energy X-ray absorptiometry (DXA), can also be used to evaluate body composition (Mazess et al., 1990). DXA is fast, easy to use and accurate to determine body composition (fat, lean and bone mineral content) in a lot of species (human, sheep, pig). It also has the advantage of not relying on other

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measurements (length, carcass temperature), unlike BIA and TOBEC (Cosgrove, King, & Brodie, 1988; Laskey & Phil, 1996).

DXA technology has already been validated in humans to determine bone mineral content (BMC), bone density and the fat and lean composition of tissues (Going et al., 1993; Mazess et al., 1990; Pritchard et al., 1993; Van Loan & Mayclin, 1992). DXA has also been shown to be effective for estimating body composition in live swine (Brunton, Bayley, & Atkinson, 1993; Mitchell, Scholz, & Conway, 1998b; Svendsen, Haarbo, Hassager, & Christiansen, 1993), pork carcasses (Brienne et al., 2001; Ellis, Shypailo, & Pratt, 1994; Marcoux, Bernier, & Pomar, 2003; Mitchell, Conway, & Potts, 1996, 1998a), chickens (Mitchell, Rosebrough, & Conway, 1997) and European and New Zealand sheep breeds (Clarke, Kirton, Bartle, & Dobbie, 1999; Rozeboom et al., 1998). However, the studies of Rozeboom et al. (1998) and Clarke et al. (1999) on lamb carcasses were carried out with a Hologic device, differing from other devices in its capacity to assess body composition (Oldroyd et al., 1998) and in a narrow range of carcasses weight and composition. On the other hand, swine have different shape, thickness and carcass composition than lambs (Field, Riley, Mello, Corbridge, & Kotula, 1974; Kempster, 1980) preventing to directly transpose to lambs the results obtained in swine. The objectives of this project were therefore to (1) study the capability of DXA to estimate dissected lean, fat and bone weights in lamb carcasses and primal cuts over a wide range of weights and tissue composition, and (2) to establish prediction equations for each dissected tissue in the overall carcass and primal cuts from DXA variables.

2. Materials and methods

2.1. Animal sampling and husbandry conditions

Vaginal sponges (Veramix, Pharmacia & Upjohn, Orangeville, ON, Canada) and PMSG (Intervet Canada, Whitby, ON, Canada) were used to synchronize the oestrous cycles of 144 Suffolk (SU) and 129 Dorset (DP) ewes on nine commercial producers in order to obtain 72 SU lambs and 72 DP lambs, 36 intact males and 36 females of each breed. Oestrous synchronization helped to reduce the variations in age and weight of the lambs at the beginning of the trial. Tail docking was performed on lambs with elastic band when they were around 7 days old. Lambs were weaned at approximately 50 days of age and transported to a lamb evaluation station (St-Jean-de-Dieu, Qué., Canada) where they were grouped and raised under the same environmental conditions.

The 144 lambs were distributed using a $2 \times 2 \times 4$ randomized complete block factorial design, in which sex (intact males and females), breed (SU and DP) and slaughter weight class (P1: 36–39 kg; P2: 41–44 kg; P3: 46–49 kg; P4: 51–54 kg) were the main factors. Lambs were distributed among 18 pens, each containing eight lambs of the same sex, four of each breed. The four slaughter weight classes were assigned to each of the lambs of the same breed within each pen. The lambs were fed ad libitum up to about 35 kg body weight with a complete starter diet (18% protein and 2.76 Mcal/kg metabolizable energy) and then a finishing diet (15% protein and 2.79 Mcal/kg metabolizable energy). Lambs had access to fresh water and good quality hay during the experiment.

2.2. Slaughter

The lambs were weighed weekly throughout the experiment until they reached slaughter weight. The lambs were weighed before departure, after a starvation of about 12 h, and prior to slaughtering. Lambs were slaughtered in a commercial abattoir. Hot carcass weight was recorded and perirenal fat removed and weighed prior to the carcasses being chilled at 4 °C for 24 h. After chilling, carcasses were classified according to Agriculture and Agri-Food Canada procedures (Agriculture Canada, 1992) and cold carcass weight was recorded. The carcasses were then split lengthwise and stored at 4 °C. Four days later, the left side of each carcass was shipped to the Agriculture and Agri-Food Canada Research Centre at Lennoxville, Qué., Canada.

2.3. Cuts and absorptiometry measurements

Upon arrival at the Research Centre, each half-carcass was weighed again. The length between the first rib and the hip bone, the number of ribs and general observations (split quality, tissues ablated, etc.) were recorded. Before the carcass cut-out, the remainder of the perirenal fat, the small part of the skirt on the loin and forelegs up to the knee joint were removed and weighed. The half-carcasses were separated into the four primal cuts (shoulder, leg, loin and flank) and weighed individually.

The four primal cuts were placed on the DXA table according to the anatomical layout of the half-carcass and scanned with the Lunar DPX-L osteodensitometer (Lunar Corp., DPX-L model; Madison, WI, USA) in pediatric medium mode. This mode was chosen on the basis of a preliminary study (results not shown) and in agreement with the manufacturers recommendations. Scans were analysed to obtain DXA total weight, lean and fat weights, bone mineral content (BMC) and the ratio between the coefficients of attenuation of the two X-ray energy levels (R-value) of the overall carcass and of each primal cut, using the DPX-L adult program (version 4.7E, Lunar Corp.; Madison, WI, USA).

Commercial cutting was performed after the scans and consisted of separation of the primal cuts into commercial cuts: square-cut shoulder, neck, shank, brisket, partial boneless leg, loin, rack and flank. Each cut was then dissected to obtain the weight of the lean, bone and the sub-

cutaneous, intermuscular and residual body cavity fat. The end of the hind leg and the tail were not dissected, and their weights were included in the dissected bone fraction.

2.4. Statistical analyses

For analysis and comparisons between dissected tissues weight and DXA tissues weight, total fat measured by DXA were considered to correspond to dissected intermuscular fat, subcutaneous fat and residual body cavity fat. We assumed that the weight of DXA lean corresponds to dissected lean and DXA BMC to dissected bones.

Dissected lean, fat and bone weights were compared with DXA estimations with a *T*-test analysis using the TTEST option within the MEANS procedure of SAS (1999). For each primal cut and for the entire half carcass, the mathematical relationships between dissection fraction weights (total, lean, fat and bone; dependent variables) and DXA estimated fraction weights (total weight, lean, fat, BMC and *R*-value; independent variables) were established by linear or multiple regression analysis using the REG procedure of SAS (1999). The accuracy of the relationship between dissection and DXA variables was evaluated on the basis of their adjusted coefficient of determination (R^2) and their residual standard deviation (RSD). The relative RSD (CVe) was calculated as the ratio between the RSD and the independent variable mean as a percent. The effect of sex, breed and slaughter weight on prediction accuracy was evaluated through variance analysis of the regression residuals.

The mean square of the prediction error (MSPE) was calculated as the sum of the square of the difference between the dissection and the corresponding DXA values divided by the number of experimental observations. The MSPE was decomposed into error in central tendency (ECT), error due to regression (ER), and error due to disturbances (ED) as suggested by Benchaar, Rivest, Pomar, and Chiquette (1998). Error in central tendency indicates how the average of DXA values deviates from the average of dissection values. Error due to regression measures the deviation of the least square regression coefficient from one, that is, the value it would have been if dissection and DXA measurements were in complete agreement. Error due to disturbances is the variation in dissection measurements that is not accounted for by a least squares regression of DXA measurements. In fact, this error is the unexplained variance and represents the portion of MSPE that cannot be eliminated by linear correction of the predictions (Theil, 1966). Finally, when expressed as a percentage of the MSPE, the error in central tendency, error due to regression and error due to disturbances are called bias proportion, regression proportion (deviation of the regression slope from one) and disturbance proportion, respectively. All calculations were performed using the appropriate statistical procedures of SAS (1999) or programmed within the same software.

3. Results and discussion

3.1. Descriptive statistics

The average slaughter weight for each class of slaughtering was: P1 = 37.5 ± 1.6 kg, P2 = 43.3 ± 1.3 kg, P3 = 48.6 ± 1.6 kg and P4 = 53.2 ± 1.3 kg. The average hot carcass weight, across all sexes, breeds and slaughter weights combined, was of 23.9 ± 3.7 kg. With regard to half-carcass composition (Table 1), the average percentages of dissected fat (24.3%) and dissected lean (55.5%) are consistent with the measurements made by Wolf, Smith, and Sales (1980) (26.7% fat and 56.3% lean), Beerman, Robinson, and Hogue (1995) (25% fat and 55.6% lean) and Hopkins (1996) (26.8% fat and 57.5% lean) for lambs of equivalent weight.

A comparison of the composition data for the half-carcasses and each primal cut obtained by dissection with those measured using DXA (Tables 1 and 2) shows that

Table 1
Total weight and dissected lean, fat and bone weights for half-carcasses and primal cuts[a]

Variable	Mean	SD[b]	Minimum	Maximum
Half-carcass				
Fat[c] (%)	24.3	5.3	10.4	37.8
Fat[d] (g)	2791	898	835	5116
Lean[e](g)	6238	849	4325	8253
Bone[f] (g)	2042	296	1480	2936
Total weight (g)	11,071	1683	7452	14,049
Shoulder				
Fat (%)	23.9	4.6	12.6	36.7
Fat (g)	976	273	384	1705
Lean (g)	2169	313	1487	2892
Bone (g)	852	146	566	1388
Total weight (g)	3997	591	2761	5310
Leg				
Fat (%)	18.5	3.8	7.7	27.9
Fat (g)	722	206	234	1259
Lean (g)	2421	320	1707	3165
Bone (g)	704	109	487	951
Total weight (g)	3848	540	2706	4870
Loin				
Fat (%)	30.4	8.3	9.7	51.4
Fat (g)	706	314	124	1676
Lean (g)	1159	178	722	1561
Bone (g)	350	70	197	559
Total weight (g)	2220	467	1195	3251
Flank				
Fat (%)	37.2	8.1	14.7	57.7
Fat (g)	387	141	93	869
Lean (g)	489	87	245	789
Bone (g)	135	26	84	202
Total weight (g)	1012	203	581	1504

[a] $N = 140$ observations for all variables studied.
[b] SD: standard deviation.
[c] The sum of dissected fat divided by total weight of the half carcass or primal cut in percent.
[d] The sum of the weights of dissected fat.
[e] The sum of the weights of dissected lean.
[f] Includes the carpal bone, the tarsal bone and tail.

Table 2
Half-carcass and primal cut composition and *R*-value obtained by dual-energy X-ray absorptiometry (DXA)[a]

Variable	Mean[b]	SD[c]	Minimum	Maximum
Half-carcass				
Fat (%)	11.4	5.6	3.8	25.1
Fat (g)	1285	762	282	3161
Lean (g)	8986	1186	6311	11,658
BMC[d] (g)	430	76	255	661
R-value[e]	1.369	0.013	1.339	1.396
Total weight (g)	10,701	1731	6909	13,845
Shoulder				
Fat (%)	11.8	5.0	3.9	23.8
Fat (g)	484	248	111	1097
Lean (g)	3297	446	2308	4330
BMC (g)	179	36	108	305
R-value	1.367	0.011	1.341	1.391
Total weight (g)	3963	614	2584	5312
Leg				
Fat (%)	9.4	4.3	3.8	21.2
Fat (g)	368	197	102	926
Lean (g)	3243	411	2364	4333
BMC (g)	177	29	113	239
R-value	1.373	0.011	1.347	1.398
Total weight (g)	3787	547	2590	4805
Loin				
Fat (%)	13.7	8.3	3.8	32.9
Fat (g)	316	248	38	1036
Lean (g)	1688	275	914	2229
BMC (g)	66	16	31	124
R-value	1.365	0.019	1.325	1.401
Total weight (g)	2070	479	993	3150
Flank				
Fat (%)	13.4	7.0	3.9	33.3
Fat (g)	130	86	20	393
Lean (g)	758	138	437	1123
BMC (g)	8	3	2	17
R-value	1.365	0.016	1.325	1.398
Total weight (g)	898	202	469	1412

[a] $N = 140$ observations for all variables studied.
[b] All body composition variables determined by DXA are different ($P < 0.001$) from its respective dissection value (mean values presented in Table 1).
[c] SD: standard deviation.
[d] BMC: bone mineral content.
[e] *R*-value: ratio between the attenuation coefficients of the two X-ray energy levels beams.

DXA underestimated total weight and fat ($P < 0.001$) and overestimated the amount of lean ($P < 0.001$). Similar observations have been reported in pork carcasses (Lukaski, Marchello, Hall, Schafer, & Siders, 1999; Marcoux et al., 2003; Mitchell, Scholz, Pursel, & Evock-Clover, 1998a, 1998b) chickens (Mitchell et al., 1997) and lambs (Clarke et al., 1999; Rozeboom et al., 1998). There are several reasons for these differences between dissection and DXA measurements. This technology was developed to estimate bone mineral content and bone density and to estimate soft tissue composition in humans by using "phantoms" composed of lard, polyoxymethylene (a resin), alcohol and water (Mazess et al., 1990). Given that these phantoms were composed only of a single type of uniformly distributed material, it can be expected that there will be differences in the DXA estimation of tissue composition on whole animals or carcasses. Animals are composed of a number of tissues that are not distributed homogeneously. In addition, the chemical composition of these phantoms is not exactly representative of the composition of the dissected tissues.

On the other hand, DXA assumes that the hydration state of the lean fraction of the soft tissue is constant. However, hydration state can vary depending on the stage of development (Roubenoff et al., 1993). Thus, in young animals such as lambs, a difference can be expected in comparison with the reference value calculated for humans. Hydration state can also differ among primal cuts from the half-carcass, since certain cuts have surfaces that are exposed to the air. Variable hydration values can change the *R*-value and introduce an error in the determination of fat and lean content (Brunton et al., 1993).

The differing dissection assessments of certain tissues can also explain the discrepancy between DXA and dissection data. For example, the end of the hind leg and the tail were not dissected, and their weights were recorded as bone by dissection. However, both parts contain lean and fat that DXA may be able to detect. The same phenomenon is observed in the shoulder with the end of the foreleg.

Another cause of error stems from the fact that DXA cannot differentiate more than two tissues at a time. DXA technology scans the subject with two X-ray beams and measures their attenuation in pixels of predetermined size. The attenuation coefficient of the two beams is constant for the pixels with bone. For those without bone, the relationship between the two attenuation coefficients varies linearly with the fat content of the soft tissue. Then, the soft tissue composition (fat and lean) of the pixels containing bone is assumed to be similar to the composition of the soft tissue in the area next to the pixels without bone (Lunar Corporation, 1998). The estimation of the composition of the soft tissue in cuts containing a high proportion of bone is therefore not as effective as estimations for areas without bone (Genton, Hans, Kyle, & Pichard, 2002). To explain the underestimation of fat and bone content, Lukaski et al. (1999) cited the fact that DXA is unable to assess the composition of soft tissues inside bone (e.g. marrow).

3.2. Predicting carcass and dissected tissue weights using DXA variables

The mathematical relationship between DXA and dissection variables for the overall half carcass and for each primal cut is presented in Table 3. Despite the significant differences observed for the variables studied between breeds, sexes and slaughter weights (Mercier, 2004) these treatments did not have any effect on the residuals of regressions. From these results, it can be concluded that the capacity of DXA to estimate the composition of lamb carcasses is independent of sex, breed or slaughter weight,

Table 3
Quality of the prediction of dissected tissue weights based on variables obtained by dual-energy X-ray absorptiometry (DXA)

Dependent variable (Dissection)	Independent variable (DXA)	N	R^2	RSD[a]	CVe[b]	Intercept[c]	Slope[c]
Half-carcass							
Fat (%)	*R*-value	137	0.771	2.5	10.4	518.24 ± 23.04	−360.80 ± 16.83
Lean (g)	Lean (g)	137	0.930	226.0	3.6	32.77 ± 146.78	0.69 ± 0.02
Bone (g)	BMC (g)	139	0.478	207.5	10.2	913.89 ± 100.99	2.61 ± 0.23
Bone (g)	Total lean (g)	139	0.594	183.0	9.0	358.16 ± 118.86	0.19 ± 0.01
Total weight (g)	Total weight (g)	139	0.996	103.7	0.9	713.68 ± 55.35	0.97 ± 0.01
Shoulder							
Fat (%)	*R*-value	138	0.684	2.6	10.8	482.71 ± 26.61	−335.54 ± 19.46
Lean (g)	Lean (g)	140	0.890	103.7	4.8	−15.67 ± 65.60	0.66 ± 0.02
Bone (g)	BMC (g)	139	0.468	101.5	12.0	369.17 ± 44.13	2.67 ± 0.24
Bone (g)	Lean (g)	139	0.606	87.4	10.3	39.23 ± 55.91	0.25 ± 0.02
Total weight (g)	Total weight (g)	139	0.993	50.6	1.3	193.34 ± 28.08	0.96 ± 0.01
Leg							
Fat (%)	*R*-value	137	0.685	2.1	11.4	421.22 ± 23.37	−293.19 ± 17.02
Lean (g)	Lean (g)	140	0.929	85.4	3.5	−11.66 ± 57.66	0.75 ± 0.02
Bone (g)	BMC (g)	137	0.426	81.9	11.6	268.89 ± 43.74	2.47 ± 0.24
Bone (g)	Lean (g)	137	0.678	61.4	8.7	−2.51 ± 42.06	0.22 ± 0.01
Total weight (g)	Total weight (g)	137	0.995	39.6	1.0	162.12 ± 23.69	0.98 ± 0.01
Loin							
Fat (%)	*R*-value	139	0.780	3.9	12.9	556.71 ± 23.76	−385.61 ± 17.41
Lean (g)	Lean (g)	138	0.826	74.5	6.4	163.00 ± 39.67	0.59 ± 0.02
Bone (g)	BMC (g)	136	0.696	38.2	10.7	113.76 ± 13.70	3.56 ± 0.20
Bone (g)	Lean (g)	137	0.318	57.5	16.5	106.16 ± 30.68	0.14 ± 0.02
Total weight (g)	Total weight (g)	136	0.996	29.8	1.3	217.68 ± 11.33	0.97 ± 0.01
Flank							
Fat (%)	*R*-value	139	0.580	5.3	14.2	564.58 ± 38.10	−386.29 ± 27.91
Lean (g)	Lean (g)	139	0.739	44.7	9.1	76.49 ± 21.16	0.54 ± 0.03
Bone (g)	BMC (g)	139	0.136	24.3	18.0	111.67 ± 5.40	2.80 ± 0.59
Bone (g)	Lean (g)	139	0.326	21.5	15.9	52.93 ± 10.19	0.11 ± 0.01
Total weight (g)	Total weight (g)	139	0.955	43.2	4.3	130.83 ± 16.77	0.98 ± 0.02

[a] RSD: residual standard deviation.
[b] Coefficient of variation of the residuals (%).
[c] Value ± standard error.

or equivalently, that this technology can be used across a wide range of carcass composition and carcass weights. Consequently, only regression results from data, all sexes, breeds and slaughter weights combined, are presented and discussed in this paper.

3.3. Carcass weight

As indicated before, DXA underestimates half-carcass weight (Fig. 1) as well as primal cut weights (Tables 1 and 2). For half-carcass weight, the majority of this difference, as estimated by the MPSE, stems from the distance between the regression and the identity line (ECT = 91%). The rest of the error is meanly explained by random variation (ED = 7%) and a small part by the slope of the regression curve (ER = 2%).

The slope of the regression line between dissected half-carcass weight and DXA-measured weight is 0.97 and is not significantly different from 1 ($P < 0.001$). This observation is also true for the four primal cuts (slopes between 0.97 and 0.98; Table 3) indicating that the underestimation of tissue weights by DXA is not affected by the size of the piece scanned (Fig. 1). In lambs, Clarke et al. (1999) have observed a slope of 0.97, which is similar to the one observed in this study.

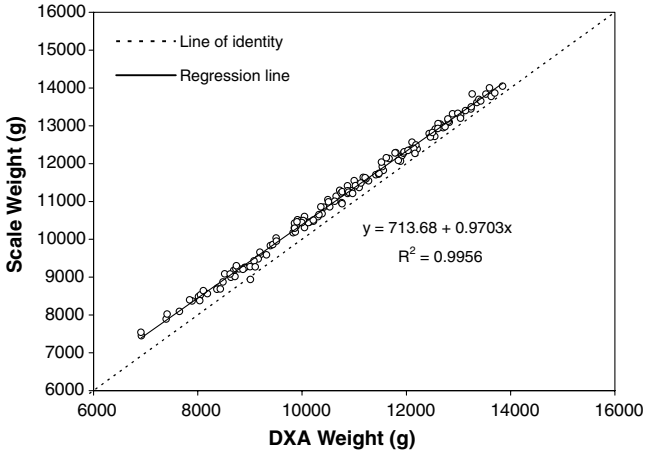

Fig. 1. Scale weight versus the weight estimated by dual-energy X-ray absorptiometry (DXA) of lamb half-carcasses ($n = 140$). Mean scale half-carcass weight = 11,070 g; root mean square prediction error (MSPE) = 3.65; error of central tendency (ECT) (%) = 91.10; error due to regression (ER) (%) = 1.53; error due to disturbances (ED) (%) = 7.37. Line of identity has intercept = 0 and slope = 1.

The weight of the overall half-carcass and the weights of the shoulder, loin and leg are predicted by equations using DXA variables with high coefficients of determination ($R^2 > 0.995$) and low errors (CVe > 1.3%) (Table 3). Flank weight is slightly less accurately predicted by the DXA variables ($R^2 = 0.955$ and CVe = 4.3%). This loss of accuracy in the prediction of flank weight using DXA can be explained by the thinness of this cut (Jebb, Goldberg, Jennings, & Elia, 1995; Mitchell et al., 1996, 1998a) which limits the instrument's ability to accurately detect the attenuation of the X-rays passing through thin cuts (Mazess et al., 1990). In our experiment, flanks from low-weight lambs tend to have frequent pixels not seen by DXA, even if they were folded before scanning.

The prediction of total weight has already been verified in a number of species, including humans, mice, chickens and swine (Mazess et al., 1990; Mitchell et al., 1997). In swine, the R^2 and CVe obtained between total tissue weight and DXA-estimated weight were of 1.0% and 2.0% (Brunton et al., 1993), 0.99% and 1.0% (Pintauro, Nagy, Duthie, & Goran, 1996), 0.99% and 1.32% (Mitchell et al., 1998a), 0.99% and 1.65% (Mitchell et al., 1998b), and 0.98% and 0.76% (Marcoux et al., 2003). However, comparisons with these studies have to be made with caution, given the higher weight of swine (around 100 kg) and, frequently, the much higher weight interval used in some studies that tend to overestimate the R^2 values (Gu et al., 1992).

The results presented in this section are consistent with those of other studies confirming the ability of DXA to estimate the weight of carcasses and primal cuts. DXA estimates these weights with systematic errors that can be easily corrected by regression, with each cut requiring specific coefficients. Furthermore, DXA weight estimations are independent of the sex, breed and carcass weight in lambs.

3.4. Fat weight

As with carcass and primal cut weights, DXA underestimates by 12.9% ($P < 0.001$) total fat weight in half-carcasses (Tables 1 and 2), which is consistent with what is found in the literature (Clarke et al., 1999; Jebb et al., 1995; Marcoux et al., 2003; Mitchell et al., 1996, 1997). Besides the reasons for the differences between DXA and dissection measurements indicated previously (see Section 3.1), and in particular the fact that for the assessment of soft tissue composition, DXA instruments have been calibrated with phantoms (Mazess et al., 1990), it should be noted that DXA fat does not exclusively represent the adipose tissue, but in fact the sum of all the adipose elements in soft tissue (Svendsen et al., 1993).

DXA uses the *R*-value to determine the fat content of the scanned cut but the relationship between these two variables seems not to be linear all over the range of carcass fatness used in this experiment (Fig. 2). In fact, the linearity between the *R*-value and DXA fat disappears for *R*-values higher than 1.38 or equivalently, for DXA fat percentages lower than 5%. As a result, DXA measurement of fat content cannot be used as such to predict dissected fat in lean carcasses or cuts. In contrast, the relationship between the *R*-value and the dissected fat percentage of half-carcasses is linear over the range of carcass fatness used in this experiment. The *R*-value is therefore a better estimator of fatness than DXA fat percentage as also observed in swine by Mitchell et al. (1998b).

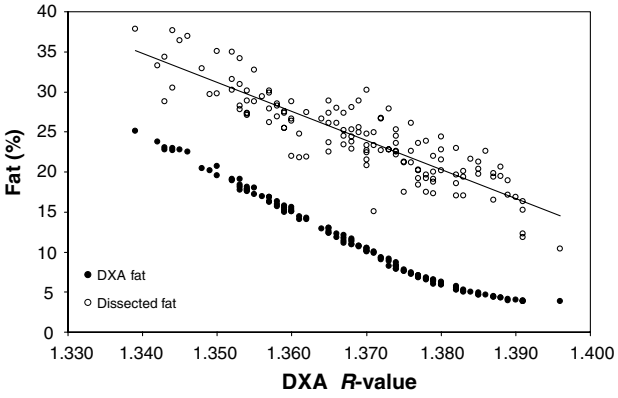

Fig. 2. Relationship between DXA *R*-value (ratio of soft-tissue attenuation coefficients) and DXA fat percentage (●) and between DXA *R*-value and fat percentage measured by dissection (○). Regression line: Dissected fat (%) = 518.24–360.80 (DXA *R*-value); $R^2 = 0.771$; RSD = 2.540.

The prediction of the half-carcass dissected fat percentage is much weaker ($R^2 = 0.77$ and CVe = 10.4%) than the prediction of carcass weight. Fatness prediction accuracy is equivalent for the shoulder, leg and loin (R^2 between 0.68 and 0.78, and CVe between 10% and 13%). As with total tissue weight, the dissected fat percentage for the flank is less accurately predicted than for the other primal cuts ($R^2 = 0.58$ and CVe = 14.2%). The large proportion of bone pixels, the thinness of the cut and the difficulty of properly isolating flank fat through dissection can explain this lower prediction accuracy.

Many studies have compared fat percentages obtained by DXA with those obtained by chemical analysis (Clarke et al., 1999; Mitchell et al., 1996, 1998a; Svendsen et al., 1993). In all cases, these studies show a stronger relationship than the one observed between DXA and dissected carcass fat ($R^2 > 0.80$ and CVe < 3%). Several reasons can explain this greater similarity between chemical and DXA fat than the observed between dissected and DXA fat. Thus, chemical fat includes the fat found in all tissues of the carcass. Dissected fat does not contain only fat; it also contains protein and water, the proportions of which may vary with age, nutrition, and other factors. Furthermore, dissected fat cannot assess certain fat fractions accounted for by DXA such as intramuscular fat and is affected by the dexterity and fatigue of the butchers. However, comparisons between studies should be made with caution. As for the prediction of total body weight, the accuracy of the relationships are affected by weight ranges, devices, and the software used to analyse the pixel data.

3.5. Lean weight

The R^2 obtained when predicting dissected lean content from DXA variables is 0.93 for the half-carcass and higher than 0.83 for all cuts other than flank. The CVe are between 3.5% and 6.5%, except for the flank, which is 9.1%. The fact that DXA lean is obtained by DXA by the difference between soft tissue and fat masses and the already observed difficulty of DXA of measure flank fat may partly explain the lower accuracy of DXA to measure flank lean. Furthermore, lean flank is difficult to dissect and operator bias can contribute to the decrease of the prediction accuracy of this lean tissue by DXA. The results obtained in this study are in agreement with those obtained by Clarke et al. (1999) (half-carcass lean: $R^2 = 0.98$ and RSD = 0.232 kg; leg lean: $R^2 = 0.96$ and RSD = 0.115 kg). The R^2 obtained are close to those observed in swine. Marcoux et al. (2003) obtained R^2 higher than 0.86 and CV lower than 5% when predicting dissected lean in half-carcass and primal cuts. As observed for fat, chemical lean is more accurately predicted from DXA variables than dissected lean as observed by Mitchell et al. (1998b) ($R^2 = 0.98$ and CV = 4%).

The slope of the regression line between the dissected lean weight and the lean weight measured by DXA for the half-carcass is 0.689. For the shoulder, leg, loin and flank, the observed slopes are 0.662, 0.750, 0.590 and 0.544, respectively. The fact that these values are lower than 1 indicates that the overestimation of DXA lean increases with fatness. In addition, this difference in lean overestimation between cuts with different lean weights is even more significant in small cuts such as the loin and flank than in heavier cuts as leg and shoulder. The intercept of the regression line for lean weight is not different from zero for the half-carcass, shoulder and leg. For the loin and flank, however, the intercept is different from zero (163 g and 76 g, respectively). This result may be an indication that for the loin and flank, DXA detects tissues that are not measured by dissection. This situation can be explained by the fact that these two cuts contain a larger proportion of cartilage than the shoulder and leg, this later tissue being characterized as lean by DXA (Roubenoff et al., 1993) without being included as lean during dissection.

An examination of the MSPE of the relationship between half-carcass dissected lean and DXA lean weights shows that the majority of the error stems from the distance between the regression line and the line of identity (ECT = 98%). Consequently, the error stems mainly from DXA overestimation (difference between the means). The rest of the error is explained by random variation (ED = 1%) and by the slope of the regression line (ER = 1%). As for the cuts, the decomposition of the MSPE in ECT, ER and ED is of the same order as for the half-carcass, except for the flank, where a larger part of the error stems from ED, which is of 6% in this case. Nevertheless, DXA estimates these lean weights with systematic errors that can be easily corrected by regression, with each cut requiring a specific regression.

3.6. Bone weight

The prediction of bone weight using BMC is not very accurate for the half-carcass, shoulder and leg (R^2: 0.48, 0.47 and 0.43; CVe: 10.2%, 12.0% and 11.6%, respectively; Table 3). The situation improves, however, for the loin ($R^2 = 0.70$ and CVe = 10.7%). The nature of the bones of the loin which, like spine bones, do not contain marrow, can be at the origin of these results (Marcoux et al., 2003). Thus, as indicated by these authors, the weight of spine bones is nearer to BMC, unlike the weight of the long bones that contain significant amounts of fat, protein and water. On the other hand, bone flank weight is poorly predicted by BMC ($R^2 = 0.136$; CVe = 18%). Flank bones contain a large proportion of cartilage which is not included by DXA as BMC (Roubenoff et al., 1993). In line with what has been assessed in pork half-carcasses, bone weight is best predicted with DXA lean than with BMC (Marcoux et al., 2003). Thus, for half-carcasses, the R^2 increases from 0.478 to 0.594 when the BMC is replaced by DXA lean in the prediction equation. The same situation is observed in the shoulder, leg and flank, which R^2 increase from 0.468 to 0.606, from 0.426 to 0.678 and from 0.136 to 0.326, respectively. In the loin, however, the coefficient of determination is lower when bone weight is predicted from lean weight instead from BMC (0.318 vs. 0.696) (Table 3).

The relationship between dissected bone weight and any DXA variable is low (R^2 between 0.136 and 0.696; Table 3). This stems from the completely different nature of bone as determined by dissection and the BMC measured by DXA. Bone mineral content accounts for only the mineral fraction of bone, but bones are not exclusively made up of minerals; they also contain fat, water and protein (Field et al., 1974). The long bones (e.g. the femur) generally contain a higher non-mineral fraction than the bones of the spine (Field et al., 1974). The non-mineral fraction of bones contributes to the increase in dissected bone weight without increasing BMC. As a result, the BMC is closer to the chemical analysis ash content ($R^2 = 0.81$ and RSD = 0.074 kg; Mitchell et al., 1998b) than the dissected bone weight as observed in this and other studies.

The decomposition of the MSPE observed in the relationship between dissected and DXA half-carcass bone weights shows that the majority of the error stems from the distance between the regression curve and the line of identity (ECT = 97.64%), that is, the difference between the means. The rest of the error is explained by the slope of the regression line (ER = 2.24%) and by random variation (ED = 0.12%). Similar results are obtained for primal cuts with the exception of the flank where a larger proportion of the error stems from the dispersion around the regression line (ED = 3.65%).

4. Conclusion

The DXA fat, lean or BMC measurements are different from the fat, lean or bones obtained by dissection in lamb half-carcasses. However, DXA and dissection variables are correlated thus allowing to predict dissected tissues masses or proportions from DXA variables. For total tissue and lean weights, DXA prediction equations are very effective. However, the prediction of fat is not as accurate as the former two variables. The relationship between dissected and DXA fat masses are affected by the fat content of the animal and are especially problematic in very lean animals (less than 5% fat). However, the proportion of fat in the half-carcass or cuts are adequately predicted using the DXA *R*-value. Other than for loin bones, bone mineral content is not an effective predictive variable of dissected bones given the different nature of these two variables. The DXA lean can be used to predict bone masses, although the relationships are only moderately accurate.

Although dual-energy X-ray absorptiometry is too slow for commercial use it can be used as reference method on carcass composition studies. In research conditions, DXA scan is quick (20 min for lamb carcasses), simple and accurate, making this technology a suitable and unbiased alternative for replacing the long and costly dissection method. The ability of DXA for estimating carcass composition by region makes this technology appealing in studies were the composition of cuts of high commercial value needs to be assessed.

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