Animal (2018), **12:6**, pp 1324–1330 © The Animal Consortium 2017
doi:10.1017/S1751731117002580

Application of bioelectrical impedance analysis in prediction of light kid carcass and muscle chemical composition

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(Received 21 February 2017; Accepted 6 September 2017; First published online 17 October 2017)

Carcass data were collected from 24 kids (average live weight of 12.5 ± 5.5 kg; range 4.5 to 22.4 kg) of Jarmelista Portuguese native breed, to evaluate bioelectrical impedance analysis (BIA) as a technique for prediction of light kid carcass and muscle chemical composition. Resistance (Rs, Ω) and reactance (Xc, Ω), were measured in the cold carcasses with a single frequency bioelectrical impedance analyzer and, together with impedance (Z, Ω), two electrical volume measurements (Vol_A and Vol_B, cm^2/Ω), carcass cold weight (CCW), carcass compactness and several carcass linear measurements were fitted as independent variables to predict carcass composition by stepwise regression analysis. The amount of variation explained by Vol_A and Vol_B only reached a significant level ($P < 0.01$ and $P < 0.05$, respectively) for muscle weight, moisture, protein and fat-free soft tissue content, even so with low accuracy, with Vol_A providing the best results ($0.326 \leqslant R^2 \leqslant 0.366$). Quite differently, individual BIA parameters (Rs, Xc and Z) explained a very large amount of variation in dissectible carcass fat weight ($0.814 \leqslant R^2 \leqslant 0.862$; $P < 0.01$). These individual BIA parameters also explained a large amount of variation in subcutaneous and intermuscular fat weights (respectively $0.749 \leqslant R^2 \leqslant 0.793$ and $0.718 \leqslant R^2 \leqslant 0.760$; $P < 0.01$), and in muscle chemical fat weight ($0.663 \leqslant R^2 \leqslant 0.684$; $P < 0.01$). Still significant but much lower was the variation in muscle, moisture, protein and fat-free soft tissue weights ($0.344 \leqslant R^2 \leqslant 0.393$; $P < 0.01$) explained by BIA parameters. Still, the best models for estimation of muscle, moisture, protein and fat-free soft tissue weights included Rs in addition to CCW, and accounted for 97.1% to 99.8% ($P < 0.01$) of the variation observed, with CCW by itself accounting for 97.0% to 99.6% ($P < 0.01$) of that variation. Resistance was the only independent variable selected for the best model predicting subcutaneous fat weight. It was also selected for the best models predicting carcass fat weight (combined with carcass length, CL; $R^2 = 0.943$; $P < 0.01$) and intermuscular fat weight (combined with CCW; $R^2 = 0.945$; $P < 0.01$). The best model predicting muscle chemical fat weight combined CCW and Z, explaining 85.6% ($P < 0.01$) of the variation observed. These results indicate BIA as a useful tool for prediction of light kids' carcass composition.

Keywords: light kid, carcass, muscle, chemical composition, bioelectrical impedance

Implications

Bioelectrical impedance analysis provided good estimates of some carcass compositional traits of light kids. Even in the case of some traits such as muscle and fat-free soft tissue weights, that were poorly estimated by bioelectrical impedance analysis parameters, they provided useful information when combined with other measurements. The accurate estimates of carcass composition now obtained can lead to the use of bioelectrical impedance analysis as a tool to assess parameters related to carcass value of light kids. Also, offers meat producers and processors the opportunity to have an objective non-destructive technique to attach a value schedule to carcass composition.

Introduction

The use of rapid, accurate, non-invasive and inexpensive techniques in carcass quality evaluation and grading is a commitment between producers, retailers and consumers' preference for high-quality meat. Several techniques have been reported as valuable tools for estimation of carcass composition for pig, sheep and cattle, but little information has been reported for kid carcass composition. One of these

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techniques is bioelectrical impedance analysis (BIA), which has provided good predictions of leaness for pig (Swantek *et al*., 1992 and 1999; Marchello *et al*., 1999a; Daza *et al*., 2006), sheep (Jenkins *et al*., 1988; Berg and Marchello, 1994; Berg *et al*., 1996), cattle (Marchello and Slanger, 1992; Velazco *et al*., 1999; Marchello *et al*., 1999b) and buffalo (Sarubbi *et al*., 2008). Other techniques such as computer tomography (e.g. Bünger *et al*., 2011; Scholz *et al*., 2015) and magnetic resonance imaging (Collewet *et al*., 2005; Scholz *et al*., 2015) have provided even better predictions of carcass and body composition. However, their cost, the low availability of the equipment required, the time taken to collect and process the data and the degree of training required for the examiner to take the necessary measurements compromise the incorporation of such techniques into existing industrial packing systems. Essentially, BIA measures the resistance (Rs) and reactance (Xc) of a constant low-intensity alternating current with a fixed frequency as it flows through a biological mass (Swantek *et al*., 1992). Given that lean tissues show high conductivity, whereas fat, bone and skin show low conductivity (Mialich *et al*., 2014), it becomes possible to estimate carcass fat and fat-free soft tissue, using a technique that is simple, rapid, non-invasive, inexpensive and portable. Therefore, the objective of this study was to examine the usefulness of BIA to predict carcass composition and carcass muscle chemical composition on light kid carcasses.

Material and methods

Animals and management

The experimental population consisted of 24 kids of Serrana Jarmelista Portuguese native breed. According to the traditional production method followed in the Northeast of Portugal, these animals were reared with their mothers for 40 days. After weaning all animals were fed on natural pasture and had *ad libitum* access to hay and water, with commercial supplement (14% CP, 3.5% crude fat, 7% crude fibre and 9% crude ash), until slaughter. Live weight (LW) at slaughter was recorded after 12 h of fasting with free access to water. The carcasses used in this study were obtained from kids that were slaughtered using standard procedures in a commercial EU licensed abattoir.

Carcass measurements, jointing and dissection

After slaughter the empty BW (EBW) was assessed. The pelt, head and all the internal organs were removed, as well as the kidney knob and channel fat. Carcasses were refrigerated for 24 h at 4°C. Cold carcass weights (CCW) were recorded. The carcasses were split along the vertebral column and the left side was cut into eight joints as outlined by Santos *et al*. (2008) in: leg, chump, loin, rib, anterior rib, shoulder, breast and neck. After weighing, each cut was separated into dissectible muscle, bone, subcutaneous fat, intermuscular fat and the remainder (major blood vessels, ligaments, tendons and thick connective tissue sheets associated with some muscles). All procedures were conducted in a dissection room under controlled environment with temperature maintained at 15°C. Several carcass measurements outlined by Fisher and DeBoer (1994) were taken from all carcasses: leg length (length from the symphysis pubis to the tarsal-metatarsal joint), width between trochanters, chest depth, chest perimeter, posterior buttock perimeter, anterior buttock perimeter and carcass length (CL) (length from cranial edge of the symphysis pubis to the cranial edge of the first rib). Carcass compactness, used as a conformation indicator, was determined as the ratio between CCW and CL.

Bioelectrical impedance parameters

A single frequency bioelectrical impedance analyser built specifically for this purpose, based on a high precision impedance converter AD5933 (Analog Devices Inc., 1 Technology Way, Norwood, MA, USA) integrated circuit, was used. This system combines an on-board frequency generator (that allows an external complex impedance to be excited with a known frequency) with a 12-bit, 1 MSPS, analog-to-digital converter (ADC) – the response signal from the impedance was sampled by the on-board ADC, and a discrete Fourier transform (DFT) was processed. After the adjustment with precision resistors and capacitors, and at the frequency point of 50 kHz, the magnitude of the impedance and relative phase of the impedance is calculated by the DFT algorithm obtaining the resistance (Rs) and reactance (Xc) values. The impedance (Z) was calculated as $Z = (Rs^2 + Xc^2)^{0.5}$. Considering that the resistance of a given homogeneous conductor with a uniform cross-sectional area is proportional to its length, L, and inversely proportional to its cross-sectional area, A, Rs can be calculated as $Rs = pL/A$, where p is the resistivity of the conductor. Given this relationship, Swantek *et al*. (1992) defined two predictors of the conductor volume as $Vol_1 = L^2/Rs$ and $Vol_2 = L^2/(Rs^2 + Xc^2)^{0.5}$, after removing p, as this is a constant, and with L as the length between detector terminals. In the present study, similar relationships were explored, just replacing L by CL: $Vol_A = CL^2/Rs$ and $Vol_B = CL^2/(Rs^2 + Xc^2)^{0.5}$. Two hypodermic needles served as electrodes. They were inserted 2 cm into the carcass, ~1 cm from the dorsal midline (avoiding contact with the spinal process) at the last cervical vertebra and at the last lumbar vertebra, and provided an attachment for the connecting clips of the BIA terminal leads. Four measurements of Rs and Xc were obtained, and the mean value was considered. All bioelectrical impedance measurements were taken in cold carcasses, which were maintained at 4°C.

Carcass muscle chemical analysis

After dissection of each joint, the muscle fraction was stored in a plastic bag at −20°C. The chemical analysis of carcass muscle followed the procedure proposed by Silva *et al*. (2005). In brief, on the day of muscle grinding, the frozen muscle samples were cut into small pieces by an electric band saw and immediately ground in a mincer (SM 200; Retsch, Haan, Germany) with an 8-mm sieve plate. Then the mixture was ground through a 4-mm

sieve plate. Short breaks were carried out during the milling process to avoid sample heating. Milled carcass muscle was homogenised in an industrial mixer (Stef, Rimini, Italy). Two random samples of ~300 g were obtained from multiple subsamples of the homogenised muscle, and placed in a sealed plastic box and stored at –20°C for later chemical analysis. The samples were analysed in duplicate for moisture, ash and CP (N × 6.25) and fat according to Association of Official Analytical Chemists (1990).

Statistical analysis of results

The data obtained from each carcass were analysed by simple linear regressions to evaluate the relationships of dissectible tissues and muscle chemical composition with CCW, carcass measurements and BIA parameters. Stepwise regression was used to determine which combinations of BIA parameters, carcass measurements and CCW best predicted dissectible tissues and muscle chemical composition. The simple regression equations were evaluated by the coefficient of determination (R^2) and residual SD (rSD). For the multiple stepwise regressions, the best fitting was also evaluated by the rSD and the adjusted coefficient of determination (Adjusted R^2). The Adjusted R^2 is useful in stepwise procedure to adjust for the number of variables in the model. All statistical analysis was performed by JMP (Version7; SAS Institute Inc., Cary, NC, USA).

Results

The summary data for the data collected on the experimental kids ($n = 24$) concerning LW, carcass traits and BIA parameters, are presented in Table 1. The mean LW was 12.5 kg, but there was a large amplitude of LWs, ranging from 4.5 to 22.4 kg, which resulted in very high CV for cold carcass weight, dissectible tissues and muscle chemical composition ($41.4\% \leqslant CV \leqslant 51.6\%$). Concerning carcass traits, only carcass and muscle yields showed a relatively low CV, ranging from 5.7% to 10.1%. Carcass compactness, BIA parameters and volume measurements showed quite a similar CV (respectively 31.3%, 24.7% to 31.9% and 25.6% to 26.8%), whereas CV for linear carcass measurements ranged from 12.1% to 18.2%.

Tables 2 and 3 show the results of simple regression analysis for predicting weights of carcass dissectible tissues and muscle chemical composition with carcass measurements and with BIA and volume measurements, respectively. The amount of variation explained for each trait was quite similar for the three BIA parameters, not reaching a significant level ($P > 0.05$) only for carcass and muscle yields (data not shown), and showing the highest accuracy in the case of dissectible carcass fat ($0.814 \leqslant R^2 \leqslant 0.862$; $P < 0.01$), which was considerably higher than the amount of variation explained by CCW, carcass compactness and carcass linear measurements for the same trait ($0.529 \leqslant R^2 \leqslant 0.709$; $P < 0.01$). For subcutaneous and intermuscular fat, the amount of variation explained by BIA parameters (respectively $0.749 \leqslant R^2 \leqslant 0.793$ and $0.718 \leqslant R^2 \leqslant 0.760$; $P < 0.01$) was lower than for dissectible carcass fat, but still higher than the amount of variation explained by CCW, carcass compactness and carcass linear measurements for subcutaneous fat ($0.379 \leqslant R^2 \leqslant 0.439$; $P < 0.01$) and by carcass linear measurements for intermuscular fat ($0.559 \leqslant R^2 \leqslant 0.702$; $P < 0.01$). Only CCW and carcass compactness explained a larger amount of variation than BIA parameters for intermuscular fat (respectively $R^2 = 0.830$ and $R^2 = 0.812$; $P < 0.01$). Although significant ($P < 0.01$), the BIA parameters only explained 36.4% to 37.9% of the variation in muscle weight, whereas CCW, carcass compactness and carcass linear measurements explained 68.7%

Table 1 *Means, SD, ranges and CV for live weight (LW), empty BW (EBW), carcass traits and bioelectrical impedance analysis (BIA) parameters (n = 24)*

Traits	Mean	SD	Range	CV
LW (kg)	12.5	5.5	4.5 to 22.4	44.0
EBW (kg)	10.6	4.5	4.2 to 18.9	42.1
Cold carcass weight (CCW) (kg)	5.2	2.3	1.9 to 9.9	44.4
Dissectible tissues (g)				
Carcass fat[1]	721	321	268 to 1356	44.6
Subcutaneous fat	291	150	83.4 to 607	51.6
Intermuscular fat	429	189	169 to 849	44.0
Muscle	3342	1581	1104 to 6537	47.3
Bone	1185	491	513 to 2189	41.4
Gross chemical composition of muscles (g)				
Fat	84.3	43.1	25.3 to 159.9	51.2
Moisture	2424	1167	775 to 4759	48.1
Protein	711.1	329.3	231 to 1317	46.3
Fat-free soft tissue[2]	3135	1492	1039 to 6052	47.6
Carcass and muscle yields (%)				
Carcass yield of BW	42.2	3.1	34.4 to 47.9	7.4
Carcass yield of EBW	49.1	5.0	37.6 to 66.3	10.1
Muscle yield	63.7	3.6	52.5 to 69.6	5.7
Carcass compactness (kg/m)	10.7	3.3	5.6 to 17.5	31.3
Carcass linear measurements (cm)				
Anterior buttock	40.7	7.0	29.0 to 51.5	17.2
Chest depth	13.8	2.5	10.0 to 17.5	18.2
Carcass length (CL)	47.1	7.6	33.5 to 59.5	16.1
Leg length	25.8	3.1	20.5 to 33.0	12.1
Width between trochanters	15.3	2.5	9.0 to 19.0	16.4
Chest perimeter	51.9	8.7	36.0 to 65.0	16.7
Posterior buttock	42.5	6.5	31.0 to 52.5	15.3
BIA parameters (Ω)				
Resistance (Rs)	88.0	21.8	59.0 to 136.5	24.7
Reactance (Xc)	110.6	35.3	65.8 to 161.3	31.9
Impedance (Z)[3]	141.6	40.7	90.5 to 211.3	28.8
Volume measurements (cm^2/Ω)				
Vol_A[4]	26.1	6.7	13.8 to 41.3	25.6
Vol_B[5]	16.5	4.4	7.9 to 28.4	26.8

[1]Carcass fat = subcutaneous plus intermuscular fat.
[2]Fat-free soft tissue = protein plus moisture mass.
[3]$Z = (Rs^2 + Xc^2)^{0.5}$
[4]$Vol_A = CL^2/Rs$.
[5]$Vol_B = CL^2/(Rs^2 + Xc^2)^{0.5}$.

Table 2 *Coefficients of determination (R^2) and residual SD (rSD) of simple regression equations for predicting weights of carcass dissectible tissues and muscle chemical composition with carcass measurements*[1]

	CCW		CC		AB		CD		CL		LL		G		U		PB	
	R^2	rSD	R^2	rSD	R^2	rSD	R^2	rSD	R^2	rSD	R^2	rSD	R^2	rSD	R^2	rSD	R^2	rSD
Dissectible tissues (g)																		
Carcass fat[2]	0.709	177.5	0.703	179.1	0.556	219.2	0.570	215.6	0.629	200.4	0.571	215.5	0.529	225.7	0.591	210.2	0.561	217.8
Subcutaneous fat	0.430	116.2	0.439	115.3	0.379	121.3	0.398	119.4	0.413	117.9	0.405	118.7	0.380	121.2	0.417	117.5	0.383	120.9
Intermuscular fat	0.830	79.5	0.812	83.8	0.607	121.0	0.614	119.9	0.702	105.3	0.607	120.9	0.559	128.2	0.632	117.1	0.614	120.0
Muscle	0.996	151.4	0.968	288.2	0.844	638.6	0.687	904.6	0.863	599.0	0.701	883.2	0.763	786.3	0.820	686.3	0.797	727.6
Gross chemical composition of muscles (g)																		
Fat	0.766	21.4	0.725	23.1	0.586	28.4	0.549	29.6	0.653	26.0	0.523	30.5	0.483	31.7	0.604	27.8	0.524	30.4
Moisture	0.986	141.1	0.962	232.2	0.839	478.8	0.685	669.7	0.858	449.1	0.696	658.1	0.757	588.2	0.817	510.3	0.792	543.9
Protein	0.970	58.0	0.942	81.3	0.851	129.9	0.697	185.2	0.863	124.8	0.753	167.5	0.777	159.2	0.849	130.7	0.808	147.5
Fat-free soft tissue[3]	0.987	170.8	0.962	295.8	0.846	599.1	0.691	848.1	0.864	563.6	0.712	819.5	0.765	739.6	0.828	632.4	0.800	683.1

CCW = cold carcass weight; CC = carcass compactness; AB = anterior buttock perimeter; CD = chest depth; CL = carcass length; LL = leg length; G = width between trochanters; U = chest perimeter; PB = posterior buttock perimeter.
[1]All coefficients of determination are significant at $P < 0.01$.
[2]Carcass fat = subcutaneous plus intermuscular fat.
[3]Fat-free soft tissue = protein plus moisture mass.

to 99.6% ($P < 0.01$). Concerning muscle chemical composition the results for protein, moisture and fat-free soft tissue were very close to those for muscle weight, again with BIA explaining much less variation ($0.344 \leqslant R^2 \leqslant 0.393$; $P < 0.01$) than CCW, carcass compactness and carcass linear measurements ($0.685 \leqslant R^2 \leqslant 0.987$, $P < 0.01$). For muscle chemical fat weight the BIA parameters only explained 66.3% to 68.4% ($P < 0.01$) of the variation observed, considerably less than the variation explained by the same measurements for dissectible carcass fat, subcutaneous fat and intermuscular fat, and also less than the variation in muscle chemical fat weight explained by CCW and carcass compactness (respectively 76.6% and 72.5%; $P < 0.01$). The amount of variation explained by volume measurements only reached a significant level of muscle, moisture, protein and fat-free soft tissue ($P < 0.01$ and $P < 0.05$, respectively for Vol_A and Vol_B), even so with low accuracy, with Vol_A providing the best results ($0.326 \leqslant R^2 \leqslant 0.366$), quite close to those of BIA parameters for the same traits.

The best predictive models for carcass composition are presented in Table 4. For dissectible tissues, the best model always included one BIA measurement, namely Rs. This was even the only independent variable selected in the best model for estimation of subcutaneous fat, which was the dissectible tissue estimated with less accuracy ($R^2 = 0.783$; $P < 0.01$). Carcass length was the only other independent variable included in the best model for estimation of carcass fat, together with Rs, explaining 94.3% of the variation observed.

Discussion

The experimental population provided data with a very large amount of variation but, despite the very high CV observed for all dissectible tissues (Table 1), which could have inflated the accuracies of the models developed, the graphs of Figure 1 show that the best prediction models obtained for carcass fat, intermuscular fat and muscle are quite robust. For subcutaneous fat, the CV observed was even higher than for the other dissectible tissues. This may be explained by the low development of subcutaneous fat in kids, already shown by Delfa *et al.* (1994) and Teixeira *et al.* (1995), as small differences in absolute weight of this trait will correspond to large relative differences. With the exception of subcutaneous fat, the inclusion of Rs and just another independent variable in the prediction model resulted in a very accurate estimates ($0.943 \leqslant R^2 \leqslant 0.998$; $P < 0.01$; Table 4), with the model for prediction of muscle showing highest accuracy. Considering the low development of subcutaneous fat in kids, even the best model for prediction of subcutaneous fat, with Rs as the only independent variable, explained a large amount (78.3%; Table 4), of the variation observed.

Although CCW and carcass compactness accounted, respectively, for 70.9% and 70.3% of the variation observed in carcass fat, whereas CL only accounted for 62.9%

Table 3 *Coefficients of determination (R^2) and residual SD (rSD) of simple regression equations for predicting weights of carcass dissectible tissues and muscle chemical composition with bioelectrical impedance analysis (BIA) parameters and volume measurements*[1]

	BIA parameters						Volume measurements			
	Rs		Xc		*Z*		Vol_A		Vol_B	
	R^2	rSD	R^2	rSD	R^2	rSD	R^2	rSD	R^2	rSD
Dissectible tissues (g)										
Carcass fat[2]	0.862	122.3	0.814	141.8	0.850	127.3	0.017Ns	326.0	0.001Ns	328.7
Subcutaneous fat	0.793	70.1	0.749	77.1	0.781	71.9	0.001Ns	153.8	0.033Ns	151.3
Intermuscular fat	0.760	94.6	0.718	102.6	0.750	96.5	0.063Ns	186.9	0.009Ns	192.2
Muscle	0.379	1273	0.364	1289	0.379	1274	0.347	1306	0.204*	1442
Gross chemical composition of muscles (g)										
Fat	0.663	25.6	0.668	25.4	0.684	24.8	0.057Ns	42.8	0.006Ns	44.0
Moisture	0.357	957	0.344	967	0.357	957	0.366	950	0.221*	1054
Protein	0.389	263	0.380	265	0.393	262	0.326	276	0.184*	304
Fat-free soft tissue[3]	0.366	1215	0.353	1228	0.367	1214	0.358	1222	0.213*	1354

Rs = resistance; Xc = reactance; $Z = (Rs^2 + Xc^2)^{0.5}$; Vol_A = (carcass length, CL)^2/Rs; Vol_B = (carcass length, CL)^2/$(Rs^2 + Xc^2)^{0.5}$.
[1]All coefficients of determination are significant at $P < 0.01$, except those marked with * or with Ns, which are, respectively, significant at $P < 0.05$ or not significant ($P > 0.05$).
[2]Carcass fat = subcutaneous plus intermuscular fat.
[3]Fat-free soft tissue = protein plus moisture mass.

Table 4 *Best multiple regression models for predicting weights of carcass dissectible tissues and muscle chemical composition (n = 24)*[1]

	Intercept	CCW	CL	Rs	*Z*	Adjusted R^2	rSD
Dissectible tissues (g)							
Carcass fat[2]	− 932.3		15.57	10.44		0.943	76.9
Subcutaneous fat	− 249.6			6.15		0.783	70.1
Intermuscular fat	181.1	0.048		4.07		0.945	44.4
Muscle	235.2	0.726		− 7.96		0.998	78.7
Gross chemical composition of muscles (g)							
Fat	− 37.4	0.011			0.460	0.856	16.4
Moisture	225.6	0.545		− 7.49		0.997	71.5
Protein	274.0	0.692		− 8.73		0.971	55.6
Fat-free soft tissue[3]	− 273.9	0.692		− 8.73		0.996	95.8

CCW = cold carcass weight; CL = carcass length; U = chest perimeter; Rs = resistance; Xc = reactance; $Z = (Rs^2 + Xc^2)^{0.5}$.
[1]All models are significant at $P < 0.01$.
[2]Carcass fat = subcutaneous plus intermuscular fat.
[3]Fat-free soft tissue = protein plus moisture mass.

(Table 2), the inclusion of CL as the only other independent variable included in the best model for estimation of carcass fat, together with Rs, is not surprising. In fact, the variation in CL is proportional to the variation in the distance between the source and detector electrodes (*L*) and, as stated by Jenkins *et al.* (1988), the value of the resistive impedance measurement is affected by *L*. With this in mind, several studies involving BIA parameters have included *L* in their best models for different species such as pigs (Swantek *et al.*, 1992 and 1999, for fat-free mass; Daza *et al.*, 2006, for dissected lean and fat; Marchello and Slanger, 1992, for muscle and fat-free muscle; Marchello *et al.*, 1999a, for carcass lean), lambs (Berg and Marchello, 1994, for fat-free mass and fat-free soft tissue; Berg *et al.*, 1996 and 1997, for carcass lean and fat-free lean) and cattle (Marchello and Slanger, 1994, for muscle and fat-free muscle; Zollinger *et al.*, 2010, for percentage saleable yield and percentage of trimmable fat). Other derived variables relating Rs with CL or *L* have been included in combined carcass and impedance models, such as CL^2/Rs and $(CL^2/Rs)^2$ (Jenkins *et al.*, 1988), L^2/Rs (Vol_1; Swantek *et al.*, 1992; Velazco *et al.*, 1999) or $L^2/(Rs^2 + Xc^2)^{0.5}$ (Vol_2; Swantek *et al.*, 1992; Velazco *et al.*, 1999), for instance. Jenkins *et al.* (1988) best model, for fat-free soft tissue, did include CL^2/Rs and $(CL^2/Rs)^2$. More comparable with the present results, where neither Vol_A nor Vol_B were included in the best models, are the results of Swantek *et al.* (1992), whose best models for fat-free mass did not include Vol_1 nor Vol_2. The inclusion of Rs in the best models for estimation of carcass fat and subcutaneous fat could be expected from the results of the simple regression

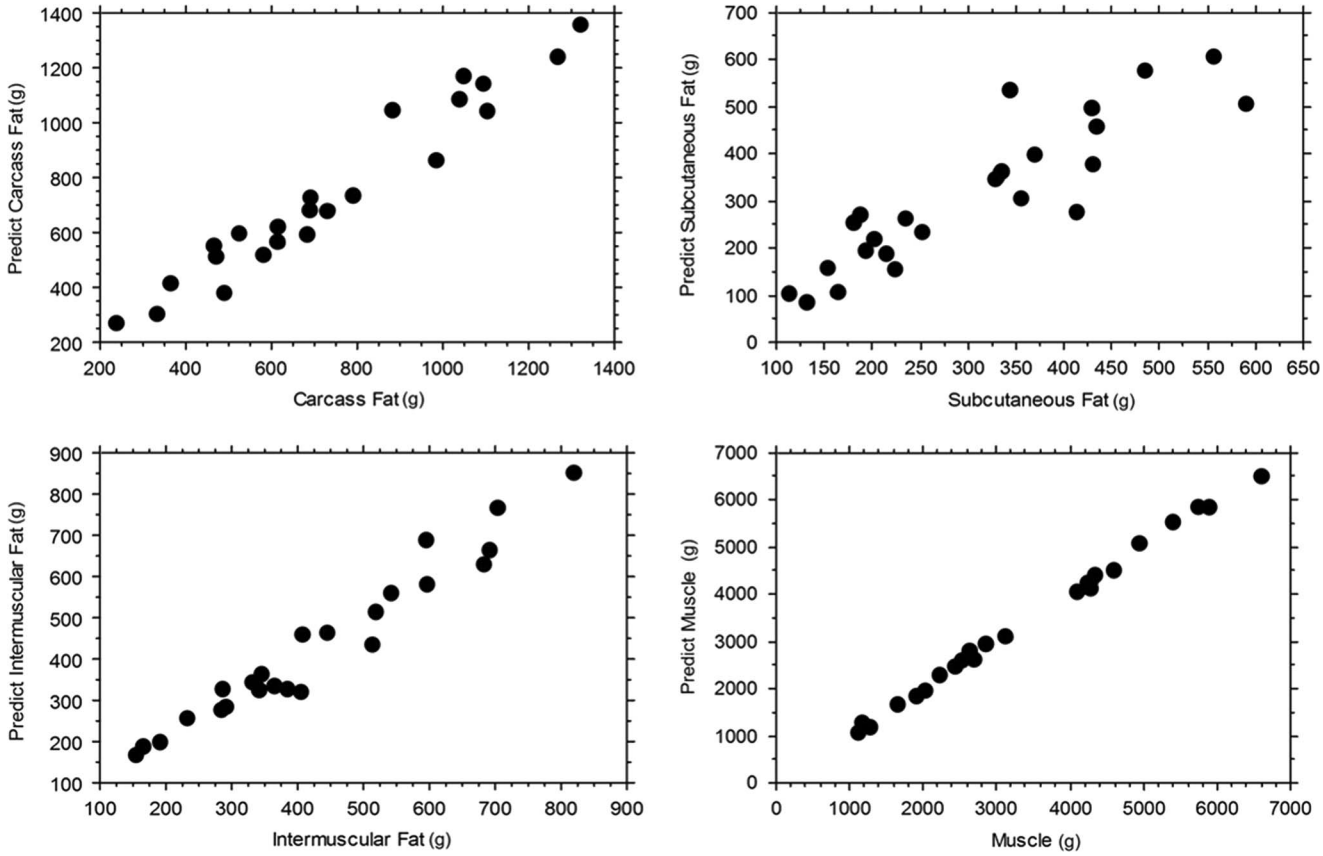

Figure 1 Relationship between carcass fat, subcutaneous fat, intermuscular fat and muscle observed and predicted with the best models.

analysis. Less expected, on the same basis, was the inclusion of Rs in the best models for estimation of intermuscular fat and muscle, as carcass compactness, for instance, explained a much larger amount of variation in these two traits than Rs. This indicates that, being CCW the independent variable that accounted for most of that variation, Rs was the independent variable that best explained the variation not accounted for by CCW. This was particularly evident for intermuscular fat, resulting in an adjusted accuracy of 94.5% for the estimates obtained with the model with CCW and Rs as independent variables, against an accuracy of 83% for the estimates based only on CCW.

Concerning muscle chemical composition, CCW was included in the best model for all traits. Despite the low accuracy of BIA parameters in the estimation of muscle chemical composition shown by simple regression analysis (Table 3), all the best models included a BIA measurement. Particularly remarkable is the effect of the inclusion of *Z* in the best model for muscle chemical fat weight, which resulted in an adjusted accuracy of 85.6% for the estimates obtained with the model with CCW and *Z* as independent variables, against an accuracy of 76.6% for the estimates based only on CCW. For muscle chemical fat weight, the results of simple regressions would already suggest the inclusion of a BIA measurement instead of any carcass linear measurement in the best model. However, the exclusion of carcass compactness from the best model for muscle chemical fat weight and of carcass compactness and carcass linear measurements from the best models for moisture, protein and fat-free soft tissue, and the inclusion in these models of a BIA parameter, indicate the higher ability of BIA to explain the variation not accounted for by CCW. As it would be expected, the coefficients for Rs concerning the estimation of muscle, moisture and protein were negative, as muscle is a highly conductive substance composed mostly of water containing electrolytes, whereas fat is an insulator that impedes the flow of an applied electrical current (Swatland, 1984). The best models now obtained for carcass yield of BW and EBW, and muscle yield (data not shown) included Xc and carcass measurements but, despite reaching a significant level ($P<0.01$) they only explained 72.1% and 75.2% respectively of the variation observed. This is consistent with the conclusion of Berg *et al*. (1996) that weights of carcass lean were more accurately predicted by BIA equations than percentages of carcass lean.

Overall, BIA parameters were useful to help predicting all the compositional traits studied, showing particular high potential in predicting carcass fat weight:

Acknowledgements

This work was supported by the Portuguese Science and Technology Foundation (FCT) under the Project PEst-OE/AGR/UID/CVT/00772/2013.

References

Association of Official Analytical Chemists 1990. Official methods of analysis, 15th ed. AOAC Inc., Arlington, VA, USA.

Berg EP and Marchello MJ 1994. Bioelectrical impedance analysis for the prediction of fat-free mass in lambs and lamb carcasses. Journal of Animal Science 72, 322–329.

Berg EP, Neary MK, Forrest JC, Thomas DL and Kauffman RG 1996. Assessment of lamb carcass composition from live animal measurement of bioelectrical impedance or ultrasonic tissue depths. Journal of Animal Science 74, 2672–2678.

Berg EP, Neary MK, Forrest JC, Thomas DL and Kauffman RG 1997. Evaluation of electronic technology to assess lamb carcass composition. Journal of Animal Science 75, 2433–2444.

Bünger L, Macfarlane JM, Lambe NR, Conington J, McLean KA, Moore K, Glasbey CA and Simm G 2011. Use of X-ray computed tomography (CT) in UK sheep production and breeding. In CT scanning – techniques and applications (ed. S Karuppasamy), pp 329–348. INTECH Europe, Rijeka, Croatia.

Collewet G, Bogner P, Allen P, Busk H, Dobrowolski A, Olsen E and Davenel A 2005. Determination of the lean meat percentage of pig carcasses using magnetic resonance imaging. Meat Science 70, 563–572.

Daza A, Mateos A, Ovejero I and López Bote CJ 2006. Prediction of body composition of Iberian pigs by means bioelectrical impedance. Meat Science 72, 43–46.

Delfa R, Teixeira A and González C 1994. Crecimiento y desarrollo de los depósitos adiposos del cuerpo de la cabra Blanca Celtibérica. Revista Portuguesa de Zootecnia 1, 131–135.

Fisher AV and De Boer H 1994. The EAAP standard method of sheep carcass assessment Carcass measurements and dissection procedures. Livestock Production Science 38, 149–159.

Jenkins TG, Leymaster KA and Turlington LM 1988. Estimation of fat-free soft tissue in lamb carcasses by use of carcass and resistive impedance measurements. Journal of Animal Science 66, 2174–2179.

Marchello MJ, Berg PT, Swantek PM and Tilton JE 1999a. Predicting live and carcass lean using bioelectrical impedance technology in pigs. Livestock Production Science 58, 151–157.

Marchello MJ, McLennan JE, Dhuyvetter DV and Slanger WD 1999b. Determination of saleable product in finished cattle and beef carcasses utilizing bioelectrical impedance technology. Journal of Animal Science 77, 2965–2970.

Marchello MJ and Slanger WD 1992. Use of bioelectrical impedance to predict leanness of Boston butts. Journal of Animal Science 70, 3443–3450.

Marchello MJ and Slanger WD 1994. Bioelectrical impedance can predict skeletal muscle and fat-free skeletal muscle of beef cows and their carcasses. Journal of Animal Science 72, 3118–3123.

Mialich MS, Sicchieri JMF and Jordao AA Jr 2014. Analysis of body composition: a critical review of the use of bioelectrical impedance analysis. International Journal of Clinical Nutrition 2, 1–10.

Santos VAC, Silva SR and Azevedo JMT 2008. Carcass composition and meat quality of equally mature kids and lambs. Journal of Animal Science 86, 1943–1950.

Sarubbi F, Bàculo R and Balzarano D 2008. Bioelectrical impedance analysis for the prediction of fat-free mass in buffalo calf. Animal 2, 1340–1345.

Scholz M, Bünger L, Kongsro J, Baulain U and Mitchell D 2015. Non-invasive methods for the determination of body and carcass composition in livestock: dual-energy X-ray absorptiometry, computed tomography, magnetic resonance imaging and ultrasound: invited review. Animal 9, 1250–1264.

Silva SR, Gomes MJ, Dias-da-Silva A, Gil LF and Azevedo JM 2005. Estimation *in vivo* of the body and carcass chemical composition of growing lambs by real-time ultrasonography. Journal of Animal Science 83, 350–357.

Swantek PM, Crenshaw JD, Marchello MJ and Lukaski HC 1992. Bioelectrical impedance: a non-destructive method to determine fat-free mass of live market swine and pork carcasses. Journal of Animal Science 70, 169–177.

Swantek PM, Marchello MJ, Tilton JE and Crenshaw JD 1999. Prediction of fat-free mass of pigs from 50 to 130 kilograms live weight. Journal of Animal Science 77, 893–897.

Swatland HJ 1984. Structure and development of meat animals. Prentice-Hall, Englewood Cliffs, NJ, USA.

Teixeira A, Azevedo J, Delfa R, Morand-Fehr P and Costa C 1995. Growth and development of Serrano kids from Montesinho Natural Park (NE of Portugal). Small Ruminant Research 16, 263–269.

Velazco J, Morril JL and Grunewald KK 1999. Utilization of bioelectrical impedance to predict carcass composition of Holstein steers at 3, 6, 9 and 12 months of age. Journal of Animal Science 77, 131–136.

Zollinger BL, Farrow RL, Lawrence TE and Latman NS 2010. Prediction of beef carcass salable yield and trimmable fat using bioelectrical impedance analysis. Meat Science 84, 449–454.