Prediction of the chemical composition of lamb carcasses from multi-frequency impedance data

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Multi-frequency bioimpedance analysis (MFBIA) was used to determine the impedance, reactance and resistance of 103 lamb carcasses (17·1–34·2 kg) immediately after slaughter and evisceration. Carcasses were halved, frozen and one half subsequently homogenized and analysed for water, crude protein and fat content. Three measures of carcass length were obtained. Diagonal length between the electrodes (right side *biceps femoris* to left side of neck) explained a greater proportion of the variance in water mass than did estimates of spinal length and was selected for use in the index L^2/Z to predict the mass of chemical components in the carcass. Use of impedance (Z) measured at the characteristic frequency (Z_c) instead of 50 kHz (Z_{50}) did not improve the power of the model to predict the mass of water, protein or fat in the carcass. While L^2/Z_{50} explained a significant proportion of variation in the masses of body water (r^2 0·64), protein (r^2 0·34) and fat (r^2 0·35), its inclusion in multi-variate indices offered small or no increases in predictive capacity when hot carcass weight (HCW) and a measure of rib fat-depth (GR) were present in the model. Optimized equations were able to account for 65–90 % of the variance observed in the weight of chemical components in the carcass. It is concluded that single frequency impedance data do not provide better prediction of carcass composition than can be obtained from measures of HCW and GR. Indices of intracellular water mass derived from impedance at zero frequency and the characteristic frequency explained a similar proportion of the variance in carcass protein mass as did the index L^2/Z_{50}.

Carcass composition: Bioelectrical impedance: Lamb

Techniques for simple, non-destructive and repeatable assessment of the absolute fat, protein and ash content of animals have application in both medical and animal science. In medicine, anthropometry or techniques requiring sophisticated, hospital-based equipment are used to gain this information. These techniques have been frequently reviewed and compared (e.g. Richardson *et al.* 1990; McNeill *et al.* 1991; Kehayias, 1993). In animal production, the need for mobility has meant marker dilution techniques have been the primary means available (Sainz & Tulloh, 1990). Recently, bioelectrical impedance analysis developed for estimating body water in human subjects has been evaluated in animals (Berg & Marchello, 1994; Slanger *et al.* 1994). In human subjects the accuracy of bioelectrical impedance analysis is comparable with more complex techniques (Richardson *et al.* 1990; Wilson *et al.* 1991; Stewart *et al.* 1993) and has the advantages of being low-cost, portable and less prone to operator error than anthropometry. In animal agriculture it is envisaged that bioelectrical impedance analysis may be useful in assessing the chemical composition of live animals, carcasses and major cuts of meat. A recent enhancement of bioimpedance capabilities is the development of multi-frequency bioimpedance analysis (MFBIA), allowing determination of both

Abbreviations: GR, rib fat depth; HCW, hot carcass weight; HWM, hot water mass; MFBIA, multi-frequency bioimpedance analysis.

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total and extracellular water pools (Cornish *et al.* 1992; Deurenberg *et al.* 1995) and calculation of the intracellular water mass by difference.

The present study was undertaken to determine the best combination of length and frequency data for use in biologically based impedance indices to predict the mass of water, protein, fat and fat-free mass in hot lamb carcasses. Impedance indices relating to total body water and intracellular body water were also investigated. In addition the ability of biologically based indices to explain variations in carcass composition was compared with that of equations developed by multiple regressions without a biological basis.

Materials and methods

Lambs

Crossbred wether lambs (*n* 103) were obtained from a commercial supplier at approximately 3 months of age (29 kg live weight). Dietary treatments imposed were early plane of nutrition (two levels) and the energy density (three levels) and level of protein supplementation (four levels) during finishing. On arrival lambs were allocated into two groups using stratified randomization. One group (low) was fed for slow growth to 35 kg live weight and the other group (high) was fed on the same diet at 1500 g/d (as fed) until the mean live weight of the group was 50 kg. Lambs were then fed *ad libitum* for a further 10–12 weeks on pelleted rations containing 7·8, 9·2 or 10·7 MJ metabolizable energy/kg DM together with 0, 30, 60 or 90 g/d formaldehyde-treated casein. Lambs were individually housed for the 34–37 weeks of the experiment then slaughtered (captive bolt and exsanguination) in a private slaughter facility by a trained slaughterman at a rate of sixteen per day. Carcasses and organs were removed and weighed immediately after slaughter and carcasses were reweighed after overnight chilling to determine drip loss.

Impedance

Immediately after slaughter and dressing, carcasses were hung from a rubber coated (non-conducting) gambrel and one pair of electrodes was pressed into the *biceps femoris* and the other into the neck while measurements were taken. A tetrapolar MFBIA instrument, model SFB1, and data capture software developed by UniQuest-SEAC (Brisbane, Australia) were used to make the measurements. The instrument measured impedance (Z, Ω) and phase angle (°) for 378 logarithmically spaced frequencies in the range 1 to 916 kHz at a constant current of 1·5 mA. Sending and receiving electrodes were held 50 mm apart in a jig with 18-gauge needles being used as contacts penetrating the carcass to a depth of 6 mm. Resistance (R, Ω) and reactance (X, Ω) were calculated from the measured impedance and phase angle at each frequency according to the relationship: $Z^2 = R^2 + X^2$. Temperature was determined by stab-thermometers inserted into the hind leg and the shoulder which were removed before impedance analysis was conducted. Approximately 2 min was required to measure each carcass in duplicate. Duplicate data sets were obtained by repeating the signal generation and data collection processes but the electrodes were not removed from the carcass between repeat analyses. The carcass was split through the sternum and was free of kidneys, kidney fat and all offal at the time of measurement.

Measures of carcass length (L_a, L_b) were determined on the hot carcass at the time of impedance analysis (Fig. 1). Due to an oversight, L_c was not determined at this time and was determined on lamb sides which had been portioned (to three pieces) after overnight chilling, and frozen. The carcass was reconstructed from the three portions and L_c measured. The location for placement of electrodes in the *biceps femoris* was readily identified as a fat-free circle approximately 30 mm in diameter. Subcutaneous fat cover was determined by the thickness of tissue over the lateral surface of the 12th rib 110 mm from the mid-line of the spine (the GR site).

The impedance of any body is in part dependent on the frequency of the current being passed through it. In seeking to maximize the precision of impedance data for predicting carcass composition it was considered important to establish the optimum frequency for measurement. Regressions were used to correlate carcass impedance and the masses of water, protein and fat in the carcass at 50 kHz, the characteristic frequency and 916 kHz (Table 3). Impedance at the characteristic frequency (Z_c) and zero frequency (Z_0) were derived by the software from Cole–Cole dispersion plots as described by Ackmann & Seitz (1984). At the characteristic frequency, biological membranes, acting as imperfect capacitors, exhibit maximal reactance (X_c), while at zero frequency impedance equals resistance (Cornish *et al.* 1992).

While the ratio water : protein is not constant in animal tissue (Searle & Graham, 1975; Berg & Butterfield, 1976) it is thought that intracellular water mass is more highly correlated with protein mass than is total body water (Ross

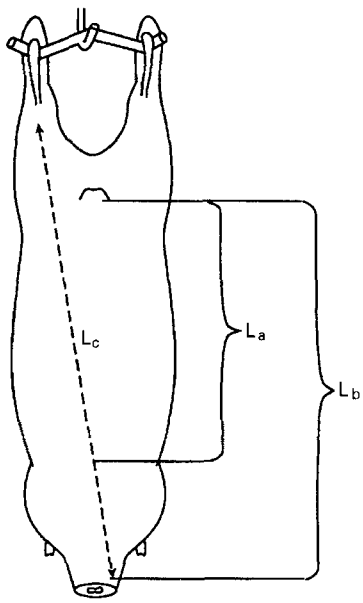

Fig. 1. Measures of carcass length. Measures L_a and L_b were made on the hot carcass while measure L_c was made after the portioned carcass had been frozen.

et al. 1992) and can be estimated as total body water minus extracellular body water. In the present study extracellular body water was not measured directly but it is known to be very closely correlated with L^2/Z_0, because at zero frequency, current is unable to penetrate cell membranes (Cornish *et al.* 1992). Study was made of the relationship between protein mass and the indicators of intracellular water mass ($Z_c - Z_0$) and ($L^2/Z_c - L^2/Z_0$).

Carcass analysis

Frozen half-carcasses were thawed overnight in drip trays then passed through a grinder which chopped the carcass, minced it, and extruded it as a thick paste. The holes in the final grinding plate were 5 mm in diameter. Half-carcasses were passed through this grinding device twice and the grinder washed and dried between carcasses. Representative subsamples (of approximately 1 kg) from each half carcass were kept and frozen for analysis. Approximately 200 g of this sample was freeze-dried and then homogenized in a high-speed blender before analysis. All chemical analyses were completed in triplicate. Absolute DM content was calculated after oven drying the freeze-dried material at 105° until constant weight. Water mass in the hot carcass (HWM) was calculated as water mass of chilled carcass plus overnight drip loss. In most cases, fat content was determined by overnight Soxhlet extraction using chloroform as the solvent and total N was determined as NH_3 after Kjeldahl digestion. Ash was determined by oxidizing (covered) samples at 600° for 6 h, after a preliminary ashing for 1 h at 500°. Fat content was able to be accurately predicted as the non-ash, non-protein residue in DM (r^2 predicted *v.* measured fat 0·97) so for some samples, fat content of the DM was predicted by this means, not measured by Soxhlet extraction.

Statistical methods

Single-factor and multi-factor regressions were developed in Genstat 5, Release 3. Stepwise regression was used to develop the optimized multiple regression equations. Presented values for r^2 and R^2 are all adjusted coefficients and indicate the proportion of variance attributable to the x variable(s).

Results

Growth pattern and carcass characteristics

The nutritional management strategies resulted in a substantial range in weight and composition of carcasses being present at slaughter (Table 1). The range of carcass weights present was normally distributed, as was the water : protein ratio in carcasses across the whole data set, permitting analysis of all data as a single population.

Impedance measurement

Each impedance profile was screened before use in regressions. Impedance plots were viewed (Fig. 2) and plots with an epicentre above the x axis (n 13) were discarded. Duplicate impedance profiles for each lamb were compared and data from a further two lambs were excluded because the duplicate Z_{50} values were not within 5 % of the mean. Chemical analysis was incomplete for four lambs so impedance and carcass composition data were available for a total of eighty-four lambs for use in regression analysis. Electrical properties of the carcasses are summarized in Table 1.

Length estimates

Simple comparisons of lengths L_a, L_b, L_c and other indices which may substitute for length were utilized in regressions with the HWM using half of the lambs (n 48). While the predictive capacity of any measure of carcass length was not great (Table 2), the diagonal length between the two electrodes (L_c) provided the greatest prediction of any length when used alone or in an index utilizing impedance data. For this reason, diagonal length L_c was used in all subsequent evaluations.

There was little effect of signal frequency on the predictive power of the equations used (Table 3), with the mean characteristic frequency being 48 (SD 16·6) kHz. On this basis, further model refinement was conducted utilizing impedance at 50 kHz for the models.

Table 1. Physical and chemical characteristics of crossbred lamb carcasses at completion of a 37-week study of nutritional manipulation of growth

(Mean values and standard deviations for 103 carcasses, unless stated otherwise in the text)

Component masses (kg)	Mean	SD	Carcass attributes	Mean	SD
Live wt	50·5	6·0	Length a (cm)*	55·7	2·70
HCW	24·2	3·8	Length b (cm)*	74·2	3·35
Fat mass	7·46	2·25	Length c (cm)*	79·0	4·05
Water mass	12·58	1·34	Temperature (°)	38·9	1·05
Protein mass	3·51	0·46	Z_c (Ω)	175·5	13·03
Fat-free mass	16·75	1·86	Z_{50} (Ω)	172·8	11·26
Ash mass	0·75	0·17	Z_{916} (Ω)	120·4	11·21
GR (mm)	17·2	5·63	Resistance (Ω)	175·5	11·15
EMA (cm^2)	14·5	1·86	Reactance (Ω)	42·0	4·91

HCW, hot carcass weight; GR, tissue depth over 12th rib, 110 mm from spinal midline; EMA, cross-sectional area of the *Longissimus dorsi*; Z_c, Z_{50} and Z_{916}, carcass impedance values measured at the characteristic frequency, 50 kHz and 916 kHz respectively.

* Lengths a, b and c are defined in Fig. 1.

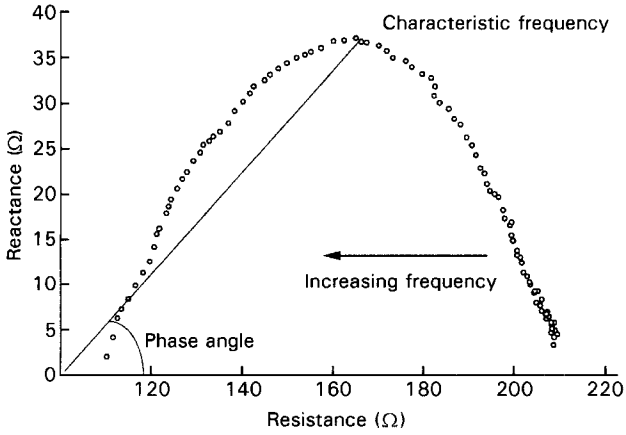

Fig. 2. Cole–Cole dispersion plot of reactance (X) and resistance (R) relationship in a hot lamb carcass. Each point represents the reactance and resistance at a specific frequency. The characteristic frequency is that frequency at which reactance is maximized. Impedance (Z) at any frequency is calculated as $Z=(X^2+R^2)^{\frac{1}{2}}$.

Table 2. Correlations between water mass in the hot carcass (HWM) and measures of length alone or in an impedance index

Predictor (x)	Equation	r^2	SE (kg)
L_a	0·049x + 2·75	0·19	1·21
L_b	0·259x − 6·6	0·41	1·03
L_c	0·242x − 6·52	0·51	0·95
L_a^2/Z_{50}	0·35x + 6·24	0·35	1·09
L_b^2/Z_{50}	0·262x + 4·18	0·56	0·89
L_c^2/Z_{50}	0·230x + 4·22	0·64	0·82

L_a, L_b, L_c, lengths a, b and c as defined in Fig. 1; Z_{50}, impedance value measured at 50 kHz.

Impedance data utilized in a biological model

Having concluded that the power of impedance data is greatest for predicting body composition when the direct length between electrodes is used and that measurement can be made at 50 kHz, tests were made to establish the most appropriate predictive index using impedance data. Early modellers likened the human body to a number of inter-connected cylinders and thus deduced that electrical signals should behave as in a cylinder of water of volume (V); the mathematical product of cross-sectional area (A) × length (L). The impedance of such a cylinder is given in equation 1.

$$Z \propto L/A, \quad (1)$$

or

$$Z = \rho L/A, \quad (2)$$

where ρ is the specific resistivity. Rearranging this equation gives:

$$V = \rho L^2/Z, \quad (3)$$

where V is the conductive volume of body water.

It is reasonable to expect, therefore, that total body water should be accurately described as some function of L^2/Z. This approach has been used in rats (Cornish *et al.* 1992) as well as human subjects and so was evaluated in the present carcasses. It should be appreciated that carcasses were freshly killed, free of viscera and had been split through the sternum at the time of measurement and, while representative of industry practice, were therefore not ideal for this model.

In addition, extra information on carcass weight and fat cover is normally readily available to animal scientists in research institutes and abattoirs. In seeking to get the most precise predictor, an impedance index (L^2/Z), HCW and GR (tissue depth over the 12th rib, 110 mm from the spine) were combined in a stepwise multiple regression analysis (Table 4).

Table 4. Coefficients of determination (R^2) for models predicting the mass of water, protein and fat in the carcass of lambs

(Coefficients of determination and standard errors of the estimate (kg substance))

	Water mass (kg)		Protein mass (kg)		Fat mass (kg)	
	R^2	SEE	R^2	SEE	R^2	SEE
HCW	0·78	0·63	0·65	0·27	0·88	0·78
GR	0·28	1·03	0·36	0·35	0·74	0·85
HCW + GR	0·89	0·41	0·64	0·26	0·91	0·53
L^2/Z*	0·64	0·82	0·34	0·38	0·35	1·83
L^2/Z + HCW	0·83	0·57	0·66	0·27	0·89	0·74
L^2/Z + GR	0·61	0·78	0·43	0·33	0·81	0·75
L^2/Z + HCW + GR	0·90	0·40	0·67	0·25	0·91	0·52

HCW, hot carcass weight; GR, tissue depth over 12th rib, 110 mm from spinal midline; L, length; Z, impedance value.

* Length used was diagonal length between electrodes (L_c); impedance was measured at 50 kHz.

Table 3. Proportion of variance in water, protein and fat in the carcass of lambs (r^2) explained by a simple impedance index at frequencies of 50 kHz (Z_{50}), 916 kHz (Z_{916}) or the characteristic frequency (Z_c)

(Proportions of variance, and standard errors (kg substance))

		Frequency for impedance measure					
		Z_{50}		Z_c		Z_{916}	
Component	Index*	Proportion	SE	Proportion	SE	Proportion	SE
Water mass	L^2/Z	0·64	0·82	0·60	0·86	0·57	0·90
Protein mass	L^2/Z	0·34	0·38	0·30	0·39	0·33	0·38
Fat mass	L^2/Z	0·35	1·80	0·28	1·90	0·37	1·80

* Length used was the diagonal length between electrodes (L_c).

The impedance index (L^2/Z) and GR were excluded from the equation predicting protein mass. Similarly, impedance index did not significantly improve the fat mass prediction but all predictors were included for HWM. The optimized equations follow. Standard error of the estimate (SEE) and the standard error of each component in the equation are provided on the line beneath.

HWM (kg)	$0{\cdot}038 \times L^2/Z + 0{\cdot}447 \times HCW$				
SEE 0·40	0·0163	0·033			
	$-0{\cdot}093 \times GR + 2{\cdot}189$			r^2 0·90	
	0·014	0·45			
Protein mass (kg)	$0{\cdot}987 \times HCW + 1{\cdot}118$			r^2 0·65	
SEE 0·27	0·079	0·194			
Fat mass (kg)					
	$0{\cdot}345 \times HCW + 0{\cdot}107 \times GR - 3{\cdot}027$			r^2 0·90	
SEE 0·53	0·032	0·018	0·55		

Multiple regression analysis

In contrast to the many studies which seek to utilize impedance data within a biological (cylinder) model (see Foster & Lukaski 1996), some animal researchers (Berg & Marchello, 1994) have put aside underlying biological mechanisms and explored simple correlations between body composition and a host of measures of resistance, reactivity and impedance. Current data were reanalysed in multiple linear regressions in the manner of Berg & Marchello (1994) to determine the most appropriate empirical model to predict HWM, protein mass and fat-free mass (Table 5).

The most appropriate equations to predict HWM and fat-free mass comprised two variables; HCW and resistance. The remaining variables length, temperature and reactance were excluded from the model. The model for protein mass also excluded all variables except HCW. Models are shown here with dependent variables. Beneath each equation is given the standard error of the estimate (SEE) in kilograms and standard errors for each component.

HWM	$0{\cdot}281 \times HCW - 0{\cdot}032R + 11{\cdot}04$				r^2 0·838
SEE 0·56	0·017	0·006	1·23		
Fat mass	$0{\cdot}577 \times HCW + 0{\cdot}031R - 11{\cdot}85$				r^2 0·899
SEE 0·74	0·224	0·008	1·62		
Fat-free mass	$0{\cdot}480 \times HCW - 0{\cdot}012R + 8{\cdot}73$				r^2 0·868
SEE 0·74	0·026	0·0075	1·64		
Protein mass	$0{\cdot}0987 \times HCW + 1{\cdot}128$				r^2 0·652
SEE 0·27	0·0079	0·194			

Correlations with intracellular water mass

There was little difference between the variance in protein mass explained by the index L^2/Z_{50} (r^2 0·34) and a more complex index (Fig. 3) reflecting the intracellular water mass ($L^2/Z_c - L^2/Z_0$; r^2 0·34). The index ($Z_c - Z_o$) was very poorly correlated with protein mass (r^2 0·01).

Discussion

The impedance of an object to the flow of current is determined by the frequency of current, and the size, geometry and intrinsic electrical properties of the object (Foster & Lukaski, 1996). Traditional indices of body mass

Table 5. Multiple regressions relating the composition of lamb carcasses to their physical characteristics and electrical characteristics measured at 50 kHz

(Values are coefficients of determination, and standard errors of the estimate (kg substance))

	Fat-free mass		Hot water mass		Protein mass		Fat mass	
Predictor	R^2	SEE	R^2	SEE	R^2	SEE	R^2	SEE
L (*n* 80)	0·524	1·30	0·514	0·95	0·391	0·36	0·481	1·64
T (*n* 84)	0·210	1·84	0·290	1·32	*	*	0·007	2·24
X (*n* 83)	0·036	1·83	0·073	1·29	*	*	*	*
R (*n* 83)	0·148	1·72	0·200	1·20	0·220	0·46	0·005	2·25
HCW (*n* 84)	0·824	0·78	0·781	0·63	0·652	0·27	0·879	0·78
R, X	0·186	1·56	0·182	1·24	0·015	0·46	*	*
L, R	0·525	1·19	0·637	0·82	0·389	0·36	0·471	1·66
HCW, L	0·854	0·66	0·777	0·64	0·658	0·27	0·878	0·80
HCW, R	0·868	0·63	0·833	0·56	0·659	0·27	0·896	0·74
L, R, X	0·532	1·18	0·638	0·82	0·415	0·36	0·485	1·64
HCW, R, T	0·866	0·63	0·831	0·56	0·664	0·27	0·895	0·74
HCW, R, L	0·867	0·63	0·839	0·55	0·654	0·27	0·898	0·73
HCW, R, X	0·868	0·63	0·833	0·56	0·658	0·27	0·895	0·74
HCW, L, R, T	0·865	0·64	0·837	0·55	0·660	0·27	0·896	0·74
HCW, L, R, X	0·866	0·63	0·837	0·55	0·654	0·27	0·896	0·74
HCW, R, X, T	0·866	0·63	0·831	0·56	0·668	0·27	0·894	0·75
HCW, L, R, X, T	0·864	0·64	0·835	0·55	0·663	0·27	0·895	0·74

L, length; T, carcass temperature; X, reactance; R, resistance; HCW, hot carcass weight.
*No variance was accounted for when these terms were added.

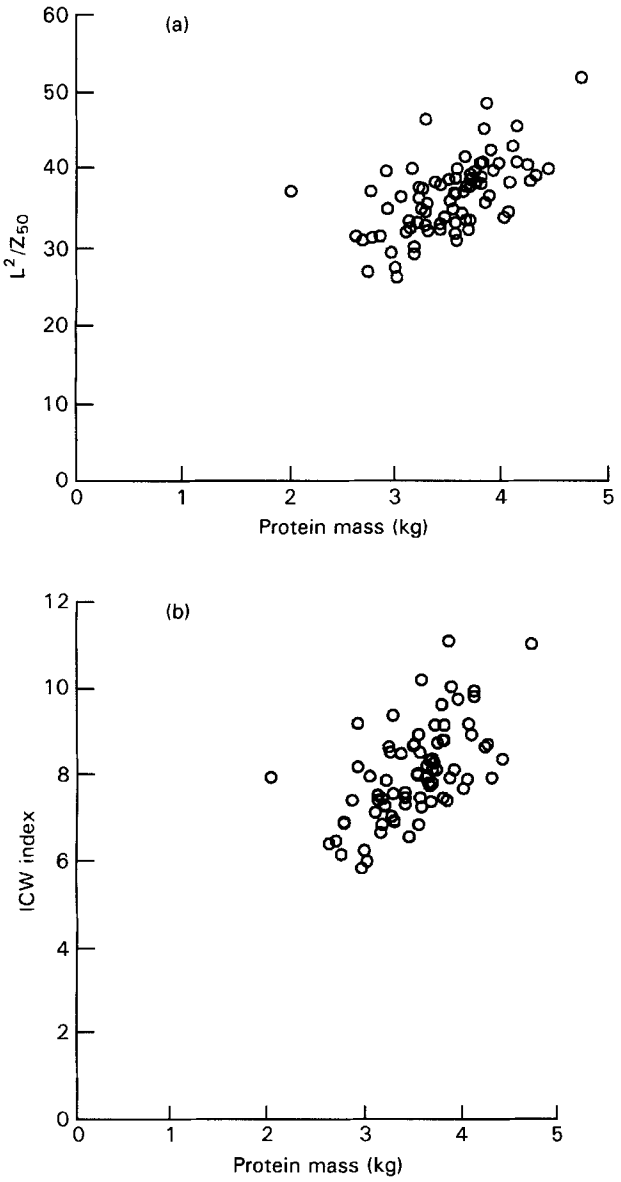

Fig. 3. (a) Relationship between carcass protein mass and an index of total carcass water (L^2/Z_{50}, where L is length and Z_{50} is impedance at 50 kHz). Protein = 0·0532 × (L^2/Z) + 1·608 (SE 0·38, r^2 0·34). (b) Relationship between carcass protein mass and an indexed intracellular water (ICW) mass, where ICW index = ($L^2/Z_c - L^2/Z$). Protein = 0·250 × ICW index + 1·157 (SE 0·38, r^2 0·34).

or lean body mass (Nevill & Holder, 1995) developed in clinical studies can be used to account for the contribution of geometrical and size variation to whole body impedance, allowing it to be tightly correlated with total body water (Settle *et al.* 1980). These same indices have been used in interpreting impedance data from animals (Cornish *et al.* 1992) but it is important that parameters contributing to such an index are optimized. The present study sought to identify the optimum impedance-based model to predict carcass water, protein and fat by evaluating measures of length, signal frequency and the need to account for geometry.

While in many reports, the estimate of length used in impedance models is unrelated to path-length, the present study found that length between electrodes (L_c) explained a greater proportion of variance in HWM than did tail-to-neck or tail-to-shoulder measures. There are probably two contributing factors to this. First, large differences in HCW existed between carcasses with similar spinal lengths (L_a, L_b). In contrast, the range L_c was greater and was more closely related to HCW (r^2 0·56 *v.* r^2 0·20 for L_a and r^2 0·35 for L_b) Second, by positioning the rear electrodes in the hind leg, a greater proportion of the carcass was contained between the current and measurement electrodes and this may have improved the accuracy of determining the whole carcass impedance. Additionally location of electrode sites on the *biceps femoris* and neck used for L_c were easily defined for accurate placement. Shoulder and neck sites required for determining L_a and L_b were, however, difficult to locate with confidence.

In contrast, Berg & Marchello (1994) recommend dorsally-placed electrodes and measures of spinal length; Cosgrove *et al.* (1988) used electrodes placed on the extremities with a measure of the length of the body cavity (first rib to hip). The evaluation in the present study suggests that diagonal placement of electrodes on the neck and hind leg and use of direct path-length for L should be adopted.

While the L^2/Z model based on cylinder volume has been widely used, it is perhaps an inaccurate reflection of carcass geometry and there was little difference in the predictive capacity of optimized indices based on the cylinder (L^2/Z) approach compared with the simple empirical multiple regressions. While path-length (a measure of size) is known to have a fundamental bearing on impedance, this parameter was able to be excluded from the empirical models of Berg & Marchello (1994) in their own studies and also in the present study without loss of predictive capability. From both the mechanistic and empirical approaches it was apparent that the greatest contribution in all predictions was made by HCW and that this is a superior indicator of tissue mass than is length.

The index L^2/Z alone was less effective in predicting HWM than was HCW alone (Table 4). Combining these two predictors slightly increased the predictive power for most carcass constituents but the increase (1·1–6·4 %) is unlikely to justify making the measurement of impedance in addition to carcass weight. Where rib-fat depth data were not available, Berg & Marchello (1994) were able to improve the proportion of fat-free mass accounted for from 0·56 to 0·72 by incorporating resistance data with HCW, but where fat depth or eye muscle area data are available, the benefit of including any electrical data is very small (Jenkins *et al.* 1988). Similarly, prediction of dissectible meat or retail yield of meat is not enhanced by inclusion of impedance measures over carcass weight and rib fat depth (Slanger *et al.* 1994; Hopkins & Hegarty, 1995).

In human studies impedance is finding favour because of its convenience but comparative studies have found it no more accurate in predicting body water mass of normal individuals than conventional means of skinfold thickness, tritiated or deuterated water, X-ray absorption, densitometry or body K (Richardson *et al.* 1990; McNeill *et al.* 1991; De Waart *et al.* 1993; Stewart *et al.* 1993). Dispute over the need for separate calibrations for human subjects

from differing ethnic groups (De Waart *et al.* 1993) and for the sexes (Richardson *et al.* 1990; Stewart *et al.* 1993) suggests variation due to sex and genotype may also need to be considered in calibrations for livestock.

The present study gives no evidence that impedance measured at the characteristic frequency is of advantage relative to impedance measured at 50 kHz when a single frequency model is used. Indices predicting intracellular water, however, require that MFBIA be used. In impedance theory the body may be likened to a circuit of capacitors (cell membranes) and resistors (intracellular and extracellular fluids). At low frequency, current is unable to pass through the capacitor (membrane and intracellular water) so the impedance observed is attributable only to the extracellular fluid. Recently the appropriateness of this theory to elongated muscle cells rather than 'ideal' spherical cells has been questioned (Foster & Lukaski, 1996) but excellent correlations between L^2/Z and extracellular water have been achieved (Cornish *et al.* 1992). The fact that our results show protein mass in freshly killed and dressed lamb carcasses was no better correlated with an intracellular water index ($L^2/Z_c - L^2/Z_o$) than a total body water index (L^2/Z_{50}) may be attributable to several factors. These may include the very small extracellular fluid space in carcasses after bleeding and evisceration and a rapid change in the electrical properties of tissue after slaughter as has been found with ischaemia (Löfgren, 1951).

In human medicine the application of MFBIA appears to be in assessing individuals with abnormal body composition due to a health disorder rather than normal healthy individuals (e.g. Holt *et al.* 1994). In animal science it is likely that single frequency impedance measurements (be they at 50 kHz or the characteristic frequency) will be most appropriately used in grading animals or carcasses for their commercial usefulness (e.g. Slanger *et al.* 1994) rather than providing accurate analysis on specific individuals. This means that fixed frequency impedance measurement, while cheap, simple and fast, is unlikely to be used to identify superior individuals in genetic selection programmes. Further investigation of appropriate models using multi-frequency data based on different principles of geometry is required to further develop the accuracy of bioimpedance as a tool for assessing carcass composition.

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