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Prediction of lamb body composition using *in vivo* bioimpedance analysis

Anderson B. Moro[a,*], Cleber C. Pires[a], Leila P. da Silva[a], Ana M.O. Dias[a], Robson R. Simões[a], Verônica M. Pilecco[a], Renius de O. Mello[b], Luis K. de Aguiar[c]

[a] *Department of Animal Science, Federal University of Santa Maria, Avenida Roraima, 1000, Cidade Universitária, Bairro Camobi, 97105-900, Santa Maria, RS, Brazil*

[b] *Department of Food Science and Technology, Federal University of Santa Maria, Avenida Roraima, 1000, Cidade Universitária, Bairro Camobi, 97105-900, Santa Maria, RS, Brazil*

[c] *Department of Food Science and Agrifood Supply Chain Management, Harper Adams University, Newport, Shropshire, TF10 8NB, England*

*Corresponding author: Anderson Bortoluzzi Moro. Email: andersondazoo@gmail.com

Abstract

The objective of this study was to evaluate the potential of *in vivo* bioimpedance analysis (BIA) as a method to estimate body composition in lambs. Thirty-one Texel x Ile de France crossbreed ram lambs were slaughtered at pre-determined intervals of average weights of 20, 26, 32, and 38 kg. Before the slaughter of the animals, their body weight (BW) and body length (BL) were measured. The values for resistance (Rs) and reactance (Xc) were collected using a single-frequency BIA equipment (Model RJL Quantum II Bioelectrical Body Composition Analyzer). The BIA main variables such as body bioelectrical volume (V), phase angle (PA), resistive density (RsD), and reactive density (XcD) were then

calculated. The soft tissue mass of the right-half cold carcass was analyzed in order to determine its chemical composition. Multiple regression analyses were performed using the lamb body composition as dependent variables and the measurements related to bioimpedance as independent variables. The best regression models were evaluated by cross-validation. The predictive model of moisture mass, which was developed by using XcD and V, accounted for 84% of its variation. Resulting models of percentage moisture (R^2 = 0.79), percentage lean mass (R^2 = 0.79), percentage fat (R^2 = 0.79), and fat mass (R^2 = 0.87) were obtained using RsD and V. Furthermore, the values of RsD regarding V, and PA in the prediction models accounted for 91% and 89% of variation in protein mass and lean mass, respectively. Bioimpedance analysis proved to be an efficient method to estimate the body composition of lambs slaughtered at different body mass stages.

Keywords: sheep, lean mass, carcass composition, impedance, resistance

1. Introduction

Sheep farming is an essential economic activity in many countries especially the poorest ones (Herrero et al., 2013). However, recent sheep meat consumption patterns are in line with current market trends indicating that increased sheep meat consumption depends on the final product quality to satisfy a higher purchasing power in emerging economies (Sepúlveda, Maza, & Pardos, 2011; Shackelford, Leymaster, Wheeler, & Koohmaraie, 2012). Therefore, to develop the lamb production sector to reach its full potential farmers need to be more efficient, achieve economies of scale as well as consider engaging in producing certified lamb to fulfil market demand. As a result, more integration among all links of the production chain is required in order to achieve the consolidation of sheep farming aimed at quality meat production (Ricardo et al., 2015).

A solid understanding of tissue growth and tissue development rate that make up lamb carcasses is extremely important, because from such information better strategic management interventions could be considered in order to improve the desired market body tissue deposition. Besides, carcasses tend to be paid according to their quality, which is related to a greater lean mass percentage and minimal fat amount to satisfy market demand (Álvarez et al., 2013; della Malva et al., 2016; Font-i-Furnols & Guerrero, 2014). The latter should be just enough to deliver the expected nutritional and organoleptic characteristics from sheep meat.

The evaluation of carcass composition using *in vivo* methodology allows firstly, for a better use of the factors of production, secondly, to determine the ideal age of slaughter, and, thirdly, to hopefully provide a uniform product for the meat processing industries. Furthermore, the use of *in vivo* body composition analysis also contributes to the reduction of error in carcass since classification tends to be subjective (Zollinger, Farrow, Lawrence, & Latman, 2010).

In vivo bioimpedance analysis (BIA) is a simple, rapid, relatively cheap, non-destructive, and minimally invasive method to estimate the body composition of sheep (Altmann, Pliquett, Suess, & Von Borell, 2004; Avril, Lallo, Mlambo, & Bourne, 2013; Berg & Marchello, 1994). Bioimpedance measures both modulus and phase of an equivalent impedance at a certain frequency, which is then calculated both resistance and reactance. Bioimpedance uses an alternating current (eg., 800 μA at 50 kHz) which is injected into the biological material (Swantek, Crenshaw, Marchello, & Lukaski, 1992). Furthermore, BIA may act as an estimator of body composition since it senses the difference in the conductivity between fat and fat-free mass (Lukaski et al., 1985). However, BIA is not a direct method to assess body composition and its accuracy, among other non-linearities, depends also on the precision of the chosen regression equations (Norman, Stobäus, Pirlich, & Bosy-Westphal, 2012). The use of resistive and reactive densities to predict beef

carcass composition has already been investigated (Zollinger et al., 2010). As far as our knowledge is concerned, the use of such predictors have not been used in lambs. The objective of this study was to evaluate the potentiality of *in vivo* bioimpedance analysis to estimate body composition in lambs at different ages of slaughter.

2. Material and methods

The research was conducted at the Laboratory of Sheep of the Department of Animal Science of the Federal University of Santa Maria (UFSM), Santa Maria, RS, Brazil, after being approved by the Ethics Committee on Animal Trials of this University, under the protocol #8259211015. All handling from the lamb rearing until their slaughter and laboratory analyzes were carried out within the Sheep Laboratory confines.

2.1 Animals

Thirty-one Texel and Ile de France crossbred three-month old weaned ram lambs were used for the purpose of this research. The animals were marked, weighed and distributed into eight pens covered from the elements. They were distributed in groups according to similar weight but on average they had live weight of 19.7 kg. The pens had slatted-floor and were equipped with feeders and water troughs. The animals were fed *ad libitum* and the amount of feed was adjusted in order to keep the leftover food at around 10% of the total amount given.

A balanced diet calculated according to the NRC (2007) guidelines was administered to the animals in order for them to gain 0.200Kg/day. The formulation based on dry matter accounted for the 30:70 ratio alfafa hay:concentrate (37.9% of maize grain, 14.4% of soy

bran, 16.4% of wheat bran, and 1.27% of calcitic lime). The mineral mixture was supplied *ad libitum* in separated feeders. Weight measurements took place at weekly intervals until they reached pre-established slaughter weights of 20, 26, 32, or 38 kg. Before the slaughter of the animals, body weight (BW) (kg) was recorded (after 14 hours of fasting of solids), body length (BL) (cm) was measured (from the last cervical vertebrae to the first sacral vertebrae), and the BIA readings were taken.

2.2 Bioimpedance measurements

A single-frequency BIA equipment (Model RJL Quantum II Bioelectrical Body Composition Analyzer) was used to make the measurements. This apparatus injects an alternating electrical current of 800 μA at 50 kHz into the different body tissues by using two electrodes and then measures the voltage resultant across other two electrodes. The equipment is connected by four cables that are attached to the electrodes by color-coded electric clips. The black and red electrodes were configured as current transmitters and current detectors, respectively. Stainless steel acupuncture needles with spiral cable (0.40 x 15 mm) were used as electrodes. They were inserted into the animal muscle at a standard depth just to make a good electrode contact in all body tissues (Berg & Marchello, 1994).

Data were collected following the methodology proposed by Jenkins, Leymaster, and Turlington (1988) and adapted for live lambs. During data collection, the lambs were initially contained with an insulating rope tied to their feet, in order to keep them immobile without the need of use of anesthetics. Then, they were laid on plastic tarpaulin for insulating them from any contact with the ground, preventing leakage current. The animals were positioned on their right side (*lateral decubitus*) and a small area of the animal wool was shaven off in a straight line on the central region of the lateral face of the leg region

131 (rear limb) and forearm region (front limb). The distal transmitter electrodes were attached
132 onto the extensor muscle complex of the front and rear limbs, approximately 3.0 cm
133 proximal to the carpal and tarsal articulations, respectively. The proximal detector
134 electrodes were inserted 10 cm from the transmitter ones, caudal to the knee region (rear
135 limb) and cranial to the elbow region (front limb) (Fig. 1).
136 Both resistance (Rs) (Ω) and reactance (Xc) (Ω) were measured once for each animal,
137 then values of conductance (C) and impedance (Z) were calculated by using the formulas
138 described by Lukaski, Johnson, Bolonchuk, and Lykken (1985), where C = 1/Rs (Ω) and Z
139 = $(Rs^2+Xc^2)^{0.5}$ (Ω). The relationship between resistance and reactance values results in an
140 angle, which is defined as phase angle (PA) (º). The PA was directly calculated as the arc
141 tangent of the ratio of reactance and resistance, where PA = $\tan^{-1}$ (Xc/Rs), expressed in
142 radians. To convert the results into degrees, the PA values were then multiplied by 180º/π
143 as described by Lukaski (2013).
144 The body bioelectrical volume (V) was obtained by the relationship between animal body
145 length and resistance, where $V=BL^2/Rs$ ($cm^2/Ω$), adapted from Jenkins et al. (1988). Both
146 resistive (RsD) and reactive density (XcD) were also calculating according to Zollinger et
147 al. (2010). They proposed to replace the half carcass weight by body weight as well as
148 replacing the distance between the electrodes by the body length of the animals.
149 Therefore, the final formula used in this work is as it follows: $RsD = BW^2/(BL^2/Rs)$ (kg^2/cm^2
150 Ω) and $XcD = BW^2/(BL^2/Xc)$ (kg^2/cm^2 Ω).
151
152 *2.3 Laboratory analyses*
153
154 After the slaughter, the carcasses were weighed and stored in a chilling chamber at a
155 temperature of 2ºC. After 24 hours, they were weighed for a second time in order to obtain
156 the cold carcass weight (CCW) (kg). The carcasses were longitudinally split into two half

157 carcasses and the right half carcasses were weighed and divided into four regional cuts;
158 neck, shoulder, ribs, and leg. These cuts were boned in order to obtain the soft tissue
159 mass of the half carcasses, which are composed basically by muscles, fat, blood vessels,
160 nerves, and connective tissue. The soft tissue mass obtained from each cut was ground,
161 homogenized, and approximately 200 g of representative sample were extracted for
162 laboratory analyses. Four samples from each carcass were analyzed in duplicates.
163 Moisture (930.15), protein (992.15), and ash (942.05) were determined in these samples
164 according to the methodology described on AOAC International (1995). Fat was
165 determined according to the method proposed by Bligh and Dyer (1959). The chemical
166 composition determined in each cut was used to calculate the weight and the proportion of
167 each chemical component of the half carcass and adjusted to the cold carcass weight. The
168 weight and percentage of the lean mass was obtained by the sum of weight and
169 percentage, respectively, of protein and moisture of the carcass soft tissue, then Lean
170 mass (kg) = protein (kg) + moisture (kg) and Lean mass (%) = protein (%) + moisture (%),
171 according to Jenkins et al. (1988).
172
173 *2.4 Statistical analysis*
174
175 Multiple regression analyses were performed using the lamb carcass composition as
176 dependent variables (weight and percentage of moisture, protein, fat, and lean mass) and
177 bioimpedance measurements as independent variables (resistance, reactance,
178 conductance, phase angle, body bioelectrical volume, resistive density, and reactive
179 density). The body weight and body length of the animals were only used to calculate V,
180 RsD, and XcD. The normality of the data was presumable based on the central limit
181 theorem, which considers an acceptable normal distribution with 30 or more observations.
182 Correlation coefficients between the BIA measurements and the carcass composition were

183 determined. Stepwise regression was used to eliminate the variables that did not increase
184 the prediction power of the model. Those variables that did not significantly contribute to
185 the model ($P > 0.05$) were eliminated. The biostatistical models were selected which
186 presented the highest coefficient of determination (R^2), lowest root mean square error
187 (RMSE), and the Mallows Cp statistic (Cp) closest to the number of parameters included in
188 the model.
189 The best regression models were evaluated by cross-validation according to the following
190 procedure, which was the same for each model. Briefly, from the complete dataset, one
191 animal was selected and regression parameters were estimated with data of the remaining
192 $n - 1$ animals. Values of weight and percentage of moisture, protein, fat, and lean mass
193 were predicted for the selected animal by this regression function. Then, the squared
194 difference between the predicted and measured chemical compounds of the selected
195 animal was calculated. This procedure was repeated for every animal. The mean of the *n*-
196 squared differences between the predicted and measured carcass compounds of all *n*
197 animals was calculated to obtain the mean squared error of the predicted weight and
198 percentage of moisture, protein, fat, and lean mass. Precision and accuracy of the
199 equations were measured by evaluating the highest coefficient of determination (R^2), the
200 lowest root mean squared error (RMSE), the mean prediction error (MPE), and relative
201 mean prediction error (RMPE; %) of the cross-validation. The statistical software SAS
202 (SAS University Edition, 2017) was used for all statistical analyses.
203
204 **3. Results**
205
206 *3.1 Descriptive statistics*
207

208 The descriptive statistics of linear measurements and bioimpedance assessments in
209 lambs are shown in Table 1. The body weight presented a larger variation range than body
210 length. The minimum and maximum resistance readings ranged from 60 to 110 Ω, while
211 the reactance variation was from 6 to 15 Ω. Body bioelectrical volume, resistive density,
212 and reactive density, which used weight and/or length values in their formulas, had larger
213 variation than resistance and reactance alone.
214 The mean values, range, and variability of carcass linear measurements and lamb body
215 composition are shown in Table 2. The weight of cold carcass and soft tissue had great
216 variation between the minimum and maximum values. The same can be observed with the
217 mass of the lamb body components. When the body composition was expressed in
218 percentage values, fat content showed to present the largest variation, ranging from 8.39
219 to 26.9%.
220
221 *3.2 Correlations*
222
223 The results of the correlations between BIA measurements and chemical analyses of the
224 lamb carcasses are presented in Table 3. The mass of body chemical constituents
225 increased with the increase in BL, BW, PA, V, RsD, and XcD. Although fat percentage also
226 increased, in contrary, protein, moisture, and lean mass percentages decreased. The
227 relationship between BL and/or BW with Rs or Xc may have affected the stronger
228 correlations between V, RsD, and XcD and the lamb body composition. Protein
229 percentage was an exception because it was not significantly correlated to any BIA
230 variables ($P > 0.05$).
231
232 *3.3 Prediction Models*
233

234 The final predictive models of the lamb body composition are shown in Table 4. The
235 amount of moisture was mostly explained by the XcD (R^2 = 0.56; Cp = 93.3). When V was
236 included in this model, they accounted for 84% of its variation on lamb carcass, and the Cp
237 value decreased to 17.6. Regarding protein and fat mass predictive models, the use of
238 RsD alone explained most of the variation of these components on carcass, 62% and
239 70%, respectively. When V was added to the models, their prediction power improved (R^2
240 = 0.89 and R^2 = 0.87) and the Cp values decreased from 87.3 and 41.2 to 9.04 and 3.56,
241 respectively. Furthermore, to estimate the protein content of the samples the PA value was
242 then added to the protein equation. The PA value together with RsD and V explained 91%
243 of protein variation on carcass. From these results, it is possible to note that predictive
244 models for protein mass and fat mass are more precise than the one for moisture mass.
245 Resistive density, alone, accounted for 63% of variation of moisture, fat, and lean mass
246 percentages on lamb carcass. When V was added to these models, there was an increase
247 of 16% in their coefficients of determination. Furthermore, the Cp values decreased from
248 20.5, 25.3, and 25.1 to 2.32, 4.70, and 4.56, respectively. However, none of the BIA
249 variables contributed significantly ($P > 0.05$) to the prediction of protein percentage. This
250 fact may be explained due to the little variation in protein percentage on lamb carcass
251 (18.9 ± 0.12%) (Table 2).
252 The lean mass model was initially mostly explained by XcD (R^2 = 0.56). Afterwards, V was
253 added to the model, which increased the prediction power in 28%. Thereafter, the addition
254 of RsD enhanced R^2 by 2%. Using the Stepwise procedure, when RsD was added to the
255 model, it was observed that XcD stopped contributing to the prediction power of the model
256 and, therefore, it was removed from the equation. Besides, when PA was added to that
257 model, it accounted for 89% of the variation of the lean mass on lamb carcass. The
258 prediction power of these equations can be observed by the statistic results of the cross-
259 validation. Regarding the R^2 of the cross-validation, the models for predicting the mass of

moisture, protein, fat, and lean mass presented good precision with R^2 of 0.93, 0.95, 0.91 and 0.93, respectively. Although the prediction models of the percentage of moisture, fat, and lean mass resulted in a lower R^2 compared to the absolute values, they also had an acceptable prediction power with R^2 of 0.86, 0.88, and 0.88, respectively.

4. Discussion

The lamb body development is typically understood as an increase in mass. Growth rates of different tissues which compound the animal carcass are influenced by many factors such as genetics, age, and nutrition (Owens, Dubeski, and Hansont, 1993). Nonetheless, the lamb body shape change over time, especially before they reach maturity, indicating they tend to take longer to grow (in centimeters) than to gain weight (in kilograms). That could be confirmed in the sample because body weight varied more than body length (Table 1).

The carcass composition can be expressed in either mass or percentage. As the increase of body weight at slaughter increases the weight of cold carcass, consequently the weight of each body compound also increases with a heavier carcass. Body composition when expressed in percentages shows that as the carcass fat content increases, the lean mass content decreases. The protein percentage had the smallest variation in the carcasses (Table 2). The small variation in protein percentage is a limitation in the prediction using the bioimpedance method.

The results of this study indicate that the electrical properties of lamb body tissues were affected by their body composition, whereas longer and heavier animals, with more body fat deposits presented higher BIA values than smaller and lighter ones (Table 3). Due to the fact that it was performed a four electrode impedance measurement, as known by transfer impedance, this agrees with the bioimpedance principle as, it depends on the

electrode geometry, volume and length of the biological conductor material, and on the frequency of the applied current (Berg & Marchello, 1994; Lukaski et al., 1985; Swantek, Crenshaw, Marchello, & Lukaski, 1992). Electrode material, distance between electrodes, and the place where they are insert also influence BIA measurements. Therefore, BIA reproducibility depends on the electrode placement.

The body volume of lambs is composed of intra- and extracellular fluids that behave as heterogeneous electrical conductors with cell membranes working as electrical capacitors, and body fat acting as an insulator material and generating electrical resistance (Altmann et al., 2004; Swantek et al., 1992). For humans, this volume is obtained by the relationship between the squared height and resistance (Lukaski et al., 1985). However, in lambs, Jenkins et al. (1988) replaced the height by carcass length. Then Berg and Marchello (1994) replaced it by the conductor length (distance between current detector electrodes). Regardless of how the volume was obtained, it is needed to estimate the body composition of lambs. This fact was evidenced in this study since this variable was selected in the prediction models for both mass and percentage of the lamb body components (Table 4).

Reactance is the property of storing alternating electrical energy under the form of an electric field. It is related to the dynamic performance of cell membranes, which work as an electrical capacitor (Swantek et al., 1992). The cell membrane capacitance can be used as an indicator of lean mass and intracellular body mass, and it is also related to extra- and intracellular hydric balance (Altmann et al., 2004). This fact may explain the model selection of volume and reactive density to estimate the water amount on lamb carcass (Table 4). The reactive density explained 56% of the variation of lean mass on lamb carcasses. This might be due to the large amount of moisture (65.4% in average) in the soft tissue mass of the lamb carcasses (Table 2). The negative correlations obtained

between XcD and moisture, protein, and lean mass percentages reinforce this fact (Table 3).

The resistive part of the impedance can be attributed to the opposition of a current flow through intra- and extracellular ions inside the tissue (Lukaski, 2013), which can be directly correlated to the difference in conductivity between fat and lean mass (Jenkins et al., 1988). Hence, Rs is directly related to the body hydration level and body fat. Animals with a larger percentage of fat in the carcass present smaller body water percentage and higher resistance to the applied current. As the mass of carcass components increases, there is an increment in body weight and in some BIA variables like PA, V, RsD, and XcD (Table 3). These increases were also related to an increase of fat percentage, but to decreased moisture, protein, and lean mass percentages on lamb carcasses (Table 3). According to Owens, Dubeski, and Hansont (1993), changes in body composition are expected since they naturally occur throughout the physiological maturity of the lambs. Based on these results it is possible to note a significant efficiency of BIA in detecting these changes in body composition of lambs slaughtered at different body masses. According to Zollinger et al. (2010), who assessed BIA in beef cattle carcasses, RsD and XcD decreased with the increase of lean mass, and increased with the increase of fat percentage on carcass. This indicates a strong relationship of RsD and XcD with lean mass and fat body contents.

The phase angle was another important variable used in this work, which was obtained by the relationship between resistance and reactance values. The PA may vary from zero (eg., medium without cell membranes) to 90 degrees (eg., a medium full of cell membranes but no fluids) (Lukaski, 2013). This angle depends on the capacitance due to the cell membranes and, in humans, it is a marker of amount and quality of soft tissue mass, as well as body hydration status (Norman et al., 2012). Therefore, its variation indicates changes in body composition, especially for protein and lean mass.

Predictive models for body composition need to be accurate in order to become suitable to farmers. Therefore, Mallows Cp statistic is considered a robust tool for predictive model selection. The Cp value that is closest to the number of parameters included in the model indicates less biased estimates and, therefore, a more precise model. Similar to what Berg and Marchello (1994) found, this study identified some possible outliers which were not removed from the database given the difficulty of identifying the origin of the error. Removal of these outliers could also improve the results from the statistical analysis.

On the one hand, the predictive models for mass of body constituents presented higher R^2 and lower RMSE values when compared to their respective percentages, and therefore, greater precision. On the other hand, if the Cp value is considered, the moisture percentage and lean mass percentage presented a higher precision to estimate the real regression coefficients and predict future answers than their absolute masses. Likewise, considering these statistical parameters, it is possible to note that predictive models for protein mass and fat mass are more precise than the one for moisture mass (Table 4).

Regarding the cross-validation, the RMPE values for predicting fat, both in absolute and relative values, were higher than the other carcass components. The RMPE values for predicting the absolute carcass compounds were also higher comparing to the relative ones. This may be due to the higher variation range of the values expressed in grams related to those presented as percentage. Nevertheless, concerning the R^2 of the cross-validation, the absolute values of the lamb carcass components had the highest accuracy. These findings indicate that the models obtained for predicting lamb carcass composition are quite robust.

5. Conclusion

Bioimpedance is an efficient method to estimate the carcass composition of lambs slaughtered at different body masses. The use of resistive and reactive densities data improved the results of *in vivo* bioimpedance analysis used to assess the lamb body composition. This might be the case of measuring lamb body composition in order to reduce errors related to subjectivity.

Conflict of interests

There is no conflict of interests involved in this work.

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453 **Table 1**

454 Descriptive statistics of body characteristics and bioimpedance assessments on lambs.

	n[1]	Min[2]	Max[3]	Mean	SD[4]	SEM[5]
Body weight, kg	31	18.1	38.6	27.9	5.48	0.98
Body length, cm	31	47.0	64.0	55.8	4.76	0.85
Resistance, Ω	31	60.0	110.0	87.7	11.9	2.14
Reactance, Ω	31	6.00	15.0	10.4	2.33	0.42
Conductance, Ω	31	0.01	0.02	0.01	0.00	0.00
Impedance, Ω	31	60.3	111.0	88.3	12.0	2.16
Phase angle, º	31	4.81	8.60	6.70	1.03	0.18
Body bioelectrical volume, $cm^2/Ω$	31	24.5	58.2	36.5	8.45	1.52
Resistive density, kg^2/cm^2 Ω	31	9.05	41.6	22.1	7.06	1.27
Reactive density, kg^2/cm^2 Ω	31	0.82	5.61	2.64	1.06	0.19

455 [1]n = number of lambs, [2]Min = Minimum, [3]Max = Maximum, [4]SD= Standard deviation, [5]SEM=
456 Standard error of mean.

457

458 **Table 2**

459 Descriptive statistics of carcass characteristics and body composition of lambs.

	n[1]	Min[2]	Max[3]	Mean	SD[4]	[5]SEM
Cold carcass weight, kg	31	6.36	17.4	11.9	2.94	0.53
Soft tissue mass weight, kg	31	5.07	14.6	9.71	2.58	0.46
Moisture, kg	31	3.55	8.59	6.26	1.35	0.24
Moisture, %	31	54.0	72.2	65.4	4.03	0.72
Ash, kg	31	0.05	0.13	0.09	0.02	0.00
Ash, %	31	0.59	1.14	0.91	0.12	0.02
Protein, kg	31	0.98	2.65	1.83	0.47	0.08
Protein, %	31	18.0	20.8	18.9	0.69	0.12
Fat, kg	31	0.49	3.61	1.53	0.83	0.15
Fat, %	31	8.39	26.9	14.8	4.40	0.79
Lean mass, kg	31	4.53	11.1	8.09	1.81	0.32
Lean mass, %	31	72.3	90.6	84.3	4.32	0.78

460 [1]n = number of lambs, [2]Min = Minimum, [3]Max = Maximum, [4]SD= Standard deviation, [5]SEM=
461 Standard error of mean.

462

Table 3

Simple Pearson correlations between body characteristics and bioimpedance assessments to lamb body composition.

	BW[1], kg	BL[2], cm	Rs[3], Ω	Xc[4], Ω	C[5], Ω	Z[6], Ω	PA[7], º	V[8], $cm^2/Ω$	RsD[9], kg^2/cm^2 Ω	XcD[10], kg^2/cm^2 Ω
Moisture, kg	0.93***	0.70***	-0.07	0.33	0.05	-0.06	0.51**	0.54**	0.75***	0.75***
Moisture, %	-0.85***	-0.59***	-0.05	-0.31	0.03	-0.05	-0.37*	-0.40*	-0.79***	-0.77***
Protein, kg	0.95***	0.70***	-0.04	0.34	0.02	-0.03	0.50**	0.52**	0.79***	0.78***
Protein, %	-0.33	-0.25	0.02	-0.02	-0.04	0.02	-0.01	-0.21	-0.32	-0.28
Fat, kg	0.90***	0.62***	0.05	0.32	-0.04	0.05	0.39*	0.42*	0.84***	0.81***
Fat, %	0.85***	0.59***	0.04	0.30	-0.02	0.05	0.36*	0.40*	0.79***	0.77***
Lean mass, kg	0.94***	0.70***	-0.06	0.33	0.04	-0.05	0.51**	0.54**	0.76***	0.76***
Lean mass, %	-0.85***	-0.59***	-0.04	-0.29	0.02	-0.05	-0.35	-0.41*	-0.79***	-0.76***

[1]BW = Body weight, [2]BL = Body length, [3]Rs = Resistance, [4]Xc = Reactance, [5]C = Conductance, [6]Z = Impedance, [7]PA = Phase angle, [8]V = Body bioelectric volume, [9]RsD = Resistive density, [10]XcD = Reactive density.

* $P < 0.05$.

** $P < 0.01$.

*** $P < 0.001$.

Table 4

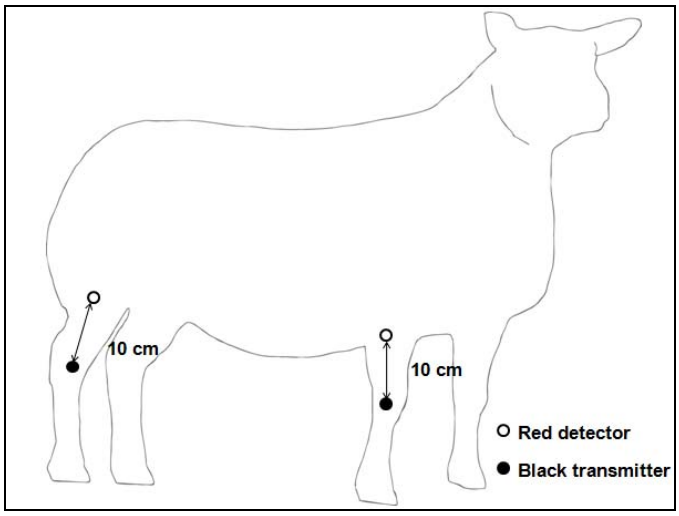
Predicting models of lamb body composition by *in vivo* bioimpedance analysis.

	Models	Calibration				Cross-validation				
		R^{2a}	RMSE[b]	Cp[c]	*P*-value	R^{2a}	RMSE[b]	MPE[d]	RMPE[e],%	*P*-value
Moisture, kg	Y = 0.66 + 0.94XcD +0.09V	0.84	0.55	17.6	< 0.0001	0.93	0.50	0.43	7.47	< 0.0001
Moisture, %	Y = 82.2 – 0.45RsD – 0.19V	0.79	1.92	2.32	< 0.0001	0.86	2.59	1.82	2.78	< 0.0001
Protein, kg	Y = - 0.70 + 0.05RsD + 0.03V + 0.07PA	0.91	0.15	5.32	< 0.0001	0.95	0.15	0.12	6.97	< 0.0001
Fat, kg	Y = - 2.11 + 0.10RsD + 0.04V	0.87	0.30	3.56	< 0.0001	0.91	0.39	0.29	20.9	< 0.0001
Fat, %	Y = - 3.69 + 0.49RsD + 0.21V	0.79	2.09	4.70	< 0.0001	0.88	2.66	1.76	12.5	< 0.0001
Lean mass, kg	Y = - 1.90 + 0.11V + 0.18RsD + 0.31PA	0.89	0.64	10.3	< 0.0001	0.93	0.65	0.55	7.36	< 0.0001
Lean mass, %	Y = 102.5 – 0.48RsD – 0.21V	0.79	2.06	4.56	< 0.0001	0.88	2.65	1.75	2.05	< 0.0001

[a]R^2 = Coefficient of determination; [b]RMSE = Root mean squared error; [c]Cp = Mallows Cp statistic; [d]MPE = Mean prediction error; [e]RMPE = Relative mean prediction error.

XcD = reactive density, V = body bioelectric volume, RsD = resistive density, PA = phase angle.

478



479 Fig. 1. Placement of transmitter and detector electrodes in live lambs for resistance
480 and reactance measurements.
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