National Diploma Animal Production
Livestock Production Part 5

Handout 6
Methods of Predicting Lamb Carcass Disposition

ELSEVIER

Small Ruminant Research 29 (1998) 241–254

Small Ruminant Research

Methods of predicting lamb carcass composition: A review

K. Stanford [a,*], S.D.M. Jones [b], M.A Price [c]

[a] Alberta Agriculture, Food and Rural Development, Agriculture Centre, Bag 3014, Lethbridge, Alberta, Canada T1J 4C7
[b] Research Centre, Agriculture and Agri-Food, Canada, Box 3000, Lethbridge, Alberta, Canada T1J 4B1
[c] Department of Agriculture, Food and Nutritional Sciences, 310 AgForestry Centre, University of Alberta, Edmonton, Alberta, Canada T6G 2P5

Accepted 16 November 1997

Abstract

Methods presently available for the prediction of body and carcass composition in lambs were reviewed in terms of cost, speed, precision and current usage. In vivo methods reviewed included liveweight, linear measurements, ultrasound, X-ray computed tomography (CT) and nuclear magnetic resonance (NMR)/magnetic resonance imaging. Methods reviewed for predicting composition of carcasses included subjective measurements, carcass weight, specific gravity, dressing percentage, linear measurements, optical probes, video image analysis (VIA), total body electrical conductivity (TOBEC) and bioelectrical impedance. All methods were not directly comparable as few studies have used multiple methods for prediction of body or carcass composition. Limited comparisons were possible through the residual standard deviations (RSD) published for the various methods. Although subjective methods for predicting body and carcass compositions are rapid and relatively inexpensive, the sheep industry should adopt objective methods in order to more readily change lamb carcass composition to meet consumer demand.

1. Introduction

The sheep industry world-wide faces a fundamental problem. With the exception of the major lamb-exporting countries (New Zealand and Australia) and some areas of the Middle East, consumption of lamb has markedly declined over the past 30 years (Lewis et al., 1993). Although consumption of other red meats has also declined during this period, lamb consumption in North America has fallen to the point where it is difficult to even assess. With a high degree of error, it is estimated on an annual per capita retail-weight basis at 0.6 to 0.7 kg in the USA (Economic Research Service, 1994) and 0.8 kg in Canada (Statistics Canada, 1995).

In order to reverse the downward trend in lamb consumption, the needs of the modern consumer have to be more closely addressed. As outlined by Ward et al. (1995), consumers require meat with more lean, less fat (the minimal fat level required to maintain juiciness and flavour), consistent quality, portions that are considered good value for money with minimal wastage, convenience/ease in cooking and a high level of choice/flexibility in available cuts. Unfortunately, the studies of Ward et al. (1995) and others (Harris et al., 1990; Beermann et al., 1995) have shown that lamb is currently failing to meet these consumer demands.

Before lamb carcasses can be changed to better meet consumer demand, carcasses must be evaluated using two equally important categories: (1) quality attributes such as tenderness, cut size, fat cover, marbling, meat and fat colour; and (2) composition attributes such as saleable meat yield, or proportions of fat, lean and bone (Harrington and Kempster, 1989). It is the intent of this paper to review and evaluate methods available for prediction of body/carcass composition in sheep which may, in some cases, also allow prediction of quality attributes.

Although prediction of carcass composition in sheep has been the subject of earlier reviews (Alliston, 1980; Kempster, 1980; Allen, 1990; Fisher, 1990; Simm, 1992), more recent reviews have either had a narrow focus (Russel, 1995) or have excluded sheep (Forrest, 1995; Jones, 1995). A re-evaluation of methods for predicting carcass composition in sheep is warranted due to changes in technology since publication of the earlier reviews.

The methods of predicting carcass composition discussed in this paper are required for a variety of purposes. Extremely rapid methods, capable of evaluating carcasses ... sheep are moderately highly heritable (Simm, 1992). Heritability estimates on a weight-adjusted basis for percentages of carcass lean and fat are commonly found to be 0.40 for lean and 0.45 for fat (Wolf and Smith, 1983; Simm et al., 1987). Improvement in carcass composition by genetic selection is possible for traits such as fat distribution which show a high degree of variation in individual animals within a breed (Butterfield, 1988), but would be limited for other traits such as muscle weight distributions which show very small variation either within or across breeds when sheep are compared at the same stage of maturity (Kempster and Cuthbertson, 1977). Ignoring genetic factors such as selection intensity which are beyond the scope of this paper, the rate of improvement would be largely dependent on the precision of the method used for estimating body/carcass composition in vivo. Other factors which need to be evaluated to determine the utility of methods for prediction of body and carcass composition include the cost/ease of taking the predicting measurements and the stability of the prediction between animals differing in sex, or feeding regime (Kempster et al., 1976). The suitability of a method for use within a particular breed must also be determined. A summary of available methods for evaluation of body composition in vivo is shown in Table

* Corresponding author. Tel.: +1-403-381-5150; fax: +1-403-382-4526; e-mail: stanford@em.agr.ca

PII S0921-4488(97)00143-0

uating a carcass in 6 s or less would be relevant for on-line use (Hopkins et al., 1995), provided that damage to the commercial value of the carcass is minimal. Relatively rapid and inexpensive in vivo methods which do not harm animal performance would be applicable for the selection of breeding stock or estimation of market-readiness. In contrast, methods of extreme accuracy and/or precision may be useful in research applications, regardless of cost or time/labour requirements.

2. Body composition in vivo

The keys to changing carcass composition to better meet consumer demand are methods of evaluating body composition in vivo. It is desirable that in vivo methods be applicable in young animals, enabling early selection of lambs with highly desirable body/carcass composition as breeding stock (Brash et al., 1992). Generally, carcass composition traits in 1.

2.1. Subjective measurements

Visual appraisal in combination with condition scoring (manual assessment of fatness) is the most rapid and inexpensive method for prediction of body composition in vivo (Kempster, 1984). However, the large variation between breeds in the proportion of fat stored subcutaneously (Fahmy et al., 1992) limits the usefulness of this method. Within breeds, trained livestock evaluators have been able to estimate lamb carcass composition with accuracies superior to that of ultrasound (Nicol and Parratt, 1984; Edwards et al., 1989). Provided breed types are relatively uniform, lamb 'drafters' in New Zealand use visual appraisal/condition scoring for prediction of carcass composition with accuracies approaching those of ultrasound (Dodd et al., 1986). However, the small number of suitably experienced/proficient personnel in countries other than New Zealand and difficulties

Table 1
In vivo methods for prediction of body composition in sheep

Method	Prediction	Predictors	Precision	Authors
Subjective appraisal	lean meat yield (%)	estimated fat 12/13 ribs	$R^2 = 0.36$, RSD = 1.52	Edwards et al. (1989)
Ultrasound		US[a] fat 12/13 ribs 'C'	$R^2 = 0.17$, RSD = 1.70	
Live weight	lean %	live weight (LW)	RSD = 2.6	Cameron and Smith (1985)
Ultrasound		LW + US 'C' 12 rib	RSD = 2.1	
Live weight	trimmed boneless meat (kgs)	live weight	$R^2 = 0.76$, RSD = 0.29	Fortin and Shrestha (1986)
Ultrasound		US LD[b] 'B'	$R^2 = 0.79$, RSD = 0.27	
Linear measures		LA[c]-dissection	$R^2 = 0.89$, RSD = 0.20	
Live weight	lean meat yield (%)	LW	$R^2 = 0.15$, RSD = 2.83	Puntilla (1986)
Ultrasound		LW + US LD 'B'	$R^2 = 0.27$, RSD = 2.65	
Ultrasound		LW + 'B' + US W[d] 'A'	$R^2 = 0.31$, RSD = 2.60	
Live weight	lean meat (kgs)	LW	$R^2 = 0.73$, RSD = 0.68	Jones et al. (1982)
Dilution (urea)		LW + urea space	$R^2 = 0.74$, RSD = 0.68	
Ultrasound		LW + US fat 'C'	$R^2 = 0.74$, RSD = 0.68	
Live weight	saleable meat yield (%)	LW	$R^2 = 0.14$, RSD = 1.5	Stanford et al. (1995a)
Ultrasound		LW + US fat 'C'	$R^2 = 0.64$, RSD = 1.2	
Linear measures	lean meat yield (%)	LW + HG[e] + SH[f]	$R^2 = 0.14$, RSD = 2.13	Berg et al. (1996)
Ultrasound		LW + US 'C' + US 'B'	$R^2 = 0.26$, RSD = 2.11	
Bioelectrical impedance		LW + BL[g] + resistance + reactant	$R^2 = 0.55$, RSD = 1.81	
Combination		LW + BL + US 'B' + US 'C' + resistance + reactance	$R^2 = 0.70$, RSD = 1.71	
Liveweight	fat-free lean (kg)	LW	$R^2 = 0.83$, RSD = 0.80	Sehested (1984)
X-ray CT		LW + X-ray CT measures	$R^2 = 0.92$, RSD = 0.61	
NMR	lean meat yield (%)	LW + NMR measures	$R^2 = 0.78$ to 0.91	Streitz et al. (1995)

[a] US, ultrasound.
[b] LD, longissimus depth.
[c] LA, longissimus area.
[d] W, longissimus width.
[e] HG, heart girth.
[f] SH, shoulder height.
[g] BL, body length.

in maintaining standards across time and geographical regions would limit the usefulness of subjective estimates of body composition.

2.2. *Liveweight*

In vivo techniques commonly use liveweight as the standard to which other predictors of body composition are compared (Kempster, 1984; Simm, 1992) although live weight may be difficult to accurately measure due to the influence of gut fill and fleece length/hydration. As outlined by Butterfield (1988), tissues within the body follow predictable patterns of development from birth to maturity. The proportion of muscle in sheep compared at fleece-free empty body weights has been shown to be relatively uniform, ranging from 28% (McClelland et al., 1976) to 30% (Thonney et al., 1987). The currently reported exceptions to this general rule are the Soay and Texel breeds, the Soay having less fat and more bone (McClelland et al., 1976) and the Texel having less fat and more lean than would be expected. The usefulness of liveweight as a predictor of body composition is limited by difficulties in assessing an animal's stage of maturity which can be influenced by genotype, nutrition, disease, physical environment, level of activity, social environment and age (Taylor, 1965). In lambs of equal maturity (same age and breed), liveweight predicted % carcass lean with a residual standard deviation (RSD) ranging from 1.4 (Cuthbertson et al., 1984) to 2.2 (Fortin and Shrestha, 1986), with R^2 values of 0.51 and 0.76, respectively. When lambs were of differing maturity (varying ages, multiple breeds), liveweight has been less useful for predicting % carcass fat (RSD of 3.9, Purchas and Beach, 1981) and % saleable meat yield (RSD of 1.5, and R^2 of only 0.14, Stanford et al., 1995a).

2.3. *Linear measurements*

Prior to development of technologies enabling in vivo prediction of carcass composition, a number of linear measurements (shoulder height, heart girth, body length…) were evaluated as predictors of body composition in sheep (Orme et al., 1962; Orme, 1963; Cunningham et al., 1967), but were found to be of marginal utility in lambs of varying age, sex or breed type. Although the use of linear measurements has been periodically re-investigated (Cuthbertson et al., 1984; Edwards et al., 1989), the inability of linear measurements to distinguish between lean and fat would limit their application as primary predictors of body composition to goats and certain breeds of sheep which have limited subcutaneous fat stores (Stanford et al., 1995b). The utility of linear measurements has also been reduced by the accuracy to which the measurements may be recorded. Most studies have used either callipers or measuring tapes, leading to increased error due to animal movement and variations in fleece cover.

Early studies reported that ultrasound was either of little (Jones et al., 1982; Hamby et al., 1986) or no use (Leymaster et al., 1985; Fortin and Shrestha, 1986; Edwards et al., 1989) for predicting body/carcass composition in sheep. The limited utility of ultrasound was attributed to the small size and lack of variation in subcutaneous fat thickness and longissimus muscle area in sheep as compared to cattle and pigs (Houghton and Turlington, 1992). Additionally, Purchas and Beach (1981) attributed the reduced utility of ultrasound in sheep to a soft, mobile subcutaneous fat layer, with wool an added complicating factor. However, in more recent work (Stanford et al., 1995a), ultrasound measurement of subcutaneous fat depth taken at the first lumbar vertebra was a better predictor of saleable meat yield (RSD = 1.2, $R^2 = 0.64$) than liveweight (RSD = 1.5, $R^2 = 0.14$). Additionally, the use of ultrasonic measurements of backfat and longissimus muscle depth ('C' and 'B' measurements, respectively of Pálsson, 1939) at the third lumbar vertebrae has been shown to improve genetic selection for carcass fatness by 10.3% and carcass grade (muscling and fatness) by 14.5%, compared to selection based on liveweight alone (Olesen and Husabø, 1994).

Regardless of the precision of ultrasound methods, sheep body composition has been significantly improved after 3–4 years of selection using indexes based on ultrasonically measured backfat, muscle

2.4. Ultrasound

Ultrasound equipment converts electrical pulses to high-frequency sound waves which are reflected from the boundaries between tissues of different bioacoustic densities (Houghton and Turlington, 1992). Two types of ultrasound equipment are used: (A) mode machines, available since the 1950's, which measure echo amplitude against time, with the distance between echoes being related to the distance between successive tissue interfaces (Simm, 1983); (B) mode or real-time machines developed in the early 1980's, where 'grey-scales' measure echo intensity in a two-dimensional scan (Stouffer, 1988). The velocity of ultrasound through soft tissues is also used to predict body composition (Miles et al., 1991), offering the advantage of absolute values instead of images requiring subjective interpretation.

depth and liveweight (Cameron and Bracken, 1992; Simm et al., 1993). Additionally, the relatively low cost and ease of portability of ultrasound equipment has led to incorporation of ultrasound measurements into national genetic programs for lamb carcass quality improvement in many parts of the world (Table 2).

2.5. X-ray computed tomography

Unlike ultrasound which was first used for military purposes, the equipment used in X-ray computed tomography (CT) was first developed for human medicine (Vangen, 1989). An X-ray generator and X-ray detectors are rotated around the subject, firing pulses of radiation and measuring the amount of radiation transmitted through the subject (Simm, 1992). The rate of attenuation of the X-rays allows computerized calculation of densities in a cross section of the subject, the densities being standard values which vary from -1000 for air to $+1000$ for bone (Standal, 1984). In vivo use of CT is applicable only for smaller livestock such as sheep, goats, chickens and pigs due to the human-scale of the equipment (Vangen, 1989).

Table 2
Use of ultrasound in national programs for genetic improvement of lamb carcass composition

Country	Site used	Measures	Program name	Year initiated	References
Denmark	1st lumbar	C, LA[a]	Central Ram Test	1979	Jensen, 1990
Australia	12th rib	C	Lambplan	1980[b]	Atkins et al., 1991
New Zealand	12th rib	C	Animalplan[c]	1981	Davis and Fennessy, 1996
Finland	1st lumbar	LA	Central Ram Test	1985	Puntilla and Nylander, 1993
UK	3rd lumbar	C, B[d]	Sheepbreeder	1986	Simm, 1992
Norway	1st lumbar	C, LA	Central Ram Test	1992	Puntilla and Nylander, 1993
Canada	3rd lumbar	C, B	Ovissey	1997	[e]

[a]C = subcutaneous fat thickness over deepest part of longissimus, LA = longissimus area.
[b]1980, program initiated as New South Wales Meat Sheep Testing Service in 1980 which became Lambplan in 1989.
[c]Animalplan, known as Sheeplan until 1988.
[d]B, maximum depth of the longissimus muscle.
[e]Shafto, A.M., 1996. Managing director, Sheep Information Center, Canadian Sheep Federation, personal communication.

Although studies where CT has been used for prediction of body composition in sheep are limited, Sehested (1984) reported that CT values with live weight could predict kg fat-free lean in lambs with R^2 values of 0.92 to 0.94, RSD 0.5 to 0.6, compared to prediction with liveweight alone ($R^2 = 0.83$, RSD $= 0.8$). Jopson et al. (1995) reported that compared to ultrasound, CT would double the rate of genetic improvement for lean meat traits in lambs as direct selection was possible for protein content and proportions of lean, intermuscular and intramuscular fat. However, the 10-fold higher cost of CT (equipment large enough for a human. The strong magnetic field tends to induce resonance of protons in the subject (Wells, 1984). The time needed for the protons to re-establish original conditions has been defined as spin-lattice relaxation time T1 and spin-spin relaxation time T2 (Groeneveld et al., 1984) which differ depending on factors such as the state of hydration or fat content of a tissue (Simm, 1992). Contrary to CT, there are no standardized values in NMR due to changes in conditions and parameters between measurements (Groeneveld et al., 1989). However, NMR has additional capabilities compared to CT, including evaluation of muscle metabolism and prediction of carcass quality attributes such as water holding capacity (Monin and Renou, 1989). Spectroscopy and magnetic resonance imaging are discrete types of NMR, although both are applicable to the prediction of body composition (Simm, 1992).

and operating expenses) as compared to ultrasound (Parratt and Simm, 1987) will likely result in general use of ultrasound for evaluation of body composition in sheep, with CT reserved for a select group of the most promising rams. X-ray CT has been used for evaluation of elite rams in the UK (Simm, 1992) and Australia (Jopson et al., 1995). Recently, CT equipment was also purchased in New Zealand for a commercial scanning service (Innervision) for high-value sheep (Davis and Fennessy, 1996).

2.6. Nuclear magnetic resonance / magnetic resonance imaging

A nuclear magnetic resonance (NMR) machine consists of an electromagnet with a central opening

The accuracy of NMR at predicting body composition is thought to be superior to that of CT (Groeneveld et al., 1984; Simm, 1992), although CT and NMR were found to be of equal value in determining adipose tissue volumes of rats (Ross et al., 1991). High operating costs for NMR, estimated to be equivalent to the wages of 20 research staff (Pedersen, 1989), have restricted access to NMR equipment for livestock species to a larger extent than access to CT. In the sole study where NMR has been used to evaluate body composition in sheep, Streitz et al. (1995) reported R^2 values ranging from 0.78 to 0.91 for percentage of lean in lambs at body weights from 10 to 50 kg. Presently, programs using NMR for the genetic improvement of carcass quality

in livestock are restricted to poultry (Mitchell et al., 1991; Liu et al., 1994). Additional studies with sheep would be required before the benefits of using NMR for prediction of body composition could be evaluated relative to costs.

2.7. Other methods for in vivo prediction of body composition

Other techniques for prediction of body composition presently used in human medicine include dual-photon absorptiometry (Mazess et al., 1990); dual X-ray absorptiometry (Dalsky et al., 1990) and underwater weighing (Wang et al., 1989). However, underwater weighing would be practical only for sheep carcasses. Additionally, radionucleotides are costly and their use in meat animals would be a perceived human health concern. Dilution techniques for estimating body water using radionucleotides (Robelin and Theriez, 1981) and urea (Jones et al., 1982) have been used to predict body composition of sheep, but due to the length of time required (up to 48 h animal^{-1}) and the amount of labour involved, are applicable only in research studies (Robelin, 1984). Discussions of total body electrical conductivity (TOBEC) and bioelectrical impedance analysis (BIA) are presented in Sections 3.6 and 3.7, respectively.

Bichard, 1965; Kempster et al., 1976), while precise and requiring little expenditure for capital equipment, would be slow, labour-intensive and result in reduced carcass marketability/value. A summary of currently available inexpensive manual, nondestructive methods of carcass evaluation ex vivo is shown in Table 3, while methods requiring sophisticated equipment are shown in Table 4.

3.1. Subjective measurements

Lamb carcass composition is commercially evaluated in many countries (Australia, USA, South Africa, UK) by subjective assessment of fatness or conformation (Jones et al., 1992). Even in New Zealand where a system for objective measurement is in place, body composition/fatness of lambs is usually subjectively evaluated (Kirton et al., 1992). Conformation and fatness are related, as lamb carcasses with good conformation are generally fatter than those with poor conformation (Kirton and Pickering, 1967; Kempster et al., 1981; Stanford et al., 1995a). The only exceptions to this are well-muscled individuals, breeds such as the Texel (Kempster et al., 1987; Leymaster and Jenkins, 1993) or genetic mutations such as the Callipyge (Busboom et al., 1996).

The utility of subjective methods for evaluating carcass composition has been largely dependent on the population of lambs evaluated. When lambs have been of varying breed types, ages or sizes, subjective

3. Carcass composition ex vivo

Carcass composition assessment serves three functions: (1) assigns carcass value; (2) allows sorting of carcasses for further processing or fresh meat merchandising; and (3) transfers information back to the production sector, hopefully ensuring that carcasses meet consumer demand. As with in vivo methods, it is desirable that methods of assessing carcass composition ex vivo be precise, accurate over time and distance and across lambs of varying breeds, sexes and ages. However, cost, ease of measurement and speed of methods are crucial. Highly precise methods such as NMR and CT would be too slow for on-line use (Forrest, 1995), even if they were cost effective. Other methods, such as dissection of small regions of the carcass (Timon and assessments have been useful predictors of carcass composition (Kirton et al., 1992; Jones et al., 1993; Stanford et al., 1997), but have had little utility in more uniform lamb populations (Kempster et al., 1981; Horgan et al., 1995). However, even in highly diverse lamb populations, subjective evaluations alone have been marginal predictors of carcass composition ($R^2 = 0.61$, RSD = 1.71% for the best equation including GR measurement and subjective conformation predicting saleable meat yield vs. $R^2 = 0.55$, RSD = 1.84% for the same equation excluding conformation; Jones et al., 1993). A global change to objective evaluation and more precise methods for assessing lamb carcass composition would be the first step in identifying and rewarding production of the lean yet well-muscled lamb needed to meet consumer demand.

Table 3
Manual/inexpensive methods of predicting carcass composition of sheep ex vivo

Method	Prediction	Predictors	Precision	Authors
Subjective appraisal	lean meat yield (%)	external fatness	$R^2 = 0.36$, RSD = 3.17	Kempster et al. (1976)
		conformation score	$R^2 < 0.20$, RSD = 3.57	
Linear measures	lean meat yield (%)	fat depth 'C'	$R^2 = 0.43$, RSD = 3.00	Kempster et al. (1976)
		LW[a] 'A'	RSD = 3.85	
		LD[b] 'B'	RSD = 3.95	
		LA[c]	RSD = 3.94	
		carcass weight (CW)	RSD = 3.78	
		CW/carcass length	RSD = 3.74	
Dissection of sample joints	lean meat yield (%)	lean in shoulder (%)	$R^2 = 0.82$, RSD = 1.67	Kempster et al. (1976)
		kidney fat + channel fat %	$R^2 = 0.32$, RSD = 3.27	
Subjective appraisal	lean meat yield (%)	CW	RSD = 3.63	Kempster et al. (1981)
		CW + external fatness (5)	RSD = 2.97	
		CW + external fatness (15)	RSD = 2.61	
Specific gravity	lean meat yield (%)	specific gravity	RSD = 1.9	Kempster (1981)
Linear measures		kidney fat %	RSD = 2.2	
Subjective appraisal		visual fat score	RSD = 2.2	
Linear measures		carcass dimensions	RSD = 2.6	
Linear measures		LA, 'A', or 'B'	RSD = 2.7	
Linear measures	lean meat yield (%)	CW	RSD = 3.80 to 4.48	Kempster et al. (1986)
		CW + subjective fat (5)	RSD = 3.08 to 3.44	
		CW + conformation (4)	RSD = 3.63 to 4.31	
		CW + fat depth 'C'	RSD = 3.00 to 3.46	
		CW + LW 'A'	RSD = 3.52 to 4.01	
		CW + LD 'B'	RSD = 3.79 to 4.48	
		CW + kidney fat %	RSD = 2.92 to 3.33	
		CW + % lean in shoulder	RSD = 1.60 to 1.81	
Linear measures	carcass fat (%)	CW	RSD = 3.31 to 3.77	Kirton et al. (1985)
		GR (manual by ruler)	RSD = 2.91 to 3.11	
		CW + GR	RSD = 2.86 to 3.11	
Subjective appraisal	lean meat yield (%)	MLC[d] fat score	RSD = 2.91 to 3.31	Miles et al. (1991)
		MLC conformation score	RSD = 3.31 to 4.52	

[a] LW, longissimus width.
[b] LD, longissimus depth.
[c] LA, longissimus area.
[d] MLC, Meat and Livestock Commission of the UK.

3.2. *Carcass weight, specific gravity and dressing percentage*

Fat has a lower density than other carcass components and the determination of carcass specific gravity [weight in air/(weight in air − weight underwater)] was the subject of early investigations (Kirton and Barton, 1958; Timon and Bichard, 1965). In these studies, carcass specific gravity was found to be equal to dressing percentage (hot carcass weight (HCW)/live weight) as a predictor of carcass fat content, although specific gravity was not deemed sufficiently accurate for individual carcass determination due to a high RSD (2.98 to 3.2 for % carcass fat) and its reduced accuracy at lower levels of fatness. Comparing carcass weight, specific gravity and dressing percentage, Barton and Kirton (1958) found carcass weight to be the superior predictor of carcass fat content in sheep as it was not subject to as many errors in measurement as was specific gravity and was not influenced by variations in gut fill as was dressing percentage. More recently, Kirton et al. (1985) reported that although the New Zealand lamb grading system was based on HCW, adding HCW

Table 4
High-tech methods of predicting carcass composition of sheep ex vivo

Method	Prediction	Predictors	Precision	Authors
Linear measures	lean meat yield (%)	CW[a]	RSD = 4.72	Harrington and Kempster (1989)
Linear measures		CW + subjective fat	RSD = 2.75	
Optical probe		fat thickness (HP[b])	RSD = 3.15	
Linear measures	carcass fat (%)	CW	RSD = 3.53	Kirton et al. (1984)
Linear measures		CW + GR (ruler)	RSD = 2.16	
Optical probe		CW + GR (HP)	RSD = 2.31	
Linear measures		CW + 'C' (ruler)	RSD = 2.78	
Linear measures		CW + 'J' ruler	RSD = 2.27	
Subjective appraisal	lean meat (kg)	visual fat score	$R^2 = 0.16$, RSD = 44.5	Jones et al. (1992)
Optical probe		GR (HP) warm carcass	$R^2 = 0.53$, RSD = 32.9	
Optical probe		GR (HP) cold carcass	$R^2 = 0.58$, RSD = 31.0	
Linear measures		fat thickness 'C'	$R^2 = 0.54$, RSD = 32.5	
Linear measures		LA[c]	$R^2 = 0.11$, RSD = 45.2	
Linear measures	saleable meat yield (%)	kidney fat (%)	$R^2 = 0.13$, RSD = 2.54	Jones et al. (1993)
Linear measures		GR (ruler), 12/13 rib	$R^2 = 0.55$, RSD = 1.84	
Linear measures		CW + GR (ruler)	$R^2 = 0.55$, RSD = 1.84	
Optical probe		GR, 12/13 rib (HP)	$R^2 = 0.40$, RSD = 2.11	
Combination		GR (ruler) + conformation score (5)	$R^2 = 0.61$, RSD = 1.71	
Optical probe	carcass fat (%)	HP	RSD = 3.07	Kirton et al. (1995)
		Swedish FTC probe	RSD = 3.25	
		Aus-Meat probe	RSD = 3.38[d]	
		Ruakura GR probe	RSD = 3.46	
		GR (ruler)	RSD = 2.97	
Optical probe	GR at 12th rib	Aus-Meat probe	$R^2 = 0.72$ to 0.80 RSD = 1.54 to 2.31	Hopkins et al. (1995)
Ultrasound (speed)	lean meat yield (%)	VUS[e], probe hind limb	RSD = 3.34 to 3.83	Miles et al. (1991)
		VUS, probe shoulder	RSD = 3.36 to 4.11	
Bioelectrical impedance	fat-free lean (kgs)	CW	$R^2 = 0.91$, RSD = 0.50	Jenkins et al. (1988)
		CW, CL[f]/resistance	$R^2 = 0.94$, RSD = 0.42	
TOBEC	lean meat yield (%)	CW	$R^2 = 0.00$, RSD = 1.66	Berg et al. (1994)
		CW + CL	$R^2 = 0.35$, RSD = 1.51	
		CW + CL + TOBEC (best 2)	$R^2 = 0.79$, RSD = 1.18	
Subjective appraisal	saleable meat yield (%)	CW + sex + conformation	$R^2 = 0.04$, RSD = 0.94	Horgan et al. (1995)
VIA		CW + sex + VIA (shape)	$R^2 = 0.16$ RSD = 0.89	

[a] CW, carcass weight.
[b] HP, Hennessy Lamb Probe.
[c] LA, longissimus area.
[d] High RSD due to inexperienced operator.
[e] VUS, velocity of ultrasound.
[f] CL, carcass length.

into a regression after Grade Rule (GR) (Kirton and Johnson, 1979) was in the model did not increase R^2 for any measure of carcass composition by more than 0.03. Similarly, Jones et al. (1993) reported that HCW was not a significant predictor of saleable meat yield in lambs. However, lamb carcasses are routinely valued based on HCW and HCW is available with limited expense. Accordingly, use of carcass composition predictors other that HCW are warranted only if they improve the accuracy of prediction compared to use of HCW alone.

3.3. Linear measurements—GR and others

Many attempts have been made to find rapid, inexpensive and accurate methods of estimating carcass composition from carcass dimensions and fat or muscle depths at various locations on the lamb carcass (Pálsson, 1939; Timon and Bichard, 1965; Kirton and Johnson, 1979; Bennett et al., 1988; Stanford et al., 1997). However, there is not one ideal measurement or set of measurements. Some measurements primarily identify carcass composition differences associated with factors such as sex, breed or weight and are useful in heterogenous populations, although the same measurements may be less useful for discriminating among uniform populations of sheep (Bennett et al., 1988).

Pálsson (1939) was first to identify a number of sheep carcass measurements, some of which remain in use today. These include 'A', the maximum width of the longissimus muscle; 'B', the maximum depth of the longissimus muscle measured at right angles to 'A'; 'C', the depth of backfat over 'B'; 'J' the greatest depth of backfat over the rib. Carcasses must be cut to determine these measurements, unless advanced imaging technologies are employed. Currently, many national ultrasound programs for lamb carcass quality improvement utilize 'C' and/or 'B' at various locations on the carcass (Table 2). Pálsson (1939) also described numerous external carcass dimensions including carcass length 'L', length of the leg 'T' and depth of the leg 'H'. However, Kempster

carcasses by use of a sharpened metal ruler (Kirton et al., 1984) or by a variety of optical probes (Jones et al., 1992; Hopkins et al., 1995; Kirton et al., 1995). GR has been shown to explain 40 to 76% and 44 to 72% of the variation in carcass fat and lean, respectively (Kirton et al., 1985; Jones et al., 1992). Comparing GR to other carcass measurements, Kirton and Johnson (1979) reported that GR was as accurate as 'C' for prediction of carcass fat. The superiority of GR over longissimus muscle area and 'B' for prediction of carcass composition was confirmed by Jones et al. (1992) in accord with Kempster (1981) who concluded that area and depth of the longissimus muscle were of limited utility in prediction of lamb carcass composition.

3.4. Optical probes

Optical probes objectively measure fat and muscle depths and are routinely used to measure GR according to New Zealand export lamb grading regulations (Price, 1995). Optical probes consist of a light-emitting diode which illuminates the meat from under an optical window. Detectors respond to an increase in reflected light when the optical window passes from muscle to fat as the probe is withdrawn from the carcass (Swatland, 1995). As reported by Kirton et al. (1995), probes currently available for prediction of lamb carcass composition include the Hennessy Grading Probe (Hennessy Grading Systems, Auckland, NZ), the AUS-Meat Sheep Probe (SASTEK, Hamilton, Queensland, Australia), the Swedish FTC lamb probe (FTC Sweden, Upplands, Väsby, Sweden) and the Ruakura GR Lamb Probe (Hamilton, NZ). Only the AUS-Meat probe is capable of func-

(1981) concluded that carcass dimensions are poor individual predictors of carcass composition, a finding supported by Bennett et al. (1988). In contrast, use of a number of carcass dimension measurements, although too time-consuming for on-line use, were good predictors of both saleable meat yield ($R^2 = 0.61$, RSD = 1.3%) and % of the leg primal ($R^2 = 0.80$, RSD = 0.6%) in lamb carcasses (Stanford et al., 1997).

GR is a measurement of total tissue thickness between the surface of a lamb carcass and the 12th rib at a point 11 cm from carcass mid-line (Kirton and Johnson, 1979). GR can be measured in intact tioning at chain speeds of nine to 10 carcasses per minute (Cabassi, 1990; Hopkins et al., 1995). On hot carcasses, optical probes have measured GR with accuracy equivalent to a manual GR knife/ruler (Jones et al., 1992; Hopkins et al., 1995). In a comparison of all commercially available optical probes (Kirton et al., 1995), manual GR probes on chilled carcasses were found to account for a higher percentage of variation in carcass fat content (59%) than optical probes on hot carcasses (49%). However, the increased accuracy of manual as compared to optical probes in the study of Kirton et al. (1995) is likely due to improvements in the accuracy of prediction of carcass composition in cold as compared to warm carcasses as noted by Chadwick and Kempster (1983) and Jones et al. (1992).

3.5. Video image analysis

Where time and labour requirements restrict, usually to one, the number of manual or optical probe measurements that can be made under commercial conditions, VIA allows for the automated collection of multiple carcass dimension and colour measurements (Jones et al., 1995). Wood et al. (1991) described VIA as a system capable of objectively measuring carcass conformation, with equipment including a video camera, controlled lighting of the carcass and computer/software necessary to digitize the video image. Although evaluations of VIA for prediction of carcass composition in lambs are limited, early indications as to its utility are promising. In lambs of uniform age and breed, Horgan et al. (1995) reported that VIA shape variables for cold carcasses, carcass weight and sex could predict saleable meat yield with greater accuracy ($R^2 = 0.16$, RSD = 0.89 kg) than carcass weight, sex and the current subjective system used in the UK ($R^2 = 0.04$, RSD = 0.95 kg). For lambs of diverse ages, breeds and sexes, VIA colour and shape variables for warm carcasses with carcass weight increased accuracy of prediction of saleable meat yield ($R^2 = 0.71$, RSD = 14 g kg^{-1}) compared to GR and subjective conformation scores ($R^2 = 0.52$, RSD = 18 g kg^{-1}) used in the present Canadian Classification System for lamb (Stanford et al., 1998). As the VIA equipment

are therefore related to lean mass (Swatland, 1995). Although this technology has been used on live pigs (EMME electronic meat measuring equipment, EMME, Phoenix, AZ), movement of the pigs led to inaccurate estimates of lean content (Forrest et al., 1991). Using TOBEC (Meat Quality, Springfield IL), electrical conductivity measurements and carcass length were able to predict % carcass lean in lambs with a reasonable degree of accuracy ($R^2 = 0.78$, RSD = 1.71%), although carcass position within the scanner, carcass temperature and geometric orientation of the carcass were recognized as sources of error (Berg et al., 1994). As carcass geometry and temperature cannot always be controlled, TOBEC technology is currently most applicable to evaluation of lean content in boxed meat (Eustace and Thornton, 1991) and in pig carcasses (Gu et al., 1992) which have less variation in inter/intramuscular fat content and size/shape than beef or lamb carcasses.

3.7. Bioelectrical impedance analysis (BIA)

Another method dependant on transmission of electric current through a carcass, bioelectrical impedance measures are related to conductor length, cross-sectional area and signal frequency; leading to the hypothesis that a fat lamb should impede the transmission of electrical current to a larger extent than a lean lamb (Berg et al., 1996). Two pairs of transmitter and detector electrodes (21 gauge needles) are located in an anterior to posterior sequence along the full length of the animal's back (Swatland, required for evaluation of lamb carcasses is approximately equal in value to the yearly wages of a livestock grader, VIA shows potential as an objective, accurate, yet cost-effective method of evaluation of lamb carcass composition.

3.6. Total body electrical conductivity

Lean tissue is approximately 20 times more conductive of electricity than fat or bone because of higher concentrations of water and electrolytes (Funk, 1991). Based on this principle, carcasses passed through an electromagnetic coil generate a relative energy absorption curve. Areas under parts of the curve and differences between positions on the curve 1995). Impedance measurements include resistance and reactance which are calculated by transmitting alternating current between the outer two electrodes and measuring the voltage drop between the inner two detector electrodes (Berg and Marchello, 1994). Jenkins et al. (1988) reported that carcass weight and resistance accounted for 93.6% of the variation in fat-free soft tissue, although carcass weight alone accounted for 91.1% of the variability. Accordingly, Berg et al. (1996) concluded that bioelectrical impedance measurements along with body length and live weight did not predict proportional carcass yield with a high degree of accuracy ($R^2 = 0.296$, RSD = 2.53, for % boneless closely trimmed primal cuts). An advantage to bioelectrical impedance is that measurements can be made in live animals as well as carcasses (Berg and Marchello, 1994; Berg et al., 1996), although the invasiveness of the procedure as well as its low precision would not favourably compare to other relatively inexpensive in vivo methods such as ultrasound.

4. Conclusions

As part of the impetus to meet consumer demand and increase consumption of lamb, a change has to be made from subjective to objective evaluation of body and carcass composition. Even though subjective methods are the most rapid and inexpensive techniques for evaluation of body and carcass composition, the sheep industry, if it is to survive in the long-term, can no longer afford the error inherent in subjective predictions. Continuance of traditional, subjective methods for evaluation of body and carcass composition, will not reverse the current decline in lamb consumption compared to other meats.

In live sheep, the high cost/limited access of some of the more precise methods for evaluation of body composition such as X-ray CT or NMR will make ultrasound the method of choice, despite its relatively low precision. In countries where the size of the sheep industry warrants greater capital expenditure by private industry, methods such as X-ray CT, NMR or others are or will likely become available for selection of breeding stock.

References

Allen, P., 1990. New approaches to measuring body composition in live meat animals. In: Wood, J.D., Fisher, A.V. (Eds.), Reducing Fat in Meat Animals. Elsevier, London, UK, pp. 201–247.

Alliston, J.C., 1980. Evaluation of carcass quality in the live animal. In: Haresign, W. (Ed.), Sheep Production. Butterworth, London, UK, pp. 75–96.

Atkins, K.D., Murray, J.I., Gilmour, A.R., Luff, A.L., 1991. Genetic variation in liveweight and ultrasonic fat depth in Australian Poll Dorset sheep. Aust. J. Agric. Res. 42, 629–640.

Barton, R.A., Kirton, A.H., 1958. Carcass weight as an index of carcass components with particular reference to fat. J. Agric. Sci. 50, 331–334.

Beermann, D.H., Robinson, T.F., Hogue, D.E., 1995. Impact of composition manipulation on lean lamb production in the United States. J. Anim. Sci. 73, 2493–2502.

Bennett, G.L., Meyer, H.H., Kirton, A.H., 1988. Effect of average carcass fat concentration on correlations among lamb carcass measurements. Anim. Prod. 47, 369–377.

Berg, E.P., Marchello, M.J., 1994. Bioelectrical impedance analysis for the prediction of fat-free mass in lambs and lamb carcasses. J. Anim. Sci. 72, 322–329.

Berg, E.P., Forrest, J.C., Thomas, D.L., Nusbaum, N., Kauffman, R.G., 1994. Electromagnetic scanning to predict lamb carcass composition. J. Anim. Sci. 72, 1728–1736.

Berg, E.P., Neary, M.K., Forrest, J.C., Thomas, D.L., Kauffman, R.G., 1996. Assessment of lamb carcass composition from live animal measurement of bioelectrical impedance or ultrasonic tissue depths. J. Anim. Sci. 74, 2672–2678.

Brash, L.D., Forgarty, N.M., Gilmour, A.R., Luff, A.F., 1992. Genetic parameters for live weight and ultrasonic fat depth in Australian meat and dual purpose sheep breeds. Aust. J. Agric. Res. 43, 831–841.

Busboom, J.R., Snowder, G.D., Cockett, N.E., 1996. Synopsis of the heavy muscled (Callipyge) lamb symposium. February 15th and 16th, Salt Lake City, UT.

Development of improved methods for carcass composition evaluation is of little utility unless these methods are eventually adopted by the meat industry. Even in New Zealand, the global leader in lamb merchandising, GR measurements are usually made subjectively due to high slaughter-chain speeds. Where wholly subjective methods are currently used, adoption of an objective measurement such as GR would be a first step towards more precise evaluation of lamb carcasses. The next step would be use of methods with higher precision than GR such as VIA, with added advantages of use on-line on warm carcasses, facilitating the early channelling of carcasses to their most profitable and/or consumer-desired endpoints.

Butterfield, R., 1988. New Concepts of Sheep Growth. Griffin Press, Australia, 168 pp.

Cabassi, P., 1990. The prediction of lamb carcass composition from objective measurements of fatness taken at slaughter chain speed with the Aus-Meat sheep probe. Proc. Aust. Soc. Anim. Prod. 18, 164–167.

Cameron, N.D., Bracken, J., 1992. Selection for carcass lean content in a terminal sire breed of sheep. Anim. Prod. 54, 379–388.

Cameron, N.D., Smith, C., 1985. Estimation of carcass leanness in young rams. Anim. Prod. 40, 303–308.

Chadwick, J.P., Kempster, A.J., 1983. The estimation of beef carcass composition from subcutaneous fat measurements taken on the intact side using different probing instruments. J. Agric. Sci. 101, 241–248.

Cunningham, N.L., Carpenter, Z.L., King, G.T., Butler, O.D., Shelton, J.M., 1967. Relationship of linear measurements and certain carcass characteristics to retail value, quality and tenderness of ewe, wether, and ram lambs. J. Anim. Sci. 26, 683–687.

Cuthbertson, A., Croston, D., Jones, D.W., 1984. In vivo estimation of lamb carcass composition and lean tissue growth rate. In: Lister, D. (Ed.), In Vivo Measurement of Body Composition in Meat Animals. Elsevier, London, pp. 163–166.

Dalsky, G.P., Kraemer, W., Zetterlund, A.E., Conroy, B., Fry, A., Judge, J.O., Smith, J., 1990. A comparison of methods to assess body composition. Proc. Am. College of Sports Med. Salt Lake City, UT, May 22–25.

Davis, G.H., Fennessy, P.F., 1996. The organisation of the sheep industry in New Zealand. Proc. Int. Symp. on the Sheep Industry, October 11–12. Sherbrooke, Quebec, pp. 37–46.

Dodd, C.J., Purchas, R.W., Bennett, G.L., 1986. Lean Lamb Selection, A Manual of Procedures. MAF Advisory Services Division, Wellington, New Zealand.

Economic Research Service, 1994. Red Meats Yearbook, US Dept. Agric. Statistical Bulletin 885.

Edwards, J.W., Cannell, R.C., Garrett, R.P., Savell, J.W., Cross, H.R., Longnecker, M.T., 1989. Using ultrasound, linear measurements and live fat thickness estimates to determine the carcass composition of market lambs. J. Anim. Sci. 67, 3322–3330.

Eustace, I.J., Thornton, R.F., 1991. Electromagnetic scanning: evaluation of cartoned meat. Proc. Symp. Electronic Evaluation of Meat in Support of Value-Based Marketing, March 27–28. Purdue Univ., West Lafayette, IN, pp. 113–122.

Fahmy, M.H., Boucher, J.M., Poste, L.M., Gregoire, R., Comeau, J.E., 1992. Feed efficiency, carcass characteristics and sensory quality of lambs with or without prolific ancestry fed diets with different protein supplements. J. Anim. Sci. 70, 1365–1374.

Fisher, A.V., 1990. New approaches to measuring fat in the carcasses of meat animals. In: Wood, J.D., Fisher, A.V. (Eds.), Reducing Fat in Meat Animals. Elsevier, London, UK, pp. 255–335.

Forrest, J.C., 1995. New techniques for estimation of carcass composition. In: Morgan Jones, S.D. (Ed.), Quality and Grading of Carcasses of Meat Animals. CRC Press, Boca Raton, pp. 157–172

Forrest, J.C., Kuei, C.H., Chen, W., Lin, R.S., Schinckel, A.P., and carcass evaluation in pigs NMR measurements. In: Kallweit, E., Henning, M., Groeneveld, E. (Eds.), Application of NMR Techniques on the Body Composition of Live Animals. Elsevier, New York, pp. 137–148.

Gu, Y., Schinckel, A.P., Martin, T.G., Forrest, J.C., Kuei, C.H., Watkins, L.E., 1992. Genotype and treatment biases in estimation of carcass lean of swine. J. Anim. Sci. 70, 1708–1718.

Hamby, P.L., Stouffer, J.R., Smith, S.B., 1986. Muscle metabolism and real-time ultrasound measurement of muscle and subcutaneous adipose tissue growth in lambs fed diets containing a beta-agonist. J. Anim. Sci. 63, 1410–1417.

Harrington, G., Kempster, A.J., 1989. Improving lamb carcass composition to meet modern consumer demand. In: Dyrmundsson, O.R., Thorgeirsson, S. (Eds.), Reproduction, Growth and Nutrition in Sheep. Agricultural Research Inst., Reykjavik, Iceland, pp. 79–90.

Harris, J.J., Savell, J.W., Miller, R.K., Hale, D.S., Griffin, D.B., Beasley, L.C., Cross, H.R., 1990. A national market basket survey for lamb. J. Food Qual. 13, 453–465.

Hopkins, D.L., Anderson, M.A., Morgan, J.E., Hall, D.G., 1995. A probe to measure GR in lamb carcasses at chain speed. Meat Sci. 39, 159–165.

Horgan, G.W., Murphy, S.V., Simm, G., 1995. Automatic assessment of sheep carcasses by image analysis. Anim. Sci. 60, 197–202.

Houghton, P.L., Turlington, L.M., 1992. Application of ultrasound for feeding and finishing animals: a review. J. Anim. Sci. 70, 930–941.

Jenkins, T.G., Leymaster, K.A., Turlington, L.M., 1988. Estimation of fat-free soft tissue in lamb carcasses by use of carcass and resistive impedance measurements. J. Anim. Sci. 66, 2174–2179.

Jensen, N.E., 1990. Performance tests of ram lambs 1990. Report 684, National Institute of Animal Science, Denmark, p. 44.

Jones, S.D.M., 1995. Future directions for carcass assessment. In: Jones, S.D.M. (Ed.), Quality and Grading of Carcasses of Meat Animals. CRC Press, Boca Raton, USA, pp. 215–228.

Jones, S.D.M., Walton, J.S., Wilton, J.W., Szkotnicki, J.E., 1982. The use of urea dilution and ultrasonic backfat thickness to predict the carcass composition of live lambs and cattle. Can. J. Anim. Sci. 69, 641–648.

Walstra, P., Kooper, H., Judge, M.D., 1991. Electromagnetic scanning: carcass evaluation. Proc. Symp. Electronic Evaluation of Meat in Support of Value-Based Marketing, March 27–28. Purdue Univ., West Lafayette, IN, pp. 85–112.
Fortin, A., Shrestha, J.N.B., 1986. In vivo estimation of carcass meat by ultrasound in ram lambs slaughtered at average live weight of 37 kg. Anim. Prod. 43, 469–475.
Funk, R., 1991. Electromagnetic scanning: basis and recent advances in technology. Proc. Symp. Electronic Evaluation of Meat in Support of Value-Based Marketing, March 27–28. Purdue Univ., West Lafayette, IN, pp. 73–84.
Groeneveld, E., Kallweit, E., Henning, M., Pfau, A., 1984. Evaluation of body composition of live animals by X-ray and nuclear magnetic resonance computed tomography. In: Lister, D. (Ed.), In Vivo Measurement of Body Composition in Meat Animals. Elsevier, London, pp. 84–89.
Groeneveld, E., Henning, M., Kallweit, E., 1989. Growth patterns
Jones, S.D.M., Jeremiah, L.E., Tong, A.K.W., Robertson, W.M., Gibson, L.L., 1992. Estimation of lamb carcass composition using an electronic probe, a visual scoring system and carcass measurements. Can. J. Anim. Sci. 72, 237–244.
Jones, S.D.M., Robertson, W.M., Price, M.A., 1993. The assessment of saleable meat yield in lamb carcasses. Int. Congr. Meat Sci. Technol. Calgary, p. 190 (Abstr.).
Jones, S.D.M., Richmond, R.J., Robertson, W.M., 1995. Instrument beef grading. Meat Focus Int. 4, 59–62.
Jopson, N.B., McEwan, J.C., Dodds, K.G., Young, M.J., 1995. Economic benefits of including computed tomography measurements in sheep breeding programmes. Proc. Aust. Assoc. Anim. Breed. Genet. 11, 194–197.
Kempster, A.J., 1980. Carcass quality and its measurement in sheep. In: Haresign, W. (Ed.), Sheep Production. Butterworth, London, UK, pp. 59–74.
Kempster, A.J., 1981. The indirect evaluation of sheep carcass

composition in breeding scheme population studies and experiments. Livest. Prod. Sci. 8, 263–271.
Kempster, A.J., 1984. Cost–benefit analysis of in vivo estimates of body composition in meat animals. In: Lister, D. (Ed.), In Vivo Measurement of Body Composition in Meat Animals. Elsevier, New York, pp. 191–203.
Kempster, A.J., Cuthbertson, A., 1977. A survey of the carcass characteristics of the main types of British lamb. Anim. Prod. 25, 165–179.
Kempster, A.J., Avis, P.R., Cuthbertson, A., Harrington, G., 1976. Prediction of lean content of lamb carcasses of different breed types. J. Agric. Sci. Cambridge 86, 23–34.
Kempster, A.J., Croston, D., Jones, D.W., 1981. Value of conformation as an indicator of sheep carcass lean content within and between breeds. Anim. Prod. 33, 39–49.
Kempster, A.J., Jones, D.W., Wolf, B.T., 1986. A comparison of alternative methods for predicting the carcass composition of crossbred lambs of different breeds and crosses. Meat Sci. 18, 89–110.
Kempster, A.J., Croston, D., Guy, D.R., Jones, D.W., 1987. Growth and carcass characteristics of crossbred lambs by ten sire breeds compared at the same estimated carcass subcutaneous fat proportion. Anim. Prod. 44, 194–201.
Kirton, A.H., Barton, R.A., 1958. Specific gravity as an index of the fat content of mutton carcasses and various joints. New Zealand J. Agric. Res. 1, 633–641.
Kirton, A.H., Johnson, D.L., 1979. Interrelationship between GR and other lamb carcass fatness measurements. Proc. New Zealand Soc. Anim. Prod. 39, 194–201.
Kirton, A.H., Pickering, P.S., 1967. Factors associated with difference in carcass conformation in lambs. New Zealand J. Agric. Res. 1, 633–641.
Kirton, A.H., Woods, E.G., Duganzich, D.M., 1984. Predicting the fatness of lamb carcasses from carcass wall thickness measured by ruler or by a total depth indicator (TDI) probe.
Kirton, A.H., Duganzich, D.M., Feist, C.L., Bennett, G.L., Woods, E.G., 1985. Prediction of lamb carcass composition from GR and carcass weight. Proc. New Zealand Soc. Anim. Prod. 45, 63–65.
Kirton, A.H., Mercer, G.J.K., Duganzich, D.M., 1992. A comparison between subjective and objective (carcass weight plus GR
phorus-31): a new technique for selecting leaner broiler chickens. Poultry Sci. 73, 1633–1641.
Mazess, R.B., Barden, H.S., Olrich, E.R., 1990. Skeletal and body composition effects of anorexia nervosa. Am. J. Clin. Nutr. 52, 438–441.
McClelland, T.H., Bonaiti, B., Taylor, C.S., 1976. Breed differences in body composition of equally mature sheep. Anim. Prod. 23, 281–293.
Miles, C.A., Fursey, G.A.J., Fisher, A.V., Page, S.J., 1991. Estimation of lamb carcass composition from measurements of the speed of ultrasound in the soft tissues of live animals and carcasses. Meat Sci. 30, 245–256.
Mitchell, A.D., Wang, P.C., Rosebrough, R.W., Elsasser, T.H., Schmidt, W.F., 1991. Assessment of body composition of poultry by nuclear magnetic resonance imaging and spectroscopy. Poultry Sci. 70, 2494–2500.
Monin, G., Renou, J.P., 1989. Spectroscopy and meat quality. In: Kallweit, E., Henning, M., Groeneveld, E. (Eds.), Application of NMR Techniques on the Body Composition of Live Animals. Elsevier, New York, pp. 121–133.
Nicol, A.M., Parratt, A.C., 1984. Methods of ranking two-toothed rams for fat-free carcass growth rate. Proc. New Zealand Soc. Anim. Prod. 44, 253–259.
Olesen, I., Husabø, J.O., 1994. Effect of using ultrasonic muscle depth and fat depth on the accuracy of predicted phenotypic and genetic values of carcass traits on live ram lambs. Acta Agric. Scand., Sect. A. Anim. Sci. 44, 65–72.
Orme, L.E., 1963. Estimating composition from linear measurements, live probe and body weight. Ann. New York Acad. Sci. 110, 307–310.
Orme, L.E., Christian, R.E., Bell, T.D., 1962. Live animal and carcass indices for estimating the carcass composition in lambs. J. Anim. Sci. 21, 666, Abstr.
Pálsson, H., 1939. Meat qualities in the sheep with special reference to Scottish breeds and crosses. J. Agric. Sci. 29, 544–625.
Parratt, A.C., Simm, G., 1987. Selection indicies for terminal sires to improve lean meat production from sheep in the United Kingdom. Anim. Prod. 45, 87–96.
Pedersen, O.K., 1989. Current and future projects. In: Kallweit, E., Henning, M., Groeneveld, E. (Eds.), Application of NMR Techniques on the Body Composition of Live Animals. Else-

or the Hennessy Grading Probe) methods for classifying lamb carcasses. Proc. New Zealand Soc. Anim. Prod. 52, 41–44.
Kirton, A.H., Mercer, G.J.K., Duganzich, D.M., Uljee, A.E., 1995. Use of electronic probes for classifying lamb carcasses. Meat Sci. 39, 167–176.
Lewis, R.M., Simm, G., Warkup, C.C., 1993. Enjoying the taste of lamb. Meat Focus Int. 2, 393–395.
Leymaster, K.A., Jenkins, T.G., 1993. Comparison of Texel- and Suffolk-sired crossbred lambs for survival, growth and compositional traits. J. Anim. Sci. 71, 859–869.
Leymaster, K.A., Mersmann, H.J., Jenkins, T.G., 1985. Prediction of the chemical composition of sheep by use of ultrasound. J. Anim. Sci. 61, 165–172.
Liu, Z., Lirette, A., Fairfull, R.W., McBride, B.W., 1994. Embryonic adenosine triphosphate: phosphate diesters ratios obtained with in vivo nuclear magnetic resonance spectroscopy (Phosvier, New York, p. 159.
Price, M.A., 1995. Development of carcass grading and classification systems. In: Morgan Jones, S.D. (Ed.), Quality and Grading of Carcasses of Meat Animals. CRC Press, Boca Raton, pp. 173–199.
Puntilla, M.L., 1986. Experiences using ultrasound scanner for evaluation of body composition in young Finnsheep rams. The 37th Ann. Meeting of EEAP, Budapest.
Puntilla, M.L., Nylander, A., 1993. Possibilities to predict body composition from live animals in pure and crossbred Finnsheep. The 43rd Ann. Meeting of the EAAP.
Purchas, R.W., Beach, A.D., 1981. Between operator repeatability of fat depth measurements made on live sheep and lambs with an ultrasonic probe. New Zealand J. Exp. Agric. 9, 213–220.
Robelin, J., 1984. Prediction of body composition in vivo by dilution technique. In: Lister, D. (Ed.), In Vivo Measurement of Body Composition in Meat Animals. Elsevier, New York, pp. 106–112.
Robelin, J., Theriez, M., 1981. Relationship between water and lipid content of empty body weight in growing cattle and sheep. Reprod. Nutr. Dev. 21, 335–353.
Ross, R., Leger, L., Guardo, R., de Guise, J., Pike, B.G., de Guise, J., 1991. Adipose tissue volume measured by magnetic resonance imaging and computerized tomography in rats. J. Appl. Phys. 70, 2164–2172.
Russel, A.J.F., 1995. Ultrasonography and body composition in sheep. In: Goddard, P.J. (Ed.), Veterinary Ultrasonography. CAB International, Wallingford, UK, pp. 315–324.
Sehested, E., 1984. Computerized tomography of sheep. In: Lister, D. (Ed.), In Vivo Measurement of Body Composition in Meat Animals. Elsevier, New York, pp. 69–74.
Simm, G., 1983. The use of ultrasound to predict the carcass composition of live cattle—a review. Anim. Breed. Abstr. 51, 853–875.
Simm, G., 1992. Selection for lean meat production in sheep. In: Speedy, A.W. (Ed.), Progress in Sheep and Goat Research. CAB International, Wallingford, UK, pp. 193–215.
Simm, G., Young, M.J., Beatson, P.R., 1987. An economic selection index for lean meat production in New Zealand sheep. Anim. Prod. 45, 307–316.
Simm, G., Dingwall, W.S., Lewis, R.M., 1993. Genetic improvement of meat production. Proc. Third Int. Sheep Vet. Conf. Edinburgh, June 27–July 1.
Standal, N., 1984. Establishment of a CT facility for farm animals. In: Lister, D. (Ed.), In Vivo Measurement of Body Composition in Meat Animals. Elsevier, New York, pp. 43–51.
Stanford, K., Clark, I., Jones, S.D.M., 1995a. Use of ultrasound in prediction of carcass characteristics in lambs. Can. J. Anim. Sci. 75, 185–189.
Stanford, K., McAllister, T.A., MacDougall, M., Bailey, D.R.C., 1995b. Use of ultrasound for prediction of carcass characteristics in Alpine goats. Small Rumin. Res. 15, 195–201.
Stanford, K., Woloschuk, C.M., McClelland, L.A., Jones, S.D.M., Price, M.A., 1997. Comparison of objective external carcass measurements and subjective conformation scores for prediction of lamb carcass quality. Can. J. Anim. Sci. 77, 217–223.
Stanford, K., Richmond, R.J., Jones, S.D.M., Robertson, W.M., Price, M.A., 1998. Video image analysis for classification of lamb carcasses. Anim. Sci., submitted.
Statistics Canada, 1995. Livestock Statistics. Publication No. 23-603E.
Stouffer, J.R., 1988. Ultrasonics for live lamb and carcass evaluation. Methods to Improve the Lean Yield of Lamb. NC-III Technical Committee for Increased Efficiency of Sheep Production Symposium, Denver, CO, pp. 26–30.
Streitz, E., Baulain, U., Kallweit, E., 1995. Investigation of body composition of growing lambs by means of magnetic resonance imaging. Zuchtungskunde 67, 392–403.
Swatland, H.J., 1995. On-Line Evaluation of Meat. Technomic, Lancaster, PA, p. 347.
Taylor, C.S., 1965. A relation between mature body weight and time taken to mature in mammals. Anim. Prod. 7, 203–220.
Thonney, M.L., Taylor, C.S., Murray, J.I., McClelland, T.H., 1987. Breed and sex differences in equally mature sheep and goats: II. Body components at slaughter. Anim. Prod. 45, 261–276.
Timon, V.M., Bichard, M., 1965. Quantitative estimates of lamb carcass composition: III. Carcass measurements and a comparison of the predictive efficiency of sample joint composition, carcass specific gravity determinations and carcass measurements. Anim. Prod. 7, 189–201.
Vangen, O., 1989. X-Ray CT for body composition. In: Kallweit, E., Henning, M., Groeneveld, E. (Eds.), Application of NMR Techniques on the Body Composition of Live Animals. Elsevier, New York, pp. 91–99.
Wang, J., Heymsfield, S.B., Aulet, M., Thorton, J.C., Pierson, R.N., 1989. Body fat from body density: underwater weighing vs. dual-photon aborptiometry. Am. J. Phys. 256, E829–E834.
Ward, C.E., Trent, A., Hildebrand, J.L., 1995. Consumer perception of lamb compared with other meats. Sheep Goat Res. J. 11 (2), 64–70.
Wells, P.N.T., 1984. Introduction to imaging technology. In: Lister, D. (Ed.), In Vivo Measurement of Body Composition in Meat Animals. Elsevier, New York, pp. 25–35.
Wolf, B.T., Smith, C., 1983. Selection for carcass quality. In: Haresign, W. (Ed.), Sheep Production. Butterworth, London, pp. 493–514.
Wood, J.D., Newman, P.B., Miles, C.A., Fisher, A.V., 1991. Video image analysis: comparisons with other novel techniques for carcass assessment. Proceedings of the Symposium Electronic Evaluation of Meat in Support of Value-Based Marketing, March 27-28. Purdue University, IN, pp. 145–169.