METHODS OF INCORPORATING MARKET SIGNALS AND MEASURES OF CARCASS SHAPE INTO GENETIC SELECTION INDICES FOR TERMINAL SIRE BREEDS OF SHEEP

HUW EUROS JONES

A thesis submitted in fulfilment
of the requirements for the degree
of Doctor of Philosophy

THE UNIVERSITY OF EDINBURGH

2002

Abstract

The price obtained for lamb carcass has a direct effect on the profitability of a sheep system and hence market requirements should be directly reflected in the objective of any breeding program for sheep. Despite their importance, market requirements are often assumed rather than known and market prices are not always used to form the objective. Moreover, although carcass shape affects commercial value, it has not been directly considered in current breeding programs. The aims of this study were (i) to develop methods of incorporating measures of carcass shape into selection programs (ii) to establish the requirements of the current and likely future markets for lamb and (iii) to develop methods for calculating economic values for selection objectives.

Carcass shape is quantified commercially using a conformation score. However, the assessment is subjective and confounded with fatness and hence an objective assessment of muscularity is undoubtedly preferable. Five measures of muscularity (three for the *M. longissimus thoracis et lumborum* (LTL) muscle, one for the hind leg and one for the whole carcass) were derived from carcass dissection data for 100 Suffolk, 40 Texel and 20 Charollais lambs. Changes with growth, relationships with tissue composition and lean distribution, as well as the relationships between the different muscularity measures were investigated. Higher muscularity at a given live weight was generally associated with higher lean to bone ratio and carcass lean content. Associations with fat content were either non-significant or negative. Relationships with lean distribution were also non-significant. Correlations between muscularity measures in different regions were low in Suffolk and Charollais lambs but higher for the Texels. This suggested that more than one measure would be required, particularly for Suffolk and Charollais lambs, if the muscularity of a carcass was to be described effectively.

The feasibility of developing live animal measurements of muscularity using measurements taken on X-ray Computer Tomography (CT) scans was investigated using data collected on the lambs described above. Measures for the LTL and the whole carcass were obtained using measurements of components similar to those used to derive the carcass measures. For the hind leg, indirect measures were developed using the ratio of two measurements taken on scans through the hind leg. Correlations between the carcass and corresponding CT measure ranged from around 0.6 for the hind leg and the whole carcass measure to around 0.35 for the LTL measures. The results indicated that the CT measures of muscularity derived provided good *in vivo* predictors of muscularity in the hind leg and through the whole carcass, but were comparatively less useful for predicting carcass LTL muscularity.

Genetic parameters for each of the CT measures of muscularity were estimated using data for approximately 950 lambs from each of the three breeds. Heritability estimates for each of the CT measures of muscularity were moderate to high (0.21-0.57) and coefficients of variation were in the range of 5–10%. Genetic correlations with lean weight, fat weight, scan live weight and ultrasound measured fat depth were generally not significantly different from zero in each breed. Genetic correlations with ultrasound measured muscle depth were positive. Given these

parameters, improvement in muscularity at an age could be achieved through selection, whilst continuing to increase the weight of lean and reduce the weight of fat. The latter are common goals for many current selection programs.

A case study was conducted to establish current and likely future markets for lamb. Questionnaires were sent to the largest lamb retailers and abattoirs in the UK. Current markets generally required a carcass of weight 16-21kg, conformation E-R and fat score 2 or 3L. The forecast for future requirements was not clear, although both abattoirs and retailers desired carcasses that fitted a narrower range of quality specifications and foresaw increasing demand for heavier carcasses (above 21kg) to supply bone-less products. This suggests that a two-market scenario, one for medium sized lambs to supply bone-in cuts, and the other for heavier, lean carcasses to supply bone-less lamb, could develop in the long term.

A bio-economic model was developed to calculate the economic value of one unit increase in the weight of lean and fat at 150 days of age. The model was designed to account for (i) seasonal fluctuations in market prices, (ii) different drafting criteria, (iii) feed requirements of individual lambs and (iv) seasonal variation in feed costs. Data collected on Suffolk cross mule, castrated male and female lambs (collected in a separate trial) was used to adapt the model to represent likely commercial conditions. The commercial value of carcasses of varying quality at different times of the year were derived using the price grid obtained from the questionnaire study (Chapter 5), and historical national weekly average prices from 1995 to 2000. The economic values varied depending on which year was used to provide market prices. Across-sex economic values for lean weight ranged from 1.10 to 1.90 £/kg and for fat from –1.93 to 0.13 £/kg. These values are specific to the scenario considered, however the model could also be adapted to obtain values for a range of other conditions.

The results presented in this thesis do not provide all the information required to develop the most suitable selection indices for use in terminal sire breeds in the UK. For example, uncertainty still exists over the requirements of future markets for lambs. Nevertheless sufficient information is provided to allow the development of a range of possible selection indices that include measures of carcass shape amongst the selection objectives. Once developed these indices could be presented to representatives from different sectors of industry and decisions made, regarding the most appropriate indices to use, following discussions with them. The results of the case study presented in this thesis would also provide a very useful base from which to develop these discussions.

Declaration

I declare that this thesis is my own composition. I wrote the manuscript and all analyses were conducted by myself, unless stated otherwise.

Huw E. Jones

August 2002

I wish to state that:

The variance covariance estimates between scan live weight, ultrasound fat and muscle depth measurements and lean and fat weight predictions, for each of the three breeds, that were used in Chapter 4, were obtained from previous analyses conducted by Dr Ron Lewis.

The programme for the bio-economic model described in Chapter 6 was developed around a smaller programme written and made available to me by Dr Peter Amer. The paper in which his original model is described in cited in that Chapter.

Publications

Refereed publications

Jones, H.E., Lewis, R.M., Young, M.J., Wolf, B.T. and Warkup, C.C. 2002 Changes in muscularity with growth, and its relationship with other carcass traits in three terminal sire breeds of sheep. Animal Science 74: 265-275 (based on Chapter 2)

Jones, H.E., Lewis, R.M., Young, M.J. and Wolf, B.T. 2002 The use of X-ray Computer Tomography for measuring the muscularity of live sheep. Animal Science 75: 387-399 (based on Chapter 3)

Jones, H.E., Lewis, R.M. and Warkup, C.C. 2002 Market requirements for lamb. British Food Journal (in press; based on Chapter 5)

Conference papers

Jones, H.E., Lewis, R.M., Young, M.J., Wolf, B.T. and Warkup, C.C. 2001 Relationships between muscularity indices and carcass traits in Suffolk, Charollais and Texel lambs. Proceedings of the British Society of Animal Science 2001 pp 42

Jones, H.E., Lewis, R.M., Young, M.J. and G. Simm 2002 Incorporating CT measures of composition and muscularity into selection programs for Suffolk sheep. Proceedings of the 7th World Congress on Genetics Applied to Livestock Production Vol 29: 461-464

Acknowledgements

Firstly I would like to thank by supervisors Dr Ron Lewis, Professor W.G. Hill and Chris Warkup. I am very grateful Ron Lewis for his excellent advice, useful discussions and for always having the time to see me. Prof. Hill is thanked for his guidance and useful comments. To this day I am still amazed by the speed with which his comments on various drafts of chapters and papers were returned. Chris Warkup is also thanked for his help particularly during my time at the MLC.

In addition to my main supervisors, I am also indebted to many other colleges at SAC that helped me during this study period, in particular Dr Mark Young, Gerry Emmans and Professor Geoff Simm. Many a useful hour was spent with Mark discussing the merits of various measures of muscularity and how best to use the CT scanning information, and similarly with Gerry discussing the merits of the biological model (Chapter 6). Geoff was always willing to give his advice when approached and to give his comments on various drafts of papers and reports that were produced. I would also like to thank Kirsty McLean, Neil Robson, Jim Fraser, Graham Hunter and Elisabeth Goodenough at the CT unit, not only for scanning the lambs, but also for taking the majority of the linear dimensions on CT scans that were used in the study described in Chapter 4.

Outwith the SAC, I would like to thank Ian White and Dave Allcroft for their advice on various statistical issues and also Peter Amer, without whom the biological model (Chapter 6) would not have been developed. Peter is thanked both for giving me a copy of his own programme and for introducing me to programming in Mathcad.

For a few months during my study period I was based at the MLC in Milton Keynes. I wish to thank all those that made my stay there both enjoyable and useful. Duncan Sinclair in particular is thanked for his hospitality and for showing me the social side of Milton Keynes. Heather Leask is thanked for always making sure I was paid on time and both Radha Ray and Lindsey Tapp are thanked for teaching me that the quickest way to get information is to first talk to the secretaries.

I am very grateful to the Biotechnology and Biological Sciences Research Council (BBSRC) and the Meat and Livestock Commission for jointly funding my CASE studentship.

On a less formal note I would like to express my gratitude to friends at SAC, the Univesity and Roslin Institute; special thanks goes to Sarah, Eileen, Jenny, Mike, Sara, Tim, Jos, Santiago, Emma, Hannah, Spiridoula, Ian, Francis, Daniel and Grant. Grant is particularly thanked for introducing me to Boroughmuir rugby club, where many an enjoyable (and often painful) time was spent over the last few years.

Special mention and thanks should go to Carolyn for her support and patience during the later years of this study.

Hoffwn ddiolch yn fawr iawn i fy nheulu i gyd (Dad, Mam, Einir, Guto, Sion, y ddwy nain a taid Minffordd) am fod yn gefn i mi ar hyd y blynyddoedd. Er fy mod

wedi symud gryn bellter o adref, ni fuasai ddim o'r gwaith hwn wedi cael ei wneud heb eu cefnogaeth.

Yn ola, hoffwn roi gair o gofion am Taid Pennant, piti na gafodd fyw i weld y gradd hwn yn cael ei orffen.

Table of Contents

Chapter 1

General Introduction

1.1 Introduction

Maximizing profit is an important aim for commercial sheep producers. For the majority of production systems the price obtained for a lamb carcass has a large effect on its profitability. When the carcasses produced do not meet market requirements the prices obtained are lower and this has an adverse effect on the level of profit achieved.

In the UK, the value of a lamb carcass is determined by its weight and subjective visual assessments of its fatness and conformation. The intent of the latter assessment is to provide an indication of carcass shape. Fatness is scored on a seven-class scale and conformation on a five class MLC scale (EUROP). Carcasses of lower fatness and higher conformation are considered better quality and hence receive premium payments over other lower quality carcasses of the same weight. Currently less than half of the carcasses produced throughout the country are classified within the fatness and conformation classes that are desired by most markets, the majority being either too fat or have poor conformation (MLC, 2000). Moreover, a number of the carcasses produced have low weights, which also results in lower returns for the producer.

Numerous options are available to effect improvements, such as changes in management (i.e. feed, ceasing castration), pharmacological methods (Bass *et al.*, 1990, review) and genetic improvement of parents through breed substitution or within breed improvement (Simm, 1992). Of these, within-breed genetic improvement through selection has emerged as one of the preferred methods since it is cost effective and permanent.

The structure of the British sheep industry is such that most lambs (73%) slaughtered in the UK are sired by rams from a relatively small number of specialised terminal sire meat breeds (Maniatis and Pollot, 1998). Genetic improvement of these breeds could therefore have a big effect on the quality of carcasses that are produced. Selection programmes have been underway within many of these breeds for some years. With the development of Sire Referencing Schemes (SRS), which allow comparison of animal performance between genetically linked yet separate flocks, rapid improvements in lean composition of pure bred animals have been and continue to be made on a national scale (MLC, 2000).

Within the SRS's selection has been based on a lean growth index developed by Simm and Dingwall (1989). An index is a method of obtaining a single value or score that can be used for selection, which reflects an animal's genetic merit for a number of different attributes that are considered important (objective measures). The overall selection objective constitutes each of these attributes weighted by its relative economic importance. Ideally selection would be based on performance records for the objective measures, however it is not always possible to measure them directly. Therefore, when using an index, selection is based on a weighted combination of measurements that can be taken on live animals (selection criteria), which are objective measures themselves or have a strong relationship with them. These criteria are weighted optimally so that the selection responses achieved reflect the overall objective.

The objective measures for the lean growth index are lean and fat weights at a fixed age of 150 days. Lean and fat weights were chosen since they were considered likely to be the major determinants of profitability in the future, and a fixed age of 150 days was chosen largely for operational reasons (Simm and Dingwall, 1989; G. Simm personal communication). The relative economic weights used for the objective measures are +3 and –1 respectively. These were chosen, following an investigation using essentially a desired gains approach, so as to achieve near maximum selection responses in lean weight whilst minimizing increases in fat weight (Simm and Dingwall, 1989). Since lean and fat weights are difficult to measure directly on live animals, selection using the lean growth index is based on measurements of live weight and ultrasound measured muscle and fat depths.

Use of the lean growth index has been shown to be successful in producing rams that can sire crossbred progeny with improved carcass quality. Lewis *et al.* (1996) and Simm and Murphy (1996) reported that commercial lambs sired by rams selected for a high lean growth index score were younger, had a greater weight of lean and a higher saleable meat yield at the same carcass weights in comparison to lambs sired by unselected rams.

Despite these results, uptake of the lean growth index by the sheep industry has been slow, with only an estimated 16% of terminal sires used in commercial flocks originating from performance recorded flocks (Simm *et al.*, 1997). This is likely due to a number of factors, which include concerns about the index itself, namely:

(i) that it does not directly consider carcass shape (conformation), and

(ii) that it does not fully address the price signals of the current lamb market.

Re-developing the index and addressing these concerns specifically may increase the benefits achieved from index selection and importantly stimulate greater uptake of the technology.

Most of the information required to develop relevant selection indices is not available at present. For example, limited information is available about the inheritance of useful measures of carcass shape. Moreover, methods of measuring carcass shape *in vivo* are not available, nor are economic values for lean and fat weights at a fixed age that are relevant to UK production systems, which could be used to develop economic indices. This would be one way of addressing the price signals of the current markets for lamb directly. The overall aim of the studies described in this thesis was to obtain the information required so that development of new selection indices, that address the concerns outlined above, could be done.

1.2 Carcass shape and muscularity

One of the main reasons for conformation not being directly considered as part of the lean growth index was that methods of making assessments on the live animal have not been available (G. Simm personal communication). Even so, considerable uncertainty also exists as to how much emphasis should be placed on conformation in breeding schemes for sheep, given that numerous studies have identified an undesirable positive association between the carcass assessment and fatness (Jackson and Mansour, 1974; Kempster *et al.*, 1981; Abdullah *et al.*, 1993; Purchas and

Wilkin, 1995; Lewis *et al.*, 1996; Jones *et al.*, 1999). Direct incorporation of conformation into the selection objective for breeding schemes would be expected to reduce the selection response currently being achieved in improving composition.

Information regarding the actual commercial importance of conformation can also be confusing. Abattoirs generally financially penalise carcasses in the lower conformation classes (O and P) and pay increasingly higher premiums for carcasses classified in classes towards the upper end of the range (U and E). This in turn directly influences breeders and producers perception of its importance. However, Kilkenny (1990), indicated that conformation score was seen as the least important aspect of carcass specification by domestic retail customers, which collectively form the largest market for UK lambs (MLC, 1999). Undoubtedly, carcass shape should be considered in selection programmes for terminal sire breeds of sheep. However, care should be taken not to overestimate its relative importance at the expense of improvements in other carcass measures.

An alternative measure of carcass shape

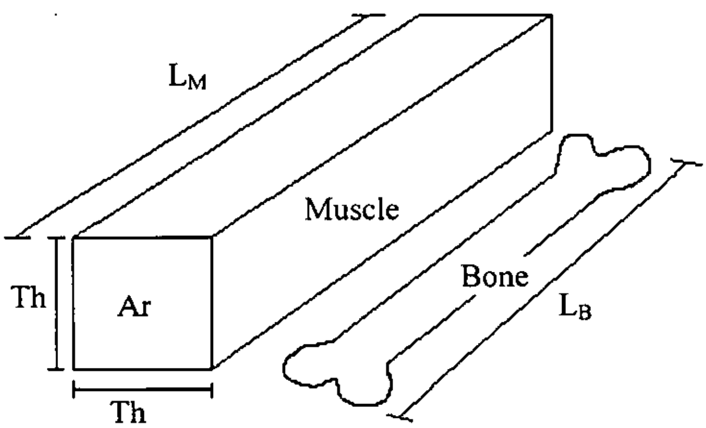
The positive confounding with fatness is a concern when assessing carcass shape using the conformation score. In view of this, an assessment of muscularity has been proposed as a preferable alternative for quantifying carcass shape (Kirton *et al.*, 1983; Purchas *et al.*, 1991; Purchas and Wilkin, 1995). When assessing muscularity the focus is on the shape of muscles and thus the assessment is not directly affected by fatness. Quantifying the shape of muscles directly is difficult since measurements of their actual length and thickness are not easy to obtain. De Boer *et al.* (1974) defined muscularity as the depth of muscle relative to dimensions of the skeleton. Whilst not directly incorporating a measure of muscle length this definition is useful since a strong association must exist between the length of muscles and that of closely associated bones, given that each muscle has specific origin and insertion points on the skeleton (Young, 1988). Using this definition also has practical advantages in that once a carcass is dissected the lengths of individual bones can be measured relatively easily in contrast to individual muscles.

The De Boer *et al.* (1974) definition lends itself to the development of objective measures of muscularity. Despite this, early development of such measures was slow and likely hindered by problems obtaining repeatable measures of muscle thickness in most regions of the carcass. This problem was largely overcome with the proposal of Purchas *et al.* (1991) that the average thickness of a muscle or group of muscles could be approximated using knowledge of their weight and the length of a closely associated bone. A dimensionless measure of muscularity was then obtained by dividing this estimated thickness by the bone's length. The dimensionless property is important, since, by being independent of scale effects, the measures of muscularity derived can be compared between animals of different sizes. Diagrammatic representation of the Purchas *et al.* (1991) approach is given in Figure 1.

The Purchas *et al.*, (1991) approach has been used in all subsequent studies of muscularity, and measures have been derived for a number of different regions of the carcass. These include the proximal and distal hind leg, proximal and distal forelimb and for muscles surrounding the spine (Waldron *et al.*, 1992b; Ward *et al.*, 1992; Abdullah *et al.*, 1993; Hopkins, 1996; Holloway *et al.*, 1994; Purchas and Wilkin, 1995; Hopkins *et al.*, 1997; Abdullah *et al.*, 1998; Wolf *et al.*, 2001). Despite this considerable volume of research, standard objective methods for measuring the muscularity of the carcass are not yet available. Further investigations are required for these to be obtained.

In all previous studies relationships between muscularity measures in different parts of the carcass have not been investigated. Lack of these investigations may partly be a consequence of a proposal made by Purchas *et al.* (1991) that any skeletal dimensions and muscles weights, even from different regions of the carcass, could be used to derive a useful measure of muscularity. This effectively presumes a strong relationship between different skeletal dimensions, the thickness of different muscles and thus muscularity within different regions of the carcass. The Purchas *et al.* (1991) proposal was based on a conclusion, drawn from the review of Butterfield (1988), that little variation exists in the way either muscle or bone is distributed throughout the carcass. Such a general conclusion can only be inferred indirectly from that reported by Butterfield (1988).

Figure 1 Diagrammatic representation of the Purchas *et al.* (1991) approach to obtain approximate measures of muscle thickness and muscularity



if density = 1, Volume ≈ Weight

assuming $L_M = L_B$ then,

Cross-section area (Ar) = Muscle weight / L_B

Muscle thickness (Th) = $\sqrt{Ar}$

= $\sqrt{(\text{Muscle weight} / L_B)}$

Given that (De Boer *et al.*, 1974):

Muscularity = muscle thickness / bone length

Then following from above:

Muscularity = $(\sqrt{(\text{Muscle weight} / L_B)}) / L_B$

The relationships between lengths of different bones in the sheep have generally not been directly investigated in previous studies. However, some bone lengths and other skeletal dimensions have been included in comprehensive genetic analyses (Waldron *et al.,* 1992a; Thorsteinsson and Bjornsson, 1982). Unfortunately, although the analyses were done, all parameter estimates were not reported in these studies. Waldron *et al.* (1992a) stated that genetic correlations between the length of individual long bones in the fore and hind legs (femur, tibia and radius) were high, as were their correlations with the length of the tibia and tarsals [T of Palsson, (1939)] (>0.83), but individual correlations were not presented. Estimates for the genetic and phenotypic correlations between the length T and carcass length (length from the gambrel to the bottom of the neck; Moxham and Brownlie, 1976) were lower, being 0.76 and 0.70 respectively. Those between the length T and side length, which is more closely related to the length of the spine, were not shown but stated to be lower than those for carcass length. Thorsteinsson and Bjornsson (1982) also reported moderate correlations between the measurement of T and body length [K of Palsson, (1939)], genetic and phenotypic estimates being 0.61 and 0.38 respectively. The above results justify the assumption of a strong relationship between the lengths of long bones in the limbs, such that the length of any bone in the leg could be used in a general index for that region. However, the relationship between limb bone length and that of the spine seems weaker, such that they should not be used interchangeably in an index of muscularity as proposed by Purchas *et al.* (1991).

Little information is available in the literature regarding the relationships between muscle thickness in different regions of the carcass. Whilst the amount of variation in the distribution of lean in different regions of the carcass is relatively small, it is important to acknowledge that some variation does exist (Wolf, 1982). Furthermore, Wolf (1982) showed that a small negative phenotypic correlation (-0.16) was estimated between the proportion of total carcass lean weight in the hind leg and shoulder. Given that a high correlation exists between the length of individual long bones in the limbs (Waldron, 1992a), this suggest that correlations between the thickness of muscles in these joints is not high.

When considered together, this information indicates that a strong relationship between muscularity in different regions of the carcass cannot be presumed, and further work is therefore required to verify the strength of these relationships.

The main focus of previous studies of muscularity has been the relationships between the derived measures and assessments of conformation (Abdullah *et al.*, 1993; Hopkins, 1996; Purchas and Wilkin, 1995; Hopkins *et al.*, 1997; Wolf *et al.*, 2001). Only limited information is available on the development of muscularity with growth and the relationships with carcass composition, and none of these investigations have used lambs from the main breeds being used in the UK (Abdullah *et al.*, 1998; Waldron *et al.*, 1992b). Moreover, no information is available about the relationship between muscularity and the distribution of lean through the carcass, which has commercially importance. Obtaining this information is not only important to improve our understanding of carcass muscularity, but is also important (as will be discussed further in Chapter 2) to aid decisions regarding the most appropriate measures to use for quantifying the muscularity of the whole carcass.

1.3 Live animal assessments of muscularity

Even if useful standard methods of assessing the muscularity for the carcass were developed, methods of assessing live animals will still be needed if muscularity measures were to be incorporated successfully into selection programs.

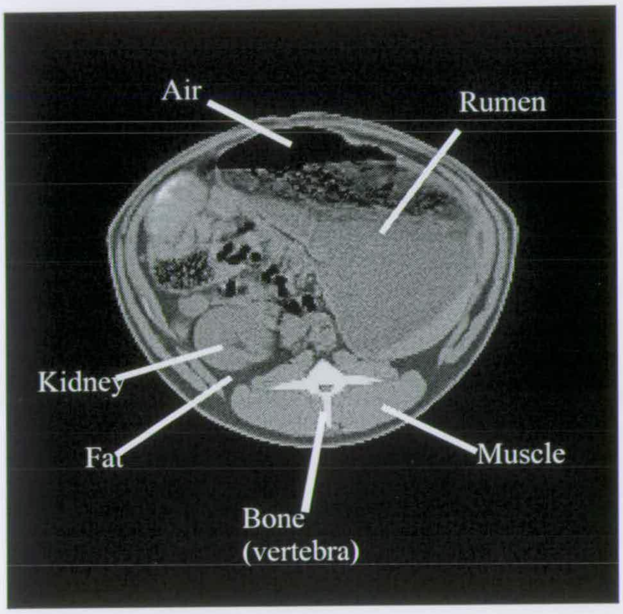
Until recently methods for *in vivo* measurement of carcass components in sheep have been limited mainly to ultrasonic techniques. Although useful for obtaining good *in vivo* measurements of *longissimus thoracis et lumborum* (LTL) depth, the technique is less useful for obtaining measurements of other LTL dimensions and those of other muscles through the body (McEwan *et al.*, 1989; Edwards *et al.*, 1989; Hopkins *et al.*, 1993; Binnie *et al.*, 1995). Moreover it does not lend itself easily to the measurement of bone lengths.

More recently X-ray Computer Tomography (CT) scanners have become available in some countries, including the UK, for scanning small and medium sized animals (Sehested, 1984; Young *et al.*, 1987; Young *et al.*, 1999). This technique provides the means to obtain detailed images of sections through a body. Its use may allow accurate measurements of different muscle dimensions and bone lengths to be obtained that could be used to develop useful *in vivo* measures of muscularity.

X-ray CT is a technique initially developed for non-invasive whole-body scanning in human medicine. It is based on the principle that the absorption of X-rays differs between body tissues depending on their density. This property is used to produce two–dimensional images of sections through the body in which tissues can be clearly differentiated. These cross-sectional images are obtained by transmitting a low dose of X-rays through a thin slice of the body from a source that rotates around it. Rotating detectors that are positioned in line with the source on the opposite side of the body, continually measure the degree to which the X-rays have been attenuated.

The information collected as the source and detectors rotate around the body is used to determine the degree of X-ray attenuation at each point in the scan plane. The scan plane is regarded as being composed of a large number of elements (pixels), and each pixel is assigned a 'CT value' depending on the degree of attenuation that occurs at that corresponding point. Each tissue has a characteristic range of CT values. By assigning different shades of grey to specific ranges of CT values, images in which tissues are clearly differentiated can be produced. An example of a cross-sectional image through the body of a sheep is shown in Figure 2. Further details of how the images are produced, and about the interpretation of images are given by Simm (1987) and Davies *et al.* (1987), respectively.

Figure 2 An example of a cross-sectional CT image through the body of a sheep at the position of the second lumbar vertebra



X-ray CT technology was first used for scanning livestock (pigs, sheep and goats) in Norway (Allen and Vangen, 1984; Sehested, 1984; Sorensen, 1984). Since then CT units for livestock scanning have been established in New Zealand, Australia and the UK. In all previous studies using the technology the focus has been on its use for predicting carcass composition, and very good results have been reported (Allen and Vangen, 1984; Sehested, 1984; Sorensen, 1984; Young *et al*, 1987; Young *et al.*, 1996; Young *et al.*, 1999). As yet no investigation of the technology's value for obtaining linear measurements of muscle and bone dimensions in the body has been conducted.

1.4 Relative economic values

When using a desired gains approach to develop a selection index, relative economic weights for objective measures are chosen so that selection responses in one or more traits equal predetermined values. The approach can be used to weight all traits in the objective, as was done in the lean growth index (Simm and Dingwall, 1989), or used to specify relative or absolute changes in some traits while maximising the overall economic response in the remaining traits (Brascamp, 1984).

The advantage of using desired gains is that economic values are not required, thus it is particularly useful where meaningful economic values are difficult to calculate, as was the case when developing the lean growth index (Simm and Dingwall, 1989). Nevertheless, Gibson and Kennedy (1990) argued that use of the desired gains approach would likely compromise the economic efficiency of index selection, with a high risk of economic progress (which is the overall aim of most selection programmes for livestock) substantially below maximum. Consequently, relative weights based on actual economic values would be preferred wherever reliable economic values can be derived. No attempt has been made previously to ascertain whether reliable economic values can be derived for lean and fat weight at a fixed age under UK conditions. If such values could be obtained, their use in the development of new selection indices would be preferable to the continued use of the desired gains approach.

Methods of calculating economic values

Before economic values (EV) can be calculated two important decisions need to be made. The first is what criterion is to be used for economic evaluation, and the second is from whose perspective are the EVs to be calculated?

Three criteria for economic evaluations have been proposed in the past: profit, economic efficiency and return on investment. Profit (P) is defined as $P = R\text{-}C$, economic efficiency (E) as $E = R/C$ and return on investment (I_w) as $I_w = (R\text{-}C)/C_w$, where R is the returns for a unit of product, C is the production cost of one unit and C_w is investment (Weller, 1994). The most commonly used criterion, and the one advocated here, is profit. This is because maximization of profit will be the primary aim of most breeders participating in a breeding programme. Use of economic efficiency does have the advantage of being unit-less and is less affected by the choice of viewpoint (see later). Moreover, improving efficiency may be the most desirable long-term objective. Nevertheless, it is less likely to be of primary importance to a breeder that is concerned with staying in business and maximising his returns in the short term (James, 1982). Return on investment is most relevant for new investors and is difficult to justify for use in long-term breeding programmes, such as those for most livestock species (Weller, 1994).

The second decision that needs to be made is from which viewpoint should the economic values be calculated. Moav (1973) suggested that economic values could be calculated from one of three viewpoints: national, individual producer and new investor. It was also shown that economic values were proportionally different when calculated from each of the different viewpoints. This anomaly has resulted in considerable debate as to the most appropriate viewpoint to be used (Brascamp *et al.*, 1985; Smith *et al.*, 1986). Even so, the issue still seems unresolved.

Of the viewpoints suggested by Moav (1973), the most commonly used perspectives are that of the national industry (for example Simm *et al.*, 1986 and Parrat and Simm, 1987) and of an individual producer (for example Simm *et al.*, 1987 and Waldron *et al.*, 1991). Calculation from a national viewpoint has the advantage of being more robust to changes in market prices, but the values obtained can be somewhat remote from the needs of those using the index i.e. the breeders. Calculation from a national perspective is likely to be useful only as part of a nationally run breeding program that is paid for from public funds. Where the costs of recording are to be borne mostly by the breeders, and the aim is to encourage more breeders to use the index technology (as is the aim here), then it seems sensible to calculate economic values from a viewpoint that is directly relevant to them, that of the individual producer. As was pointed out by Weller (1994), the breeding objective needs to be relevant to the decisions makers, otherwise implementation will not occur.

In calculating EV from the viewpoint of an individual producer it is assumed that any extra output can be sold without a reduction in profit per unit output. If selection is done by a large group of breeders this assumption is unlikely to be true in the long term. This concern has been the main criticism of using the individual producer viewpoint. However, as was pointed out by Simm *et al.* (1987), the rate of genetic improvement is likely to be slow and new markets may develop as a direct result of the improvement attained. Consequently, changes in profit per unit may well be relatively stable in the short to medium term. Even so, if the individual producer viewpoint was used periodic review of the economic values would be important to ensure the efficiency of selection was not being compromised.

When deriving economic values using the profit criteria the aim is to determine the change in profit resulting from a unit genetic change in the trait of interest when all other traits in the objective are held constant. The method most often used in previous studies to calculate these values is a profit equation (see review by Harris and Newman, 1994). In general, a profit equation is a single equation that describes the changes in net economic returns as a function of physical, biological and economic parameters. The economic value of the trait of interest is obtained as the first partial derivative of the profit equation evaluated at the current population mean for all traits (see review by Harris and Newman, 1994).

Production systems are typically complex and cannot always be described by a single profit function. An alternative method is to use a bio-economic model, in which the relevant biological and economic aspects of the system are described using a series of equations. Using this approach economic values for trait *i* are derived as follows (Dekkers, 2001):

1. The model is run for current population means for all traits, including the current mean for trait *i* (μ_i), and the average profit per animal is recorded ($P_{\mu i}$).
2. The mean for trait *i* is increased by Δ to $\mu_i + \Delta$, while keeping the means of other traits at their current values. The model is re-run and the average profit per animal recorded ($P_{\mu i+\Delta}$).
3. The economic value for trait *i* is derived as EV*i* = $(P_{\mu i+\Delta} - P_{\mu i}) / \Delta$.

Bio-economic models have become increasingly popular over recent years and have been used to derive EV for pigs (Tess *et al.*, 1983a, b; de Vries, 1989; Skorupski *et al.*, 1995a, b), beef cattle (Hirooka *et al.*, 1998a, b; Amer, Emmans and Simm, 1997), dairy cattle (Groen, 1989a, b) and sheep (Wang and Dickerson 1991; Conington, 2000). In addition to allowing the description of complex systems, an important benefit of using this approach is the relative ease with which the model can be adapted to account for different market prices, production systems or different breeds. This allows the robustness of the economic values to changing conditions to be investigated. Given this flexibility, a bio-economic model is likely to be the preferred method for calculating economic values for terminal sire breeds. This is because their progeny are expected to perform under a range of conditions, over which the robustness of the economic values would need to be investigated.

1.5 Market requirements

Meaningful economic values can only be derived if information about current market requirements and prices for lamb carcasses is obtained. Since the benefits of genetic improvement are gradually accumulated with continued selection over a number of years, it is also important to consider the likely requirement of future markets for lamb to ensure that the breeding objective will be relevant in the longer term. This information is not widely available and would need to be obtained before economic values could be calculated.

1.6 Conclusions

Development of new selection indices for terminal sire breeds in the UK, that incorporate measures of carcass shape and directly address the requirements and price signals of markets for lambs is desirable. The information required to develop such indices is not available at present and needs to be obtained.

Quantifying the shape of a carcass using an assessment of muscularity as opposed to conformation is preferable. However, further research is required to develop standard methods for assessing the carcass and to further our understanding of muscularity, not least how muscularity develops through the carcass with growth and the relationships with other important carcass characteristics, particularly in British terminal sire breeds.

If standard methods of assessment were to be developed, good *in vivo* measures of muscularity and genetic parameters for the relevant carcass and *in vivo* measures would also be needed before they could be considered for inclusion in selection programmes. CT scanning may provide a useful method for developing useful *in vivo* measures, but this needs to be investigated further.

The most appropriate way of addressing the requirements and price signals of markets for lamb is to develop an economic index. For this to be done, economic values for the objective measures would need to be estimated. Presently, a useful method for estimating economic values relevant to UK commercial conditions is not available and needs to be developed. The most appropriate approach is likely to a bio-economic model but this needs to be investigated further. Such a model can only be developed once information regarding prices and requirements of current markets for lamb and those likely in the future has been obtained.

All of the above issues are addressed as part of this thesis. In addition to this first Chapter, relevant literature is further reviewed in each of the subsequent Chapters of this thesis.

1.7 Outline of the thesis

In the first study, described in Chapter 2, the relationships of carcass muscularity measures with composition and the distribution of lean was investigated, along with the relationships between muscularity measures in different parts of the carcass. The data used were from carcass dissections of a total of 150 lambs from three terminal sire breeds (Suffolk, Texel and Charollais), that were slaughtered at a series of ages. The results were also used to infer the differences between these breeds in the development of muscularity with growth.

In the second study (Chapter 3) *in vivo* measures of muscularity were developed using measurements taken on CT scans. Each of the lambs from which data had been used in the first study had been CT scanned prior to slaughter. Measurements were taken on the available scans and suitable *in vivo* measures derived. The relationships between these *in vivo* measures and the carcass measures of muscularity developed in the first study were investigated.

In the third study (Chapter 4), the measurements needed to derive the most useful *in vivo* measures of muscularity, as determined in the second study, were taken on CT scans that were available for approximately 950 lambs from each of Suffolk, Texel and Charollais breeds. The data were then used to estimate within breed genetic parameters for each of the *in vivo* muscularity measures and their correlations with lean weight, fat weight, live weight and ultrasonic measures of fat and muscle depth. Estimates of the correlations between the carcass measures of muscularity and each of the other *in vivo* measures were also derived.

As was stated earlier, for meaningful economic values to be derived the requirements of the current markets and those likely in the future need to be established. In Chapter 5, details of a questionnaire survey designed for this purpose and sent to abattoirs and lamb retailers in the UK is presented.

In the last study (Chapter 6), a bio-economic model was developed and used to calculate the economic value of a unit increase in the weight of lean and fat at 150 days of age, in the context of a commercial slaughter lamb production system. Data collected on Suffolk cross lambs as part of a previous trial at SAC were used to adapt the model so that it was representative of a typical production system for the UK. The market requirements and prices reported in Chapter 5 were incorporated into the model.

A general discussion of the main points raised in each of the preceding Chapters is given in Chapter 7. These are discussed in the context of using the information presented to develop selection indices that would be suitable for use in breeding schemes for terminal sire breeds in the UK.

Chapter 2

Changes in muscularity with growth, and its relationship with other carcass traits in three terminal sire breeds of sheep

2.1 Introduction

The shape of a lamb carcass is considered important commercially, as is its weight and fatness. In abattoirs, carcass shape is evaluated subjectively as conformation and assessed using a scale such as the linear EUROP score. Shorter more blocky carcasses are considered of better shape and are given higher conformation scores. Traditionally, these carcasses were perceived to have a higher lean to bone ratio, higher proportions of lean in the high value joints and greater thickness of muscle at the same carcass weight, each attribute having commercial value (Jackson and Mansour 1974; Kempster *et al.*, 1981; Harrington and Kempster, 1989; Purchas and Wilkin, 1995). In practice the positive association between higher conformation and lean to bone ratio and increased muscle thickness has been shown but found to be weak. Moreover, higher conformation has been shown to have an undesirable positive association with fatness (Jackson and Mansour, 1974; Kempster *et al.*, 1981; Abdullah *et al.*, 1993; Purchas and Wilkin, 1995; Lewis *et al.*, 1996; Jones *et al.*, 1999).

Since fatness and conformation are confounded, an assessment of muscularity has been proposed as a preferable alternative for quantifying carcass shape (Kirton *et al.*, 1983; Purchas *et al.*, 1991; Purchas and Wilkin, 1995). Muscularity is a term used to describe, usually subjectively, the appearance/shape of muscles on a carcass. But, as yet, no standard objective methods for measuring the muscularity of a carcass are available.

De Boer *et al.* (1974) defined muscularity as 'the thickness of muscle relative to a skeletal dimension.' Despite this clear definition, early development of useful objective measures was slow, and likely hindered by problems obtaining measures of muscle thickness in most regions of the carcass. This problem was largely overcome with the proposal of Purchas *et al.* (1991) (discussed in Chapter 1). The Purchas *et al.*, (1991) approach has been used in all subsequent studies of muscularity.

Most subsequent studies have focused on the relationship between muscularity and conformation scores and a positive, but not strong, association has been shown (Abdullah *et al.*, 1993; Purchas and Wilkin, 1995). Although of interest, the strength of associations with the conformation score should not be the main determinant of the most appropriate muscularity measures for a lamb carcass. The aim should be to develop a single or relatively few measures (to be practical), that are strongly associated with the carcass lean to bone ratio, the shape of different commercial cuts and if possible, with the distribution of carcass lean, both within and across breeds. The focus should therefore be on establishing the relationships between muscularity and these other measures and between muscularity in different parts of the carcass. Obtaining a good understanding of how muscularity throughout the carcass changes as lambs from different breeds grow would greatly aid these investigations.

Some of these questions have been addressed in previous studies, but much remains unknown. Abdullah *et al.* (1998) showed that measures of muscularity in the hind leg and shoulder increased as Southdown lambs grew, but no information is available for measures in other regions of the carcass or in different breeds. Waldron *et al.* (1992b) investigated the relationship between muscularity and composition, but only measures in the loin were used and their relationships with lean distribution were not investigated. No previous study has investigated the relationship between measures based in different parts of the carcass.

This study had three main objectives: (i) to investigate how different muscularity measures change in different breeds and sexes as lambs grow; (ii) to describe the relationships between muscularity and carcass composition and lean distribution; and (iii) to determine the relationships between muscularity measures located in different parts of the carcass.

2.2 Materials and Methods

2.2.1 Data

Data were collected in 1997 at the Scottish Agricultural College (SAC) on 50 Suffolk male and 50 Suffolk female lambs, 40 male Texel lambs and 20 male Charollais lambs. Suffolk lambs were obtained from the SAC Suffolk flock and consisted of equal numbers within sex from the lean growth selection and control lines. Further details of the SAC Suffolk flock are given by Lewis *et al.* (1996) and Simm *et al.* (2002b). Texel lambs were obtained from the ANTUR flock at the Institute of Rural Studies (IRS), Aberystwyth and consisted of equal numbers from the lean growth and leg conformation selection lines. Further details of the ANTUR flock are given by Wolf *et al.* (2001). Charollais lambs were obtained from two commercial pedigree flocks. The Suffolk, Texel and Charollais lambs were the progeny of 14, 8 and 8 sires respectively.

Management of animals

Suffolk lambs were weaned at approximately 8 weeks of age. From 1 to 2 weeks prior to weaning they were offered free access to a performance test ration (12.4 MJ metabolizable energy and 178g crude protein per kg dry matter). Texel and Charollais lambs were purchased at approximately 8 weeks of age. These lambs were gradually introduced to this same ration while providing *ad libitum* access to hay during an adjustment period. All lambs were group penned according to breed and sex, with *ad libitum* access to the ration for at least six weeks prior to slaughter.

Slaughter measurements

One fifth of lambs within each genotype were slaughtered at each of 14, 18, and 22 weeks of age. The remaining two fifths were slaughtered at 26 weeks of age. All lambs were assigned at random within sire families to a slaughter age. Live weights prior to slaughter were recorded. After slaughter carcasses were chilled for 24 hours and then weighed. The carcass was then split and side length was measured as the distance from the cranial end of the *symphysis pubis* to the cranial dorsal edge of the first thoracic vertebra. The left side of the carcass was subsequently frozen and retained for dissection.

After thawing the width (A) and depth (B) of the *longissimus thoracis et lumborum* (LTL) muscle were measured on the caudal surface when the side was cut between the last and second to last thoracic vertebrae (Palsson, 1939). The area of the LTL surface was not directly measured but approximated by A*B*0.8 as done by Hopkins *et al.* (1993).

The left side of the carcass was separated into the 8 joints as described by Cuthbertson *et al.* (1972). Each joint was weighed and then dissected into lean, bone, fat (subcutaneous and inter-muscular) and waste. Three muscles from the hind leg (*semitendinosus, semimembranosus* and *gluteobiceps*) were individually separated and their weights recorded. Length of the femur was measured. Further details of measurements recorded are given in Table 1.

Muscularity and LTL cross-section shape measures

A large number of measures would be required if the relationships between muscularity in all regions of the carcass were to be investigated comprehensively. From a commercial viewpoint increased muscularity is likely most important in the high priced joints. It therefore follows that measures based in the loin and leg should form the main focus of investigations into potential measures of carcass muscularity.

Three measures of muscularity for the LTL were derived based on cross-sectional dimensions of the LTL muscle and side length. These were the ratio of LTL width (A) to side length (ASL), the ratio of LTL depth (B) to side length (BSL) and the ratio of 'average thickness' of the muscle at the point of measurement (square root of its area) to side length (ABSL). A measure of muscularity for the hind leg was obtained using the approach of Purchas *et al.* (1991), and was based on the length of the femur and the combined weight of the three dissected muscles (3MFL).

Two other measures were also derived, a general whole carcass measure and a measure of the shape of the LTL cross-section. The whole carcass measure was obtained using the Purchas *et al.* (1991) approach, and was based on the total weight of lean in the side and side length (TMSL). The LTL shape measure was derived as the ratio of muscle depth to width (B:A). The latter measure was chosen since it can be obtained relatively simply on the cut carcass (B:A). Details of each of the muscularity and B:A measures are given in Table 1.

2.2.2 Statistical analysis

Data for two Suffolk males and three Suffolk females were removed. Their live weights were greater than two standard deviations below the mean for their respective slaughter age groups (within breed-sex) causing the distribution to be highly skewed ($P<0.05$).

The distribution of live weight across slaughter age groups was continuous in each breed-sex with considerable overlap between contiguous age groups. This allowed a linear regression on live weight to be fitted across age groups. Within each breed-sex, for each muscularity measure, once a linear regression on live weight was fitted, age group and a quadratic regression on live weight did not explain additional variation ($P>0.05$). The same was true for each composition and lean distribution measure considered. The effect of age group and a quadratic regression on live weight were therefore not included in any of the subsequent models fitted.

Regression on live weight

Values for each of the muscularity and B:A measures were regressed individually on live weight within each breed-sex to investigate how these measures change with growth. Prior to analysis each lamb's live weight was expressed as a deviation from the mean live weight for the 14 week slaughter group in their respective breed-sex. The intercept for the regression on adjusted live weight within each breed-sex was then used to assess whether breeds and sexes differed in their muscularity values at the start of the study. Mean weights for the 14 week slaughter groups were 41.7, 36.7, 38.1 and 30.0 kg for the Suffolk males, Suffolk females, Charollais and Texels, respectively.

In order to facilitate comparisons between breed-sexes, all data were combined and breed-sex fitted as an effect in the model. In preliminary investigations, slopes for the regression of each muscularity and B:A measure on live weight did not differ between the Suffolk males, Suffolk females and Charollais males, but were frequently different from that estimated for the Texel males ($P<0.05$). A single common slope was therefore fitted for data from the Suffolk males, Suffolk females and Charollais lambs in the analysis, whilst a separate slope was fitted for the Texel lambs.

Allometry

Changes in muscularity with growth occur as a consequence of differences in the relative growth rate of the measure's components. These relative growth rates can be investigated in more detail using allometry (Huxley, 1932). Allometric coefficients (β) were derived from the slope of a log/log regression of each muscle thickness (included in the measures) on its associated skeletal dimension.

Relationship with composition and lean distribution

Relationships between the muscularity measures and carcass composition and lean distribution after accounting for the effect of live weight were investigated using multiple regression (Genstat, 1998). The models fitted included the effect of breed-sex, live weight and one of the muscularity or B:A measures as linear co-variates. The interaction between breed-sex and both co-variates was also fitted in preliminary analyses, however, slopes for the regression on live weight were not different ($P>0.05$) between the Suffolk males and females and the Charollais and therefore a single common slope was fitted for these breed-sexes. This was also true for the regression on the muscularity and B:A measures and therefore a common slope was also fitted for this regression for the Suffolk and Charollais lambs.

Table 1 Abbreviations and calculations used to derive the different measures for the carcass side

Trait	Abbreviation	Calculations †
Composition		
Tissue content	Lean, Fat	weight of tissue (g) / side weight (kg)
Lean to bone ratio	L:B	weight of lean / weight of bone
Lean distribution		
	Leg, Loin, Best end, Shoulder	weight of lean in the joint (g) / total weight of lean in the side (kg)
Mean muscle thickness		
LTL †	AB_th	$\sqrt{(A * B * 0.8)}$
Three dissected leg muscles	3M_th	$\sqrt{3M / FL}$
Total carcass muscle	TM_th	$\sqrt{TM / SL}$
Muscularity		
LTL	ASL	(A / SL)*10
	BSL	(B / SL)*10
	ABSL	(($\sqrt{A * B * 0.8}$) / SL)*10
Hind Leg	3MFL	($\sqrt{3M / FL^3}$) *10
Whole Side	TMSL	($\sqrt{TM / SL^3}$) *1000
Shape		
LTL cross section	B:A	(B / A)*10

† A and B are the width and depth of the *longissimus thoracis et lumborum* (LTL) muscle respectively (mm); SL, FL are the length (cm) of the carcass side and femur respectively; 3M is the combined weight of the *semitendinosus, semimembranosus and gluteobiceps* muscles dissected from the hind leg (g); TM is the total weight of lean in the left side of the carcass (kg).

Correlations between the muscularity and B:A measures

Correlations between residuals (from the regression of each measure on live weight), for each of the five muscularity measures and LTL shape were estimated within each breed-sex separately (Genstat, 1998). These estimates were then compared by transforming them to z values using the Fisher transformation and testing the difference between these values (Zar, 1996). Comparisons were conducted initially across all four estimates using a multiple sample test (experiment wise error rate of 5%), and subsequently between pairs where differences had been detected (comparison wise error rate of 5%).

Correlation estimates for the Suffolk male, Suffolk female and Charollais lambs did not differ (P>0.05). A common correlation coefficient was therefore calculated for these breed-sexes. The common coefficient was subsequently compared to that estimated for the Texels.

2.3 Results

Muscularity measures were consistently higher in the selection than in the control line in both Suffolk sexes. Hind leg muscularity was also higher in the leg conformation line than in the lean growth line in the Texels (results not shown). However, differences were small relative to the standard errors for line means (P>0.05). The effect of selection line was therefore ignored in subsequent analyses.

Numbers of animals, within breed-sex means and pooled standard deviations for the raw data for each of the traits derived are shown in Table 2.

Table 2 Within breed-sex means and pooled standard deviation for each of the different measures derived for the carcass side

	Mean				
	Suffolk		*Charollais*	*Texels*	
	males	*females*	*males*	*males*	s.d.†
Number	48	47	20	40	
Live weight	64.36	54.43	55.88	45.19	14.84
Composition					
Lean (g / kg)	530.41	518.29	565.03	643.21	67.41
Fat (g / kg)	297.64	321.50	267.59	190.08	81.02
L:B	3.26	3.47	3.57	4.19	0.52
Lean distribution					
Leg (g / kg)	286.78	298.00	279.92	291.81	13.30
Loin (g / kg)	118.59	116.85	112.48	108.90	8.34
Best end (g / kg)	58.29	58.00	56.56	53.99	4.06
Shoulder (g / kg)	195.15	193.85	207.51	203.36	9.86
Mean muscle thickness					
AB_th	45.27	42.71	43.61	45.17	4.55
3M_th	0.23	0.22	0.22	0.22	0.02
TM_th	0.34	0.32	0.34	0.34	0.03
Muscularity					
ASL	10.25	10.24	10.46	11.96	1.04
BSL	5.91	5.55	5.64	6.82	0.81
ABSL	6.95	6.74	6.87	8.07	0.78
3MFL	4.15	4.10	3.90	4.35	0.30
TMSL	5.17	5.00	5.33	6.16	0.52
Shape					
B:A	5.76	5.45	5.40	5.69	0.51

† Pooled across breed-sex

Regression on live weight

Intercepts for the regression of the muscularity measures on adjusted live weight for each breed-sex are shown in Table 3. The intercept for each of the muscularity measures was higher for the Texel than any of the other breed-sexes suggesting that greater development in muscularity had occurred in this breed by 14 weeks of age.

Differences at this age between the Suffolk and Charollais lambs were less pronounced.

Table 3 Intercepts (α) for each breed-sex from the regression of the muscularity and B:A measures on live weight (adjusted) †

	Suffolk males α (s.e)	Suffolk females α (s.e)	Charollais males α (s.e)	Texel males α (s.e.)
Muscularity				
ASL	10.65 (0.15) ^{a}	10.55 (0.14) ^{a}	10.77 (0.18) ^{a}	11.94 (0.20) ^{b}
BSL	5.87 (0.13) ^{bc}	5.52 (0.12) ^{a}	5.61 (0.16) ^{ab}	6.21 (0.17) ^{c}
ABSL	7.06 (0.12) ^{b}	6.82 (0.10) ^{a}	6.95 (0.14) ^{ab}	7.69 (0.15) ^{c}
3MFL	3.99 (0.05) ^{b}	3.97 (0.05) ^{b}	3.77 (0.06) ^{a}	4.16 (0.07) ^{c}
TMSL	5.10 (0.05) ^{b}	4.95 (0.05) ^{a}	5.27 (0.06) ^{c}	5.98 (0.06) ^{d}
Shape				
B:A	5.51 (0.09) ^{b}	5.25 (0.08) ^{a}	5.21 (0.11) ^{a}	5.17 (0.12) ^{a}

† Live weights were adjusted such that intercepts represent values at the mean weight for the 14 week age group within each breed-sex, which were 41.7, 36.7, 38.1 and 30.0 kg for the Suffolk males, Suffolk females, Charollais and Texels, respectively.
^{a,b,c} Within rows, intercepts with different superscripts differ ($P<0.05$)

The coefficients for the regression on live weight represent the rate of development in muscularity between 14 and 26 weeks of age. These coefficients, pooled residual standard deviations (R.S.D), and coefficients of variation (CV%) (calculated using the R.S.D), are shown for each of the muscularity and B:A measures in Table 4. Increases in live weight were associated with increases in the B:A measure and a number of the muscularity measures. A significant negative coefficient was estimated only for the ASL in the Suffolk's and Charollais (Suff/Char). Coefficients tended to be higher in the Texels, particularly for BSL and ABSL where the difference between the Texels and Suff/Char was most pronounced ($P<0.001$).

Table 4 Coefficients (β) for Suffolks/Charollais and Texels for the regression on live weight and residual standard deviations (R.S.D.) and coefficients of variation (CV%) for each of the muscularity and B:A measures

	Suff/Char β (s.e.) †	*Texels* β (s.e.)	diff ‡	R.S.D §	CV% §
Muscularity					
ASL	-0.02 (0.01) ***	0.00 (0.01) ns	ns	0.70	6.4
BSL	0.00 (0.00) ns	0.04 (0.01) ***	***	0.58	9.4
ABSL	-0.01 (0.00) ns	0.03 (0.01) **	***	0.52	7.1
3MFL	0.01 (0.00) ***	0.01 (0.00) ***	ns	0.24	5.6
TMSL	0.00 (0.00) ns	0.01 (0.00) ***	*	0.23	4.0
Shape					
B:A	0.01 (0.00) ***	0.04 (0.01) ***	***	0.43	7.7

† Superscripts indicate the significance of differences from zero. Regression coefficients shown as 0.00 are less than 0.005

‡ Significance of the difference between the two coefficients

§ Pooled within breeds-sex estimates. CV% calculated using the residual standard deviation

Allometry

The allometric coefficients reflect differences in relative growth between muscle thickness and its associated skeletal dimension (Table 5). Muscle thickness increased at a greater rate than its associated bone length (β>1.0), except for measures of LTL thickness for the Suff/Char. Coefficients were generally higher for the Texels than for the Suff/Char. The differences were again most pronounced for measures based on the LTL (P<0.001).

Table 5 Allometric coefficients (β) for Suffolks/Charollais and Texels derived from the double logarithmic regressions of muscle thicknesses on their associated skeletal lengths or muscle width

		Suff/Char	*Texels*	
X	Y	β (s.e.)	β (s.e.)	diff †
SL	A	0.64 (0.09) ‡	1.05 (0.12)	**
SL	B	0.95 (0.13)	1.77 (0.18) ‡	***
SL	AB_th	0.79 (0.10) ‡	1.41 (0.14) ‡	***
FL	3M_th	1.16 (0.10)	1.21 (0.12) ‡	ns
SL	TM_th	1.03 (0.06)	1.16 (0.08) ‡	ns
A	B	1.06 (0.10)	1.53 (0.12) ‡	**

† Significance of the difference between the two allometric coefficients

‡ Different from 1 ($P<0.05$)

Relationship with composition and lean distribution

Intercepts and coefficients for the regression of each composition and lean distribution variable on adjusted live weight are shown in Appendix 1. Results for lean distribution are only shown for the four joints where the additional regression on one or more of the muscularity measures was significant. Comparison between breed-sexes of how these variables change with live weight is not the focus of this study and therefore will not be considered in any detail.

Partial coefficients for the regression of composition and lean distribution on each of the muscularity and B:A measures, when fitted individually with live weight are shown in Table 6 and 7.

All five of the muscularity measures were positively associated with increased lean content and negatively associated with carcass fat content in the Suff/Char. The positive association with leanness was also present for most of the muscularity measures in Texels. Muscularity was not associated with fatness in the Texels (P>0.05). Increases in each muscularity measure were associated with increases in the carcass lean to bone ratio in Texels. However, this was only so for 3MFL and TMSL in the Suff/Char. The regression on B:A was not significant for any of the composition measures.

The relationship between the muscularity measures and proportion of lean in the high priced joints (leg and loin) was weak. A significant relationship was only present with 3MFL in the Suff/Char, where an increase in 3MFL was associated with a higher proportion of total lean in both joints. Differences in muscularity however, were associated with the proportion of lean found in the best end and shoulder joints. Higher LTL muscularity was associated with an increase in the proportion of lean found in the best end joint in each breed, as was a higher value for 3MFL in the Texels. Increases in each muscularity measure was also associated with a reduction in the proportion of total lean in the shoulder for Texels, but this association was only important for 3MFL in the Suff/Char. Even where these associations were significant, the amount of total variation in lean proportion in any joint accounted for by both the regression on live weight and the muscularity measure was low (<50%).

Table 6 Partial coefficients (s.e.) for LTL muscularity measures derived from the multiple regression of each composition or lean distribution variable on live weight and the muscularity measure for Suffolks/Charollais and Texels

	ASL			BSL			ABSL		
	Suff/Char †	Texels	diff‡	Suff/Char	Texels	diff	Suff/Char	Texels	diff
Composition									
Lean (g / kg)	21.62 (3.63) ***	19.17 (5.24) ***	ns	17.15 (4.88) ***	10.96 (6.26) ns	ns	26.06 (5.16) ***	17.80 (6.66) **	ns
Fat (g / kg)	-26.35 (4.37) ***	-11.79 (6.30) ns	ns	-17.95 (5.84) **	-4.72 (7.49) ns	ns	-29.56 (6.22) ***	-9.36 (8.03) ns	*
L:B	0.04 (0.04) ns	0.25 (0.06) ***	**	0.10 (0.05) ns	0.20 (0.07) **	ns	0.10 (0.06) ns	0.28 (0.08) ***	ns
Lean distribution									
Leg (g / kg)	-0.75 (1.43) ns	0.15 (2.07) ns	ns	0.52 (1.75) ns	2.27 (2.24) ns	ns	-0.05 (1.95) ns	1.82 (2.51) ns	ns
Loin (g / kg)	0.34 (0.99) ns	2.53 (1.42) ns	ns	0.95 (1.25) ns	0.76 (1.55) ns	ns	0.95 (1.35) ns	1.86 (1.73) ns	ns
Best end (g / kg)	1.77 (0.44) ***	3.25 (0.63) ***	ns	1.83 (0.56) ***	3.09 (0.71) ***	ns	2.43 (0.60) ***	3.93 (0.77) ***	ns
Shoulder (g / kg)	-0.42 (1.12) ns	-4.76 (1.62) **	*	-0.85 (1.37) ns	-4.89 (1.77) **	ns	-0.88 (1.52) ns	-6.06 (1.96) **	*

† Superscripts indicate the significance of differences from zero

‡ Significance of the difference between the two coefficients

Table 7 Partial coefficients (s.e) for the 3MFL, TMSL and B:A measures, derived from the multiple regression of each composition or lean distribution variable on live weight and the muscularity or B:A measure for Suffolks/Charollais and Texels

	3MFL			*TMSL*			*B:A*		
	Suff/Char †	Texels	diff ‡	Suff/Char	Texels	diff	Suff/Char	Texels	diff
Composition									
Lean (g / kg)	54.27 (13.18) ***	3.00 (13.47) ns	ns	86.12 (13.50) ***	31.72 (12.23) *	**	-2.77 (6.55) ns	-3.77 (11.04) ns	ns
Fat (g / kg)	-39.81 (16.20) *	11.70 (16.55) ns	*	-82.06 (16.96) ***	5.48 (15.36) ns	***	7.68 (7.65) ns	8.39 (12.89) ns	ns
L:B	0.64 (0.11) ***	1.13 (0.12) ***	**	0.63 (0.13) ***	1.02 (0.12) ***	*	0.09 (0.07) ns	0.10 (0.12) ns	ns
Lean distribution									
Leg (g / kg)	13.39 (4.62) **	8.10 (4.72) ns	ns	-1.29 (5.30) ns	3.47 (4.80) ns	ns	2.18 (2.20) ns	4.69 (3.71) ns	ns
Loin (g / kg)	9.53 (3.21) **	6.04 (3.28) ns	ns	0.46 (3.68) ns	2.99 (3.34) ns	ns	1.19 (1.54) ns	-1.83 (2.60) ns	ns
Best end (g / kg)	0.57 (1.63) ns	4.49 (1.66) **	ns	2.30 (1.82) ns	2.87 (1.65) ns	ns	0.56 (0.76) ns	2.59 (1.29) *	ns
Shoulder (g / kg)	-13.00 (3.54) ***	-13.94 (3.62) ***	ns	-6.10 (4.07) ns	-13.39 (3.68) ***	ns	-0.94 (1.78) ns	-4.59 (3.00) ns	ns

† Superscripts indicate the significance of differences from zero

‡ Significance of the difference between the two coefficients

Correlations between the muscularity and B:A measures

Correlation between residuals (from the regression of each measure on live weight), for each muscularity and shape measure, estimated for the Texels, and the common coefficient calculated for the Suffolk and Charollais are shown in Table 8.

Table 8 Residual correlations (from regressions on live weight) between the muscularity and B:A measures for Suffolks/Charollais (pooled estimates) and Texels

(a) Suffolks/Charollais

Indices		ASL	BSL	ABSL	3MFL	TMSL	B:A
<u>*Muscularity*</u>							
LTL	ASL	-					
	BSL	0.56	-				
	ABSL	0.84	0.93	-			
Hind Leg	3MFL	0.14 †	0.19 †	0.20 †	-		
Whole Side	TMSL	0.53	0.52	0.59	0.38 †	-	
<u>*Shape*</u>: LTL	B:A	-0.15	0.74	0.43	0.11	0.19	-

Correlations less than 0.18 do not differ from zero (P>0.05)

(b) Texels

Indices		ASL	BSL	ABSL	3MFL	TMSL	B:A
<u>*Muscularity*</u>							
LTL	ASL	-					
	BSL	0.71	-				
	ABSL	0.89	0.96	-			
Hind Leg	3MFL	0.52 †	0.56 †	0.60 †	-		
Whole Side	TMSL	0.56	0.61	0.64	0.74 †	-	
<u>*Shape*</u>: LTL	B:A	0.16	0.81	0.60	0.38	0.40	-

Correlations less than 0.27 do not differ from zero (P>0.05)

† Correlations are significantly different between the two groups (P<0.05)

Correlations between the ASL and BSL were high (0.56 to 0.71). As expected correlations between both these and ABSL were also high (>0.84). All correlation estimates were higher in the Texels than in the Suff/Char, with the differences often being significant. This was the case for correlations between hind leg muscularity and each of the LTL muscularity measures where estimates for Suff/Char were consistently low (<0.21) whereas those for Texels were high (>0.52). The same was also true for estimates between hind leg muscularity and the whole carcass measure (TMSL). With the exception of BSL and ABSL, correlations between the measures of muscularity and the LTL shape were comparatively low.

2.4 Discussion

Regression on live weight and allometry

The results presented here agreed with to those of Abdullah *et al.* (1998) for Southdown in that for each breed-sex, hind leg muscularity increased with growth. However, muscularity in other regions of the carcass did not develop in the same way across all breeds and sexes.

Differences between the Texels and both Suffolk and Charollais lambs in the developments of muscularity with growth were observed. Despite being lighter, Texel lambs had higher values for each of the muscularity measures at 14 weeks of age. The subsequent rate of development also tended to be higher for each measure, particularly for LTL muscularity. In addition to these results, partial correlations between the different measures in the subsequent analysis were also consistently higher for the Texels, implying that they differed in the way muscularity developed throughout the carcass, tending to be more uniform than in the other breeds.

Numerous studies have shown that Texels differ from other breeds in terms of composition, being leaner and with a higher lean to bone ratio when compared at either a fixed weight or fatness (Wolf *et al.,* 1980; Cameron and Drury, 1985; Kempster *et al.,* 1987; Ellis *et al.,* 1997). Although thought to be more muscular, few studies have compared muscularity in Texels with that in other breeds. Holloway *et* *al.* (1994) and Hopkins *et al.* (1997) considered a measure in the hind leg and found that the crossbred progeny of Texel rams at a fixed carcass weight were more muscular than those sired by rams from four other breeds. However, neither study included lambs sired by Suffolk or Charollais rams which, along with the Texel, are the most important terminal sire breeds in the UK (Maniatis and Pollott, 1998).

The greater and more uniform development of muscularity with growth in Texels coincided with lighter live weights at all ages compared with the Charollais and Suffolks. Direct comparisons of weights at an age should be made cautiously since the lambs were obtained from different sources. Nevertheless, it is worth noting that Suffolk and Charollais males were on average 39% and 27% heavier respectively than Texel males at 14 weeks and this increased to 49% for the Suffolks in the 26 week age group. Slower rates of growth for Texels, particularly in relation to Suffolk lambs, have also been reported in numerous other studies for pure bred and crossbred lambs (Wolf *et al.*, 1980; McEwan *et al.*, 1988; Leymaster and Jenkins, 1993).

Relationships with composition

Although dimensionless, the muscularity measures were not completely independent of live weight across breeds-sexes. So too composition changed as animals grew. Once adjustments for the effects of live weight were made, higher muscularity was associated with an increased carcass lean content and decreased fat content in the Suff/Char. The same was true of lean content in the Texels yet not for fatness.

Only one previous study has investigated the relationships between muscularity and composition. Waldron *et al.* (1992b) estimated phenotypic and genetic correlations between four muscularity measures, based on the weight or dimensions of the LTL and carcass length, and lean and fat weight and lean to bone ratio in the carcass of Romney cross lambs. Phenotypic correlations with lean weight and lean to bone ratio were positive for each measure. Phenotypic correlations with fatness were small yet positive with three of the measures (<0.30), but negative with the fourth measure that incorporated the width of the LTL. The fact that Waldron *et al.* (1992b) used tissue weights and fitted age as a covariate in their model does not allow good comparisons to be made with the results of this study. Nevertheless, Waldron et al's results are in general accordance with those presented here.

In contrast, Purchas *et al.* (1991) and Abdullah *et al.* (1998), reported higher muscularity at a fixed carcass weight, in Southdown lambs from lines selected for high *versus* low weight-adjusted back fat depth for five generations. This suggests a positive association exists between muscularity and fatness in the Southdown breed, but neither study quantified the strength of the relationship, which although positive, may be weak. Abdullah *et al.* (1998) stated that their results were in agreement with those reported by Simm and Murphy (1996) where crossbred progeny of Suffolk rams selected for improved lean growth had lower conformation scores at the same carcass weight than those of unselected rams. However, it is important to note that the progeny of rams from the unselected line were fatter which, given the positive correlation between fatness and conformation, would contribute towards a higher conformation score. The Suffolk lines used in the current study are the same as for the rams used by Simm and Murphy (1996). Results of our preliminary analyses contradict the conclusions of Abdullah *et al.* (1998). When compared at the same live weight, differences between lines in each of the muscularity measures were non-significant, but tended to be higher in the selection line. Since pure bred lambs were used in this current study, any line differences are expected to be more pronounced than for the crossbred lambs considered by Simm and Murphy (1996). Differences in conformation score should not therefore, be used as an indication of differences in muscularity, especially where carcasses vary in fatness.

Relationships with lean distribution

Relationships between muscularity and lean distribution tended to be weak. The proportion of lean found in the higher priced joints was only associated, albeit positively, with increases in the hind leg measure in the Suff/Char. Any correlated changes in joint proportions as a consequence of differences in muscularity are therefore likely to be of negligible commercial importance. Similar conclusions were drawn in previous studies investigating the effect of conformation on the distribution of lean in the carcass (Jackson and Mansour, 1974; Kempster *et al.*, 1981). The results of this study show that even when measures are used which are specifically related to the shape of individual joints and are largely independent of fatness, there remains little scope for affecting the distribution of lean in the lamb carcass through changes in shape.

Correlations between the muscularity and B:A measures

Due to their higher commercial value, muscularity is likely to be most important in the loin and hind leg joints. It therefore follows that measures in these two joints should be the main focus when investigating the value of different possible measures of muscularity. The relationships with these measures can also be used as a good basis to evaluate the usefulness of more general whole carcass measures (TMSL), or measures which can be obtained relatively simply on the cut carcass (B:A).

Correlation estimates between the three LTL muscularity measures were high suggesting that the LTL muscularity may be adequately described using either measure. Estimates between these measures and muscularity in the hind limb also tended to be high in the Texels (>0.51), but were low in the Suff/Char (<0.21). This implies that muscularity in one region may not always be a good indicator of the degree of muscularity in the other, across breeds. Equally, correlations between TMSL and measures in the loin and leg were high in the Texels, but less with hind leg muscularity in the Suff/Char. Whereas carcass muscularity may be adequately described using a single measure such as TMSL in Texels, this seems less appropriate for lambs from the Suffolk and Charollais breeds. Two or more separate measures may be required if characterising the muscularity of each region is considered sufficiently important.

With the exception of BSL and ABSL, correlations between B:A and other muscularity measures tended to be low and hence the B:A measure is unlikely to be useful as a general measure of muscularity through the carcass. This may in part reflect a greater effect of measurement errors given that both dimensions in the measure are small and are taken on soft tissues. Nevertheless, the B:A measure may have some value as an indicator of BSL where a measure of side length is not available.

Live weights for animals in the present study, with the exception of animals in the lower age group, were similar to the range over which pedigree animals are evaluated as part of selection programs in the UK. The results of the study indicate that improved muscularity is not associated with detrimental effects in composition or lean distribution at the phenotypic level, once adjustments for differences in live weight are made. This suggests that muscularity could be incorporated into selection programs, which include reducing fatness among the objectives, without undue reductions in selection responses. However, to be incorporated effectively methods of assessing the muscularity of the live animal may be required. At present, such methods are not available and further research would be needed for these to be developed.

Selection for improved muscularity *per se* is relevant only if improvement in the shape and thickness of muscle in cuts has commercial value. As mentioned by Hopkins (1996), unless consumer purchasing decisions are significantly affected by the surface area of muscle and shape of cuts, then the development of methods for assessing muscularity would not be useful. At present a consumer preference for cuts from more muscular joints is assumed rather than known. This still requires confirmation through market research.

Conclusions

This study has shown that muscularity can be assessed objectively in the carcass in a way that is largely independent of fatness. Following adjustments for live weight, increases in muscularity are associated with increases in L:B ratio, carcass lean content, and in the Suffolk and Charollais breeds, with decreases in fat content.

Additionally, increased muscularity is not deleterious to the proportion of lean in the high value joints.

The challenge now is to determine genetic and phenotypic parameters among muscularity measures and other carcass traits and to assess the feasibility of incorporating such measurements into selection programs. The latter is likely to depend on the scope for developing useful measures of muscularity on the live animal.

Chapter 3

The use of X-ray Computer Tomography for Measuring the Muscularity of Live Sheep

3.1 Introduction

Muscularity has increasingly been advocated as being preferable to conformation as a measure of the shape of a lamb carcass (Kirton *et al.,* 1983; Purchas *et al.,* 1991; Waldron *et al.,* 1992b; Abdullah *et al.,* 1993; Hopkins, 1996; Chapter 2). That is because, unlike conformation, muscularity when defined as 'the thickness of muscle relative to a skeletal dimension' (De Boer *et al.,* 1974) is independent of carcass fatness. Moreover, whereas conformation can only be assessed subjectively, objective measures of muscularity can be obtained using the ratio of a muscle thickness to a bone length or muscle weight to a bone length, as proposed by Purchas *et al.* (1991).

If the shape of the carcass and hence muscularity is considered commercially valuable then it should be considered as a selection goal in breeding schemes for meat breeds of sheep. For this to be done effectively, methods of accurately assessing the muscularity of a live animal will be required. Such methods are not available at present.

The aim should be to develop *in vivo* measures that are closely associated with measures considered most important in describing the muscularity of a carcass. In Chapter 2 it was proposed that muscularity measures based on the *M. longissimus thoracis et lumborum* (LTL) muscle and hind leg were the most important since they affect the shape of the most valuable joints (loin and leg). Phenotypic correlations between muscularity measures in the loin and leg were low for Suffolk and Charollais lambs, indicating that measures would be required for both regions to describe muscularity of a carcass in these breeds. However, a single measure of whole carcass muscularity was found to provide a good measure of muscularity throughout the carcass for Texel lambs.

The measures of muscularity for the carcass derived in Chapter 2 were based on the ratio of two components. Measures for the loin were based on the ratio of a LTL cross-section dimension to carcass side length. Measures for the whole carcass and hind leg were derived using the approach of Purchas *et al.* (1991). Whole carcass muscularity was derived using total muscle weight in the half carcass and side length, while hind leg muscularity used the weight of three muscles surrounding the femur and femur length. Similar muscularity measures for the live animal could be derived if reliable *in vivo* measurements of the same components could be obtained.

The most widely used method *in vivo* measurement of carcass components in sheep is ultrasound scanning. Whilst providing good measurements of the depth of the LTL muscle, the image produced is relatively poor and measurements of LTL width and area are less precise (McEwan *et al.*, 1989; Edwards *et al.*, 1989; Hopkins *et al.*, 1993; Binnie *et al.*, 1995). In addition, the technique does not lend itself readily to the measurement of muscle depth in other areas of the body nor for *in vivo* measurement of bone lengths.

In recent years, X-ray Computer Tomography (CT) scanners have become available in some countries for scanning small and medium sized animals. These scanner provide a means of obtaining detailed images of sections through various regions of a sheep's body. Reported studies using CT for scanning sheep have focused on its value in predicting tissue weights or volumes and very good results have been achieved (Sehested, 1984; Young *et al.*, 1987, 1996, 1999). Young *et al.* (1999) showed that, by using live weight and tissue areas from three CT scans as predictors, a prediction accuracy (R^2) of 96, 98 and 89% could be achieved for the total weight of muscle, fat and bone, respectively, in the carcass for Suffolk lambs. Muscle weight in different parts of the carcass (i.e. leg/chump) could also be predicted accurately using live weight and muscle area from just one cross-sectional scan (R^2 >91%).

Given the high quality of images produced, accurate *in vivo* measurements of cross-sectional dimensions on the LTL muscle and of skeletal dimensions may be possible. Such measurements, along with the predictions of muscle weight, could be used to develop *in vivo* measures of muscularity similar to those derived for the carcass post-slaughter in Chapter 2. The value of CT for measuring such dimensions *in vivo* has not been investigated in previous studies.

The aim of this study was to investigate whether useful, objective measures of muscularity could be derived for live sheep using data extracted from CT scan images.

3.2 Materials and Methods

3.2.1 Data

Data were collected in 1997 at the Scottish Agricultural College (SAC) on 50 Suffolk male, 50 Suffolk female, 40 male Texel and 20 male Charollais lambs. Suffolk lambs were obtained from the SAC Suffolk flock and consisted of equal numbers within sex from the lean growth selection and control lines. Texel lambs were obtained from the ANTUR flock at the Institute of Rural Studies (IRS), Aberystwyth and consisted of equal numbers from a lean growth and a leg conformation selection line. Charollais lambs were obtained from two commercial pedigree flocks. Further details about the origin and management of these lambs are provided in Chapter 2.

One fifth of lambs within each breed-sex category were slaughtered at 14, 18 and 22 weeks of age. The remaining two fifths were slaughtered at 26 weeks of age. All lambs were ultrasound and CT scanned 24-72 hours prior to slaughter.

Slaughter measurements

Live weights were recorded prior to slaughter. After slaughter carcasses were chilled for 24 hours and then weighed. The carcass was then split and side length (SL) was measured as the distance from the anterior end of the *symphysis pubis* to the anterior dorsal edge of the first thoracic vertebrae. The left side of the carcass was frozen and retained for subsequent dissection.

After thawing the depth (B) and width (A) of the LTL muscle were measured on the posterior surface when the side was cut between the last and second to last thoracic vertebrae (Pálsson, 1939). The left side of the carcass was separated into eight joints as described by Cuthbertson *et al.* (1972). Each joint was weighed and then dissected into muscle, bone, fat (subcutaneous and inter-muscular) and waste. Three muscles from the hind leg (*M. semitendinosus, M. semimembranosus* and *M. gluteobiceps*) were individually separated and their weights recorded. The length of the femur (FL) was measured. Further details of the carcass measurements collected are provided in Chapter 2.

Dissection measures of muscularity

Two measures of muscularity were derived for the LTL: the ratio of LTL width to side length (ASL) and the ratio of LTL depth to side length (BSL). One measure of muscularity for the hind leg and one for the whole carcass were derived using the approach of Purchas *et al.* (1991). The hind leg measure was based on the length of the femur and the combined weight of the three dissected muscles (3MFL), while the whole carcass measure was derived using the total weight of muscle in the side and side length (TMSL). Further details of how these measures were calculated are given in Table 2.

Ultrasound scanning

Measurements of LTL depth were taken by ultrasound with a view to comparing results with those obtained using CT. Measurements were taken on the right side of the lambs at the position of the $12/13^{th}$ thoracic vertebra using a Vetscan real-time B-mode ultrasonic scanner with a 3.5mHz transducer, within 24 hours of CT scanning. Muscle depth was measured vertically at the deepest point of the muscle. The resolution of measurements taken using this machine was 1 mm.

CT scanning

All lambs were fasted for a minimum of 4 hours before scanning to minimise any risk of pneumonia due to inhalation of regurgitated fluid. Fifteen minutes prior to scanning lambs were injected intramuscularly with a mild sedative to minimise the amount of movement during the scanning process [0.1-0.2 mg xylazine hydrochloride / kg body weight (ROMPUN 2%, Bayer plc.)]. Body weights were measured just prior to injection to determine the correct dosage.

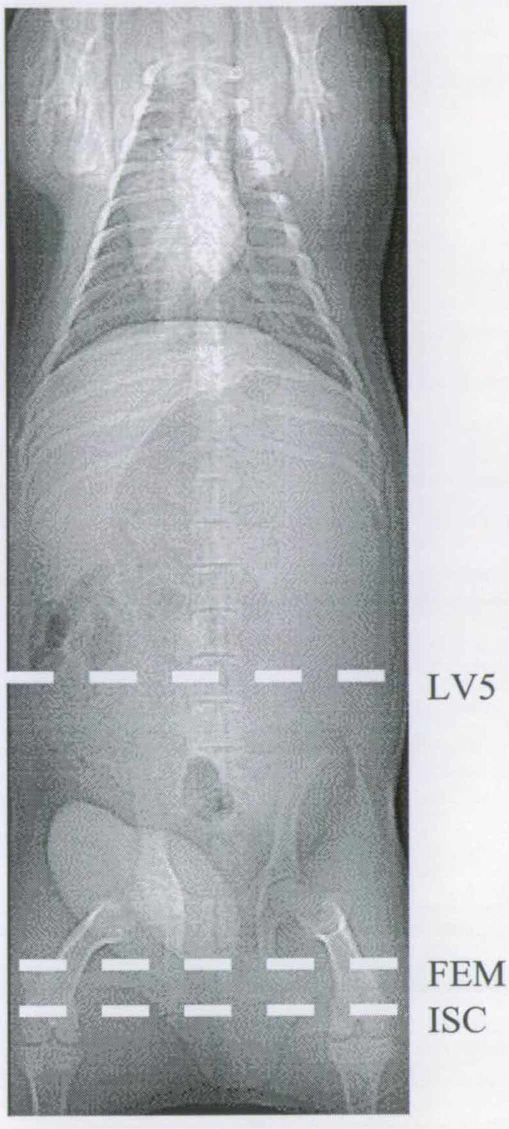
Once sedated, lambs were placed on their backs in a semi-cylindrical plastic cradle for scanning. Foam pads and straps were used to restrain the lamb with the hind legs extended and the fore legs held along its chest. Each lamb was scanned following a standard scanning protocol. Firstly, two partly overlapping longitudinal scans of the body were taken (topograms), one covering predominantly the thoracic region (topogram 1) and the other covering the abdomen and thighs (topogram 2). When combined, the scans covered the area from just below the knee joint (caudal to the ischium) to just cranial of the first rib. A series of cross sectional scans (tomograms) were then taken at specific sites identified and positioned in relation to bony landmarks on the topograms.

A total of seven tomograms were available for each lamb, having been taken as part of a separate trial (see Young *et al.,* 1999). Three of these were selected for use as part of the current study. These were positioned (i) through the 5th lumbar vertebrae (LV5), (ii) through the mid-shaft of the femur (FEM), and (iii) through the ischium (ISC). The LV5 scan was chosen to obtain measurements of LTL dimensions since a scan through the 12/13th thoracic vertebrae, where ultrasound and carcass measurements were taken, was not available. An example of the image obtained from the topograms depicting positions of the three tomograms is shown in Plate 1.

Image analysis

Analysis of scan images was undertaken using the Sheep Tomogram Analysis Routines software (STAR, version 0.6), which was developed jointly by Biomathematics and Statistics Scotland (BioSS) and SAC. The software was used to determine the total area of fat, muscle and bone in each image and to measure linear dimensions and areas of individual tissue units on CT scans. The resolution for these measurements is determined by the resolution of images. Since each image is composed of a number of 2 mm X 2 mm pixels, measurement resolution was 2 mm.

Plate 1 Ventral view of the skeleton, as obtained from the two longitudinal scans (topograms), and the position of the three cross sectional scans (tomograms) used



Prediction of total carcass muscle weight

Young *et al.* (1999) showed that the total weight of muscle in the carcass of Suffolk lambs could be predicted accurately (R^2 = 96%) using equations that included live weight and the area of muscle on CT scans from the 8th thoracic vertebra (TV8), LV5 and ISC positions. Similar breed specific equations, which include the same predictors were also developed for Charollais and Texel sheep (using the data described here), with prediction accuracies (R^2) of 98 and 96% respectively (M.J. Young, unpublished). The relevant equation was used to predict the total weight of muscle (TM_{CT}) for each lamb in the current study.

Linear Measurements: Spine length

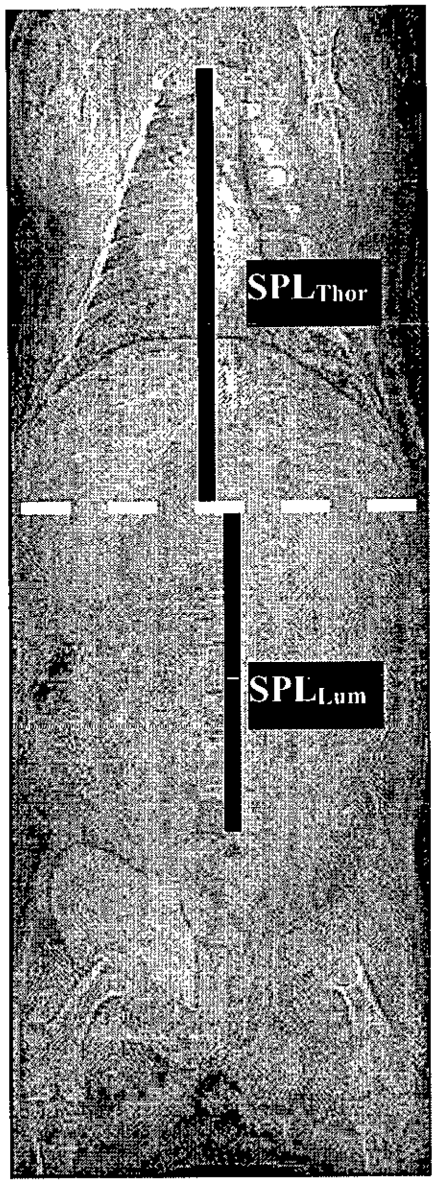
The exact position of the *symphysis pubis* was not always clear on the topogram 2 scan, but the disc between the pelvis and the last lumbar vertebrae could be seen. The length of the lumbar-thoracic spine was therefore measured in preference to side length. Since the whole spine could not be seen on a single topogram, separate measurements of the thoracic and lumbar sections were taken. The length of the thoracic section of the spine (SPL_{Thor}) was measured on the topogram 1 scan as the distance from the first disc caudal to the last rib to the first disc cranial to the first rib. The length of the lumbar section (SPL_{Lum}) was measured on the topogram 2 scan as the distance from the disc on the cranial side of the pelvis to the first disc caudal to the last rib. The number of vertebrae in each of the measured sections was also recorded. Overall spine length (SPL) was calculated as the sum of the lengths of the two sections. Diagrammatic representation of these measurements is shown in Plate 2.

M. longissimus thoracis et lumborum (LTL) dimensions

Measurements of width and depth of the cross-section through the LTL muscle were taken on both the left and right muscles on the LV5 CT scan using the method described by Pálsson (1939) for measurements on the carcass (see Plate 3). Care was taken to exclude skin and subcutaneous fat when measuring LTL depth. Means of measurements made on the two sides were used subsequently.

Plate 2 Diagrammatic representation of the measurements of the length of the thoracic and lumbar regions of the spine taken on the two topogram scans †

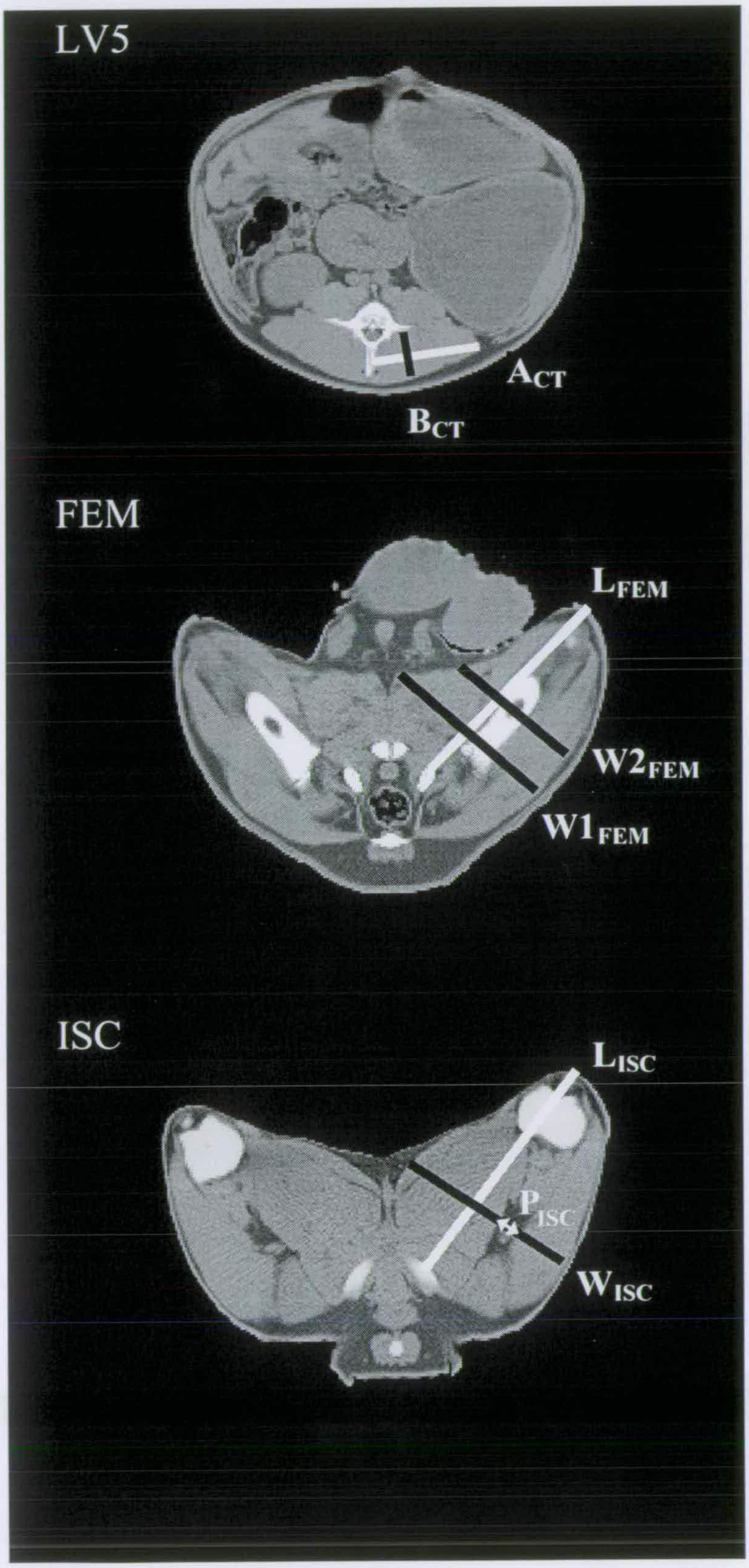
Topogram 1



Topogram 2

† The broken white line represents where the two topograms have been overlapped to show the complete longitudinal scan of the body.

Plate 3 Examples of tomograms obtained from the three positions and diagrammatic representation of the measurements taken on each scan



Hind leg

Both femurs could clearly be seen on the topogram 2 scan and the length of each femur was measured as the distance from the central point on the head to the deepest point in the *intercondyloid fossa.* Coefficients of determination (R^2) for the regression of femur length, measured directly on the dissected carcass, and the mean of the two measurements on the topogram 2 scan were, however, consistently low (<5%), indicating that these measurements were a poor indicator of actual femur length.

Indirect measures of hind leg muscularity were therefore considered as an alternative approach. Four dimensionless ratios, two on the FEM scan and two on the ISC scan, were derived. These were based on the ratio of two linear measurements taken on the same scan, one of the width and the other of length of the thigh. Measurement positions on the scans were defined in relation to anatomical features that were reliably present and distinguishable on scan images with the aim of achieving highly repeatable measures. Measurements were taken on the right and left thighs in a scan and the mean value used.

Thigh length (L_{FEM} and L_{ISC}) was measured on each scan as the distance from the centre of the ischium bone to the tip of the leg. This measurement passed through the femur. Two width measurements were taken on the FEM scan. The first was defined as a straight line from the furthest point (from the femur) on the *gracilis* muscle to the lateral muscle boundary, crossing the 'length line' at 90^0 ($W1_{FEM}$). The second width measurement was defined as a straight line from the medial to the lateral muscle boundary passing through the fat depot between the *adductor/gracilis* and *semimembranosus* muscles, and crossing the 'length line' at 90^0 ($W2_{FEM}$). Two width measurements were taken on the ISC scan. The first was defined as a straight line from the medial to the lateral muscle boundary, passing through the popliteal fat depot and crossing the 'length line' at 90^0 (W_{ISC}). The thickness of the popliteal fat depot on this line (P_{ISC}) was also measured and then subtracted from the initial thigh width to obtain a second width measurement, that due only to muscle. Care was taken to exclude any skin and visible subcutaneous fat when width measurements were taken on both scans. Measurements taken on the tomograms are shown in Plate 3.

CT measures of muscularity

Seven CT measures of muscularity were derived: two for the LTL, one for the whole carcass and four for the hind leg. LTL measures were calculated as the ratio of LTL width to spine length ($ASPL_{CT}$) and the ratio of LTL depth to spine length ($BSPL_{CT}$). The whole carcass measure was based on the approach of Purchas *et al.* (1991), and incorporated the predicted carcass muscle weight and spine length ($TMSPL_{CT}$). Further details about the calculations for these measures and the four dimensionless measures for the hind leg ($W1L_{FEM}$, $W2L_{FEM}$, WL_{ISC} and WPL_{ISC}) are given in Table 5.

3.2.2 Statistical analysis

Data for two Suffolk males and three Suffolk females were removed. Their live weights were greater than two standard deviations below the mean for their respective slaughter age groups (within breed-sex) causing the distribution to be highly skewed ($P<0.05$). Data for one Texel lamb were also removed due to poor quality of CT images.

Repeatability of measurements on scans

CT scans for 15 male Suffolk lambs from a single slaughter age group were used to assess the within and between operator repeatability for each of the CT linear measurements defined. One operator first repeated the same set of measurements three times at approximately 24-hour intervals. Three other operators then measured this same set of CT scans once. Repeatability was assessed as the intra class correlation between measurement occasions, either within operator or between operators as appropriate. Within and between animal variances were obtained using analysis of variance (ANOVA).

Correlations

Simple and residual correlations (after regressing each variable on live weight) between corresponding measurements taken on the carcass and by CT or ultrasound were initially derived for each breed-sex. Differences between correlation coefficients for each breed-sex category were then tested following a Fisher transformation of these coefficients to *z* values (Zar, 1996). Comparisons were conducted across all four breed-sexes using a multiple sample test (experiment wise error rate of 5%). Correlation coefficients were not different ($P<0.05$) between breed-sex categories for the same pair of variables and therefore a common (pooled) coefficient was calculated across breed-sexes.

Side and spine length

Correlation coefficients between side length (SL) and the individual lengths of the lumbar (SPL_{Lum}) and thoracic regions (SPL_{Thor}), and their sum (SPL), were determined. The correlation of SL with SPL_{Lum} and SPL_{Thor} individually was used to investigate the possibility of using just one of these measurements to represent spine length.

M. longissimus thoracis et lumborum (LTL) dimensions

Correlations between the CT dimensions and their corresponding carcass dimensions were determined, and between the ultrasound measurement and corresponding carcass LTL depth.

CT and dissection measures of muscularity

Correlations between each of the four dissection measures of muscularity and the equivalent CT measures of muscularity were determined. These included, between ASL and $ASPL_{CT}$; BSL and $BSPL_{CT}$; TMSL and $TMSPL_{CT}$ and between 3MFL and each of $W1L_{FEM}$, $W2L_{FEM}$, WL_{ISC} and WPL_{ISC}.

Regression analysis

Although correlation coefficients between the CT and dissection measures of hind leg muscularity were not different between breed-sexes, preliminary investigations suggested that the nature of the relationships differed. These differences were further investigated using regression analysis. Data across breed-sex categories were combined and the effect of breed-sex and the linear regression of hind leg muscularity on a CT scan ratio were fitted. In preliminary investigations, slopes for the regression on each individual ratio were not different between breed-sexes ($P>0.05$), although intercepts differed ($P<0.05$). A single common slope was therefore fitted. Once the regression on either CT scan ratio was fitted the additional affect of live weight was not important ($P>0.05$) and therefore was excluded from the model. All statistical analyses were performed using Genstat (1998).

3.3 Results

Repeatability of measurements on scans

Within and between operator repeatability for each of the key measurements taken on CT scans are shown in Table 1. Generally repeatabilities were high indicating that measurement positions could be clearly identified on each scan with low measurement error. The repeatabilities for overall spine length (SPL), although lower than for both component measurements, were also high.

Summary statistics

Table 2 details simple means, pooled standard deviations and pooled residual standard deviations (after regressing on live weight) within breed-sex for each of the individual carcass, CT and ultrasound measurements, and the dissection measures of muscularity. Pooled estimates of standard deviations and residual standard deviations are presented since within breed-sex estimates were found not to be different when tested using a Bartlett's test ($P>0.05$). Within breed-sex means for CT muscularity on the hind leg are not shown, but these ranged from 0.85 to 0.81 for $W1L_{FEM}$, 0.67 to 0.64 for $W2L_{FEM}$, and 0.65 to 0.59 for WPL_{ISC}, with Texels consistently having the highest means and Charollais lambs the lowest. Means for WL_{ISC} ranged from 0.74 to

0.70, and were lowest for Charollais, but in contrast to the other measures, means for both Suffolk sexes tended to be higher than that for Texels. Although not tested this is likely to be the result of a tendency for Suffolks to have a greater thickness of popliteal fat in the hind leg in comparison to the Texels. Pooled standard deviations and residual standard deviations for each of the four measures in the hind leg were in the range of 0.04 to 0.06.

Table 1 Within and between operator repeatability (%) for measurements taken on the CT scans †

Measurement	*Within*	*Between*
SPL_{Lumb}	99	98
SPL_{Thor}	92	87
SPL‡	86	79
A_{CT} §	99	92
B_{CT} §	95	90
L_{FEM} §	99	99
$W1_{FEM}$ §	98	95
$W2_{FEM}$ §	91	85
L_{ISC} §	99	99
W_{ISC} §	91	82
P_{ISC} §	97	91

† Diagrammatic representations of each of the measurements are shown in Plates 2 and 3.
‡ Sum of SPL_{Lum} and SPL_{Thor}
§ Mean of the measurements taken on the left and right hand side of the image

Although mean live weights differed between breed-sexes, a number of general trends were apparent. CT measured spine length (SPL) was consistently 0.82 of side length measured on the carcass (SL). Similarly, for the CT measurements the thoracic region of the spine accounted for around 0.58 of the total spine length across

Table 2 Means, pooled standard deviation and residual standard deviation for linear measurements taken on the carcass and on the live animal using CT or ultrasound for Suffolk, Texel and Charollais lambs

		Mean					
		Suffolk		*Texel*	*Charollais*		
	Abbreviation	*males*	*females*	*males*	*males*	s.d. †	r.s.d. †
Number		48	47	39	20		
Live weight		64.4	54.4	45.93	55.9	12.90	
<u>*Side and spine length (cm)*</u>							
Carcass, Side	SL	65.54	63.30	56.25	63.68	4.42	1.46
CT, Spine	SPL	54.02	51.69	45.92	52.39	3.64	1.62
CT, Lumbar	SPL_{Lum}	22.87	22.09	19.06	22.16	1.93	1.35
CT, Thoracic	SPL_{Thor}	31.15	29.59	26.86	30.23	2.15	1.19
<u>*LTL depth* (mm)</u>							
Carcass ‡	B	38.40	35.26	38.77	35.85	4.48	3.37
CT, LV5 scan	B_{CT}	39.72	37.36	35.69	34.84	5.18	3.31
Ultrasound ‡	B_{US}	30.04	28.65	26.17	26.36	3.08	2.65
<u>*LTL width* (mm)</u>							
Carcass ‡	A	67.08	64.77	67.46	66.40	5.29	4.25
CT, LV5 scan	A_{CT}	80.98	76.34	76.31	78.90	6.19	3.92
<u>*Dissection muscularity*</u> §							
LTL	ASL	10.25	10.24	12.00	10.46	0.73	0.70
LTL	BSL	5.91	5.55	6.88	5.64	0.59	0.58
Hind leg	3MFL	4.15	4.10	4.38	3.90	0.25	0.24
Whole carcass	TMSL	5.17	5.00	6.18	5.33	0.24	0.23

† Pooled within breed-sex estimates; r.s.d. is after adjustment for live weight.

‡ Measurements were taken at the 12th/13th thoracic vertebrae.

§ ASL = (A/SL)*10; BSL = (B/SL)*10; TMSL = $(\sqrt{TM / SL^3})$ *1000; 3MFL = $(\sqrt{3M / FL^3})$ *10. TM is the total weight of muscle in the left side of the carcass (kg), FL is the length (cm) of the femur; 3M is the combined weight of the *M. semitendinosus, M. semimembranosus and M. gluteobiceps* muscles dissected from the hind leg (g).

breed-sexes. The relative differences between the ultrasound and CT measurement of LTL depth were also fairly consistent, the former being 0.73 to 0.77 of that measured using CT at the more caudal position along the spine. This was not unexpected given that the LTL muscle becomes deeper moving from the last rib towards the pelvis (Davies *et al.*, 1987).

Correlations: Side and spine length

The correlation between side length measured on the carcass and the combined length of the thoracic and lumbar regions of the spine was high (Table 3). However, the correlations between side length and the length of the individual regions was lower, indicating that the length of both regions needs to be measured to ensure a reliable gauge of side length in the carcass.

The lower correlation between side length and its two components was expected given that the correlation between the individual regions themselves was low (residual corr. -0.09). This low correlation was in part because of variation in the number of vertebrae found in the two regions between lambs within each of the breed-sex categories (Table 4). When the correlation was estimated within groups of lambs with the same number of lumbar and of thoracic vertebrae, the correlation between the length of full spine and the individual regions was higher.

Although numbers of vertebra in both regions of the spine varied within each breed-sex, it is worth noting that the Texels tended to have fewer vertebrae than the other breed-sexes (Table 4). Whilst 13 thoracic vertebrae was most common in all breed-sexes the incidence of 12 thoracic vertebrae was higher in Texel lambs. Similarly in the lumbar region, six rather than seven vertebrae occurred more often in Texel lambs.

Table 3 Pooled simple and residual correlation coefficients (across breed-sex) between measurements on the carcass and corresponding or similar measurements taken using CT or ultrasound †

Side and spine length	SL	SPL	SPL_{Lum}
SL	-		
SPL	0.92 (0.62)	-	
SPL_{Lum}	0.76 (0.40)	0.86 (0.71)	-
SPL_{Thor}	0.86 (0.48)	0.90 (0.66)	0.54 (-0.09 ^{ns})
LTL depth	**B**	**B_{CT}**	
B	-		
B_{CT}	0.70 (0.45)	-	
B_{US}	0.59 (0.42)	0.66 (0.50)	
LTL width	**A**		
A	-		
A_{CT}	0.64 (0.41)		

† Residual correlations (after regressions on live weight) are shown in parentheses. Correlation coefficients differ from zero ($P<0.05$), unless indicated otherwise (^{ns}). Abbreviations are defined in Table 2.

M. longissimus thoracis et lumborum (LTL) dimensions

CT measurements of LTL depth and width were moderately correlated with equivalent measurement on the carcass (residual correlation >0.41, see Table 3). The CT measure of LTL depth was more strongly related to the equivalent carcass measurement than was the ultrasound measurement although the difference between the residual correlations was small.

Table 4 Proportion of lambs within each breed-sex with each thoracic and lumbar vertebrae number combination

No. vertebrae		*Suffolk males*	*Suffolk females*	*Charollais*	*Texel*
Thor.	Lumb.	(n = 48)	(n = 47)	(n = 20)	(n = 39)
12	6	0	0	0	0.03
12	7	0.02	0	0	0.10
13	6	0.17	0.23	0.30	0.69
13	7	0.75	0.74	0.55	0.15
14	6	0.06	0.02	0.15	0.03

CT and dissection measures of muscularity

Correlations between dissection muscularity and CT muscularity are shown in Table 5. Accounting for differences in live weight had very little effect on correlations with both simple and residual estimates being similar for the same pair of measures. All estimates were moderate to high in magnitude, residual correlations ranging from 0.33, for muscle width to skeletal length, to 0.60 for hind leg muscularity. Of the four CT measures of muscularity for the hind leg, three ($W2L_{FEM}$, WL_{ISC} and WPL_{ISC}) had similar high residual correlations with the dissection measure (0.57-0.60). This suggests that any of these three measures would provide a good prediction of the dissection measure. The residual correlation with the remaining $W1L_{FEM}$ measure, although still high, was lower in comparison (0.48), suggesting that it was less reliable than the other three measures.

Regression analysis

Intercepts for the regression of hind leg muscularity on each of the CT measures differed between breeds ($P<0.05$; Table 6). However, the intercepts were not different between the male and female Suffolk's, with the exception of $W2L_{FEM}$. The estimates were consistently highest for Texel lambs followed by Suffolk and then

Charollais lambs. This indicates that if either of these CT measures were to be used to compare across breeds, breed specific equations to predict hind leg muscularity would need to be developed. Using a single equation across breed-sex categories would result in under prediction of hind leg muscularity for the Texels and over-prediction for the Charollais.

Table 5 Pooled simple and residual correlation coefficients (across breed-sex) between corresponding dissection and CT measures of muscularity †

	Carcass	CT	Corr. ‡
LTL	ASL	$ASPL_{CT}$	0.32 (0.33)
	BSL	$BSPL_{CT}$	0.44 (0.45)
Whole carcass	TMSL	$TMSPL_{CT}$	0.55 (0.54)
Hind leg	3MFL	$W1L_{FEM}$	0.49 (0.48)
	3MFL	$W2L_{FEM}$	0.64 (0.60)
	3MFL	WL_{ISC}	0.69 (0.60)
	3MFL	WPL_{ISC}	0.63 (0.57)

† $ASPL_{CT} = (A_{CT}/SPL)*10$; $BSPL_{CT} = (B_{CT}/SPL)*10$; $TMSPL_{CT}=(\sqrt{TM_{CT}/SPL^3})*1000$; $W1L_{FEM} = W1_{FEM}/L_{FEM}$; $W2L_{FEM} = W2_{FEM}/L_{FEM}$; $WL_{ISC} = W_{ISC}/L_{ISC}$ and $WPL_{ISC} = (W_{ISC} - P_{ISC})/L_{ISC}$. TM_{CT} is the predicted carcass muscle weight (kg). Abbreviations for other components and the carcass measures of muscularity are defined in Figure 3 and Table 2.

‡ Residual correlations (after regressions on live weight) are shown in parentheses. All correlation coefficients differ from zero ($P<0.05$).

Table 6 Intercepts (α) for each breed-sex and common slope (β) for the regression of dissection hind leg muscularity on each of four CT measures of muscularity in the hind leg

		α				β	R^2
Y [†‡]	X [†]	*Suffolk male*	*Suffolk female*	*Texel*	*Charollais*		
3MFL	$W1L_{FEM}$	1.95 (0.32) [b]	1.86 (0.33) [ab]	2.20 (0.33) [c]	1.77 (0.32) [a]	2.64 (0.39)	48.0
3MFL	$W2L_{FEM}$	1.56 (0.25) [b]	1.46 (0.26) [a]	1.74 (0.26) [c]	1.39 (0.25) [a]	3.97 (0.38)	57.1
3MFL	WL_{ISC}	1.98 (0.19) [b]	1.93 (0.19) [b]	2.27 (0.18) [c]	1.83 (0.18) [a]	2.94 (0.25)	61.6
3MFL	WPL_{ISC}	2.49 (0.17) [b]	2.48 (0.17) [b]	2.69 (0.17) [c]	2.36 (0.16) [a]	2.59 (0.26)	55.3

[†] Y is the response (dependent) variable and X is the independent variable. Other abbreviations are defined in Table 2 and 5.
[‡] Raw standard deviation for 3MFL across breed-sexes is 0.29
[a,b,c,d] Within rows, intercepts with different superscripts differ ($P<0.05$)

3.4 Discussion

Side and spine length

In the past, skeletal dimensions could be approximated on the live animal only by using external measurements on the body measured with a tape measure, ruler or calliper. Even when clear measurement protocols have been developed, measurement positions are often obscured by subcutaneous fat or wool (where lambs are not sheared) and this can lead to high measurement errors. This is the case for measurements of body length (e.g. anterior point of shoulder to posterior extremity of the pin bone), which is similar to the spine length used here (Taneja 1955; Tallis *et al.*, 1964).

These problems were not encountered with the CT measurement of spine length since measurement position could be clearly delineated on each topogram. Measurement errors would therefore be expected to be less. Although the external measurement of body length has been used in numerous sheep studies as a measure of skeletal size, the correlation with side length measured on the carcass has not been estimated (Taneja, 1955; Tallis *et al.*, 1964; Weiner and Hayter, 1974; Wolf *et al.*, 2001). Therefore direct comparisons with the results presented here was not possible. Nevertheless, Taneja (1955) and Tallis *et al.* (1964) reported the repeatability of measurements of body length taken on the same animal by a single operator as 0.61 and 0.49 respectively. Taneja (1955) reported the repeatability between two measurements taken at the same catching and thus is similar to the within operator scenario reported in this study. However Tallis *et al.* (1964) calculated the repeatability across four measurements, two at each of two catching events. Between scanning repeatability of CT measurements of spine length was not estimated in this study, but this has been estimated in a small separate trial at SAC (n=15; H. Jones & M.J. Young, unpublished). The repeatability was found to be 0.75, despite repeated measurements being taken at three weekly intervals. This supports the expectation of higher accuracy for the CT measurements.

The existence of variation in the number of thoracic and lumbar vertebrae, as found in this study, has been well established for sheep from previous carcass based studies (Hammond, 1932; Pálsson, 1940; Thorgeirsson, 1982). Pálsson (1940) suggested that the variation in vertebrae number was of great economic importance since the addition of vertebrae increased the length of a region and thus the number of chops or cutlets that can be obtained from it. He further proposed that, due to this economic value, it would be of interest to breeders to acquire knowledge of how the variation in vertebrae number is inherited, with a view to incorporating selection for vertebrae number into selection programmes. Whether a carcass with a higher number of lumbar or thoracic vertebrae is of greater economic value to today's retailers is unclear. However, even if the commercial value is difficult to determine, it remains of interest to establish how vertebrae number is inherited. Doing so would improve our understanding of sheep development, which, as the results presented in this study suggest, may differ between breeds, particularly between the Texel and other breeds. Whilst the relatively small number of lambs in this study did not allow strong conclusions to be drawn, the observed differences between the Texel and other two breeds have been found to be persistent and a true breed effect in other larger data sets (M.J. Young, data not shown).

Despite Pálsson's suggestions, no study of the inheritance of vertebrae number has been conducted. Presumably that is because to obtain sufficient information to undertake such a study would require the dissection of a large number of carcasses, which would be expensive. Given that a number of lambs have already been CT scanned as part of commercial breeding programmes (Young *et al.*, 2001b) there is now the opportunity to examine the genetic control of this trait and possible associations with other carcass characteristics.

M. longissimus thoracis et lumborum (LTL) dimensions

The images produced using CT were much clearer than those produced using ultrasound. Nevertheless, the partial correlation with the carcass measurements of LTL depth was only marginally higher for the CT as opposed to the ultrasound measurement and both estimates were similar to those reported for ultrasound in previous sheep studies (McEwan *et al.*, 1989; Ward *et al.*, 1992; Hopkins *et al.*, 1993). This suggests that there was little benefit in using CT over ultrasound for measuring LTL depth. A number of factors may account for this finding. The position of the CT scan used was different from that for the carcass and ultrasound measurements (5^{th} lumbar *vs* $12/13^{th}$ thoracic), and the resolution of the measurements on CT scans was lower in comparison to that for ultrasound (2 *vs.* 1 mm). Furthermore, operators of ultrasound scanners can adjust the position or orientation of the scanner head to account for the animal's posture, whereas such corrections cannot be made using CT. Some increase in the correlation between the CT and carcass LTL depth may be achieved by the measures being taken at the same anatomical position, but the increase is unlikely to be large. In preliminary analyses, correlations with measurements taken on a scan at the LV2 position, which is closer to the position on the carcass, were very similar to those obtained with measurements on the LV5 scan.

The partial correlation between the carcass and CT measurement of LTL width was substantially higher than previous estimates for ultrasound, which are typically less than 0.10 (McEwan *et al.*, 1989; Hopkins *et al.*, 1993; Binnie *et al.*, 1995). Thus CT scanning is better than ultrasound for measuring this dimension. Ultrasound is considered to be less effective for measuring LTL width than depth because the reflective characteristics and hence image definition of the lateral boundary of the muscle is poor (McEwan *et al.*, 1989). X-ray CT images, in contrast, are based on the absorption of X-rays, which differs between tissues; all tissue boundaries are therefore clearly delineated allowing equally good measurements of both LTL width and depth (Young *et al.*, 1996). LTL area can also be measured with CT. However, LTL area was not measured on the carcasses in this study and so a direct comparison of *in vivo* and dissection LTL area could not be made.

In previous studies, correlations between *in vivo* measurements and the corresponding dissection measurement have been interpreted as a measure of the accuracy of the *in vivo* measuring technique (i.e. Houghton and Turlington, 1992). However, these correlations are likely to be an underestimate of the 'true' accuracy of the technique in most studies, and particularly in this study. That the shape of the LTL muscle can change post slaughter as a consequence of the carcass being hung, chilled and split is widely accepted (Fortin and Shrestha, 1986; Binnie *et al.*, 1995). Some increase in area and depth likely result due to the effects of cold shortening of the muscle prior to the onset of rigor mortis. This is particularly true where carcasses have been hung by the Achilles tendon as opposed to the pelvis, as was done in the current study, since the skeletal restraints on the LTL muscle are reduced (Houghton and Turlington, 1992; Lawrie, 1991). The degree of cold shortening has been shown to vary with time delay before chilling, chilling conditions, body size and, in particular, fatness (Smith *et al.*, 1976). The lambs used in this study were slaughtered at four different ages and varied in fatness and body size both within and between breed-sex categories (Chapter 2). Although reducing the amount of variation present, the regression on live weight used in the analysis would not be expected to fully account for variation in both fatness and body size between lambs. In addition to this, the carcass measurements of LTL dimensions were taken on the thawed carcass. Once thawed the muscle is fairly pliable and can be distorted with handling such that measurement errors on the carcass are likely to be higher than if measured on the chilled or frozen carcass as done in other studies (McEwan *et al.*, 1989; Binnie *et al.*, 1995).

CT and dissection measures of muscularity: LTL and whole carcass

Since each of the carcass and CT muscularity measures derived were dimensionless, the minor difference between the simple and residual correlations for these measures was not surprising. For the LTL and whole carcass measures the magnitude of the correlations generally reflected how well the individual components were predicted by the CT measurements. The upper limit for the estimates was likely determined by the correlation between the CT spine length and side length on the carcass (0.62), and hence all estimates were lower. That the highest correlation was between the whole carcass measures was also to be expected given that total muscle weight was predicted with near perfect accuracy for lambs of each breed from CT information using the prediction equations available (R^2 = 96-98%).

Hind leg

In contrast to spine length the relationship between femur length measured on the topogram and actual measurement on the dissected carcass was poor. The orientation of the spine relative to the plane of the topogram is relatively constant. In contrast, the angle of the hind leg can vary in the X, Y and Z planes but the topogram only displays an X-Y image. Hence we cannot account for variation in leg angle relative to the Z-dimension from just one topogram. Some improvement may be achieved by modifying the way in which the lamb's hind legs are restrained in the scanning cradle but this is unlikely to be sufficient to allow good measurements of femur length to be obtained.

This study used the ratio of two perpendicular measurements on a CT scan to characterise hind leg muscularity. It was assumed that as the angle between the plane of the CT scan and the femur changed both the length and the width of the thigh were expected to change to a similar extent such that changes in their ratio would be small. Whether this assumption is correct remains to be tested.

CT muscularity was a good predictor of dissection muscularity in the hind leg. The ischium scan is one of the three tomograms used in the prediction of composition in terminal sire breeds of sheep (Young *et al.*, 1999). From a practical perspective, a measure of hind leg muscularity on this scan would therefore be preferred, so that additional scans are not required.

The correlation of carcass hind leg muscularity with the WL_{ISC} measure was marginally higher than with WPL_{ISC}. This is likely the result of measurement errors being higher for WPL_{ISC} compared to WL_{ISC}, through the additional measurement of popliteal fat thickness, which was often small and approached the resolution of the image (2 mm). Nevertheless, ignoring the thickness of the popliteal fat depot, may be undesirable if doing so results in a positive association between the measure of leg muscularity and carcass fatness. A further investigation of the relationship between WPL_{ISC} and WL_{ISC} with fatness would be required for this to be established.

Conclusions

This study has shown that good *in vivo* measurements of muscularity in the hind leg and the whole carcass can be obtained for sheep by using a combination of measurements that can be taken on CT scans. *In vivo* measurements of LTL muscularity can also be obtained, but these are less useful as predictors of the carcass measures in comparison to these for the hind leg and whole carcass.

If *in vivo* muscularity measures are to be included in selection programs for sheep estimates of genetic and phenotypic parameters for such measures and the correlations between them and other important traits are required. Obtaining these estimates should be the main focus of future work in this area.

Chapter 4

Genetic parameters for *in vivo* measures of composition and muscularity for sheep measured using X-ray Computer Tomography

4.1 Introduction

The availability of X-ray Computer Tomography (CT) scanners in some countries for scanning small and medium sized animals provides very good opportunities for sheep breeders that are interested in improving growth and composition of the lamb carcass. Near perfect predictions of lean and fat weights in the carcass can be obtained using CT (Sehested, 1984; Young *et al.*, 1987, 1996, 1999). As a result, substantially higher responses to selection could be achieved by incorporating this information into current selection programmes (Simm, 1987; Jopson *et al.*, 1995). As was shown in Chapter 3, CT scanning also provides the means to obtain good *in vivo* measures of muscularity. Measures of muscularity are of interest as a method of quantifying the shape of a carcass objectively and independently of fatness. In the past, however, assessments could be made only by dissecting the carcass (Purchas *et al.*, 1991; Waldron *et al.*, 1992b), and thus these measures could not be incorporated easily into selection programmes. The *in vivo* measures presented in Chapter 3 provide a means of overcoming this problem.

Despite its obvious advantages, the high cost associated with CT does prohibit the scanning of a large number of animals as part of a breeding programme. Cost-effective use of the technology is likely to be achieved only as part of a two-stage selection programme, where a subset of animals are put forward for CT scanning following initial screening of the larger population using more practical and less costly methods (Jopson *et al.*, 1995; Jopson *et al.*, 1997). Live weights and ultrasound measurements of muscle and fat depths are routinely recorded on farm as part of current breeding programmes for meat breeds of sheep and therefore provide ideal methods for the initial screening (Simm, 1994, review; Simm *et al.*, 2002a)

If suitable two-stage selection programmes are to be developed, genetic parameters for the different CT measures and their correlations with ultrasound and live weight measurements are required. Given the high accuracy with which lean and fat weights can be predicted using CT information (>96%, Young *et al.*, 1999), little is to be gained by regarding the CT and carcass measures as separate traits. However, the same is not true for the measures of muscularity, since the phenotypic correlations between the CT and carcass measures are less than 0.60 (Chapter 3). Moreover, muscularity measures in more than one part of the carcass may need to be considered since the phenotypic correlations between them are low in some breeds (Chapter 2).

The aim of this study was to obtain a consistent set of genetic parameters in terminal sire sheep for CT measures of composition and muscularity, carcass measures of muscularity, live weight and ultrasound measurements, that could be used to develop two-stage selection programmes in such breeds to improve carcass quality

4.2 Materials and Methods

4.2.1 Data

Two data sets were used for this study. The first (data set 1) consisted of live weight, ultrasound and CT records that were collected on lambs from member flocks of the Sire Referencing Schemes (SRS) for the Suffolk, Texel and Charollais breeds in the UK. The second (data set 2) consisted of records collected as part of a trial conducted at SAC during 1997, which is described in Chapters 2 and 3.

Data set 1: Live weight and ultrasound measurements

Sire referencing schemes (SRS) are effectively group breeding schemes where genetic links between flock are maintained by mating a proportion of ewes in each member flock to one or more of a pool of common sires, mainly through the use of AI. These genetic links permit the use of Best Linear Unbiased Prediction (BLUP) methods to produce reliable Estimated Breeding Values (EBV's) for across-flock comparisons of animals available for selection.

SRS have proved popular in the UK, where pedigree flocks are typically small and cover a wide geographical area, and schemes have been formed in a number of breeds (Simm *et al.*, 2002b). SRS within the Suffolk and Charollais breeds were the first to be established in the UK in 1990, closely followed by the Texel SRS in 1992.

These schemes are now the largest in the UK, and contained 66, 39 and 58 member flocks respectively in 1999 (Simm *et al.*, 2002a).

In each of these schemes members are asked to mate, using artificial insemination, 30 ewes in their flock each year to two or three rams from a team of five or six reference sires. Typically half the reference sire team is replaced annually with rams selected from the top 5-10% of ram lambs based on their lean growth index score (Simm and Dingwall, 1989), produced within the scheme. The remaining reference sires are typically retained in the team for at least two breeding seasons to strengthen genetic links between years. Lewis and Simm (2000) provides further details about the design of these schemes, and justification for the guidelines in their implementation.

The Meat and Livestock Commission (MLC) initially conducted the performance recording in the flocks of members of these schemes. More recently that function was done by Signet, an MLC owned agency that provides sheep recording services in the UK. As part of the performance recording, lambs in each flock were weighed and ultrasound scanned at a mean age of approximately 21 weeks (150 days). Ultrasound measurements of muscle and fat depth were taken at the position of the third lumbar vertebrae.

Data collected from 1990 to 1999 from SRS for each of the three breeds were available and used as part of this study.

CT scanning

Between 1997 and 1999, approximately 980 lambs from each of the three breeds were scanned at the CT unit at SAC. One fifth of the lambs from each breed were scanned in 1997 and two fifths in each of 1998 and 1999. A summary of the number of flocks across years from which these lambs were sampled is given in Table 1. Generally between 48 and 60 lambs (approximately 50% from each sex) were obtained from each flock within a year (in 82% of the flock-year groups). The minimum number of lambs within a flock-year was 24, whilst the maximum number was 100.

Table 1 Summary of the number of flocks across years from which CT scanned lambs were sampled for each breed

	No. flocks sampled in			*No. flock present in each of*		*Total no. of flocks*
	1997	1998	1999	3 years	2 years	
Charollais	5	8	8	3	2	13
Texel	4	8	8	4	2	10
Suffolk	5	7	8	3	3	11

Genetic links existed between the flocks from which the lambs were sampled since a number of these lambs were the progeny of reference sires. Six sires were represented in more than one year and 12 were represented in more than one flock in the CT data for the Charollais. Corresponding numbers were 13 and 9 for the Suffolks and 15 and 12 for the Texels. At least four progeny for these sires were present within a flock-year group. Since a number of the flocks sampled were long-term members of the SRS, further genetic links between flocks also occurred as a result of historic use of reference sires.

All lambs were CT scanned within two weeks of being weighed and ultrasound scanned on-farm as part of the usual recording schedule for the SRS. The CT scanning was performed following the procedures described in Chapter 3. In addition to the two longitudinal scans (topograms), three cross-sectional scans (tomograms) were taken on each lamb and these were positioned: (i) through the 8th thoracic vertebrate (TV8), (ii) through the 5th lumbar vertebrae (LV5) and (iii) through the ischium bone (ISC). These tomograms correspond to those used for predicting tissue weights by Young *et al.* (1999).

Image analysis

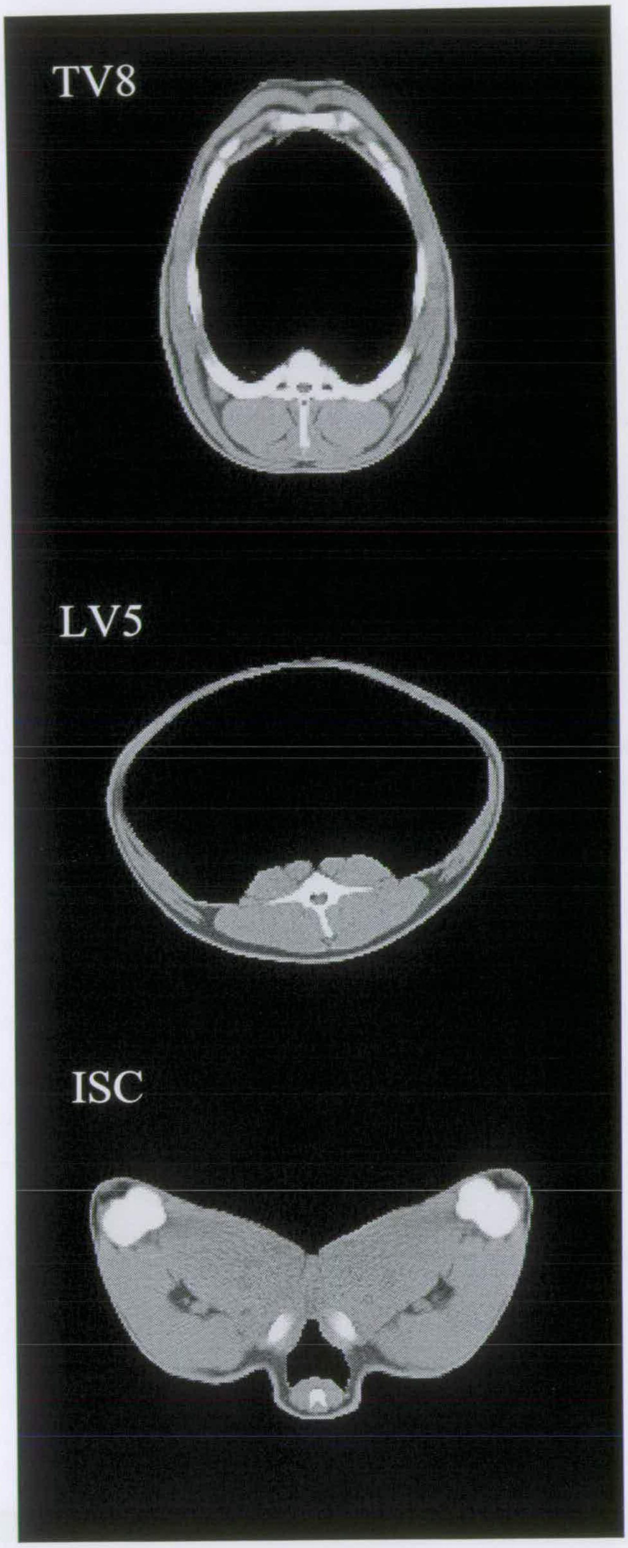
Determination of the area of lean, fat and bone on each tomogram scan and the measurement of linear dimensions were done using the Sheep Tomogram Analysis Routines software (STAR, version 0.6), which was developed at SAC in collaboration with Biomathematics and Statistics Scotland (BioSS).

To obtain the area of each tissue on a scan using the STAR software, an operator first traced the position of the boundary between the carcass and internal organ interface, a process known as segmentation. Once completed, the internal organs were removed from the image, along with the cradle, to produce gutted images. The number of pixels corresponding to lean, fat and bone in the gutted image was then determined automatically by the software. Examples of gutted images from the three positions are shown in Plate 1.

Linear measurements of the lengths of the lumbar and thoracic regions of the spine were measured on the two topograms. Overall spine length (SPL) was then calculated as the sum of these two lengths. Width, depth and area of the *M. longissimus thoracis et lumborum* (LTL) were measured on both the left and right hand side parts of the muscle on the LV5 scan and the mean of each pair of measurements was recorded (A_{CT}, B_{CT} and Ar_{CT}, respectively). Measurements of area were obtained by tracing the boundary around the LTL muscle, including the small adjacent *multifidi* muscle but excluding the supraspinous ligament.

Length and width measurements were taken on both thighs on the ISC scan as well as the thickness of the popliteal fat depot along the width line. The mean of each pair of measurements was recorded (L_{ISC}, W_{ISC} and P_{ISC} respectively). Chapter 3 provides further details about each of these linear measurements.

Plate 1 Examples of the gutted tomograms obtained from scans taken at each of the three positions



CT predictions of tissue weights and measures of muscularity

Total weight of lean and fat in the carcass were predicted using the breed specific prediction equations developed at SAC, which included live weight and the area of the relevant tissue in each of the three scans (TV8, LV5 and ISC) as predictors (Young *et al*, 1999; M.Young, unpublished). The weight of bone was also predicted and used to calculate the ratio of lean to bone (L:B) in the carcass.

Five of the CT measures of muscularity described in Chapter 3 were derived. These included two for the LTL ($ASPL_{CT}$ and $BSPL_{CT}$), two for the hind leg (WL_{ISC} and WPL_{ISC}), and one whole carcass measure ($TMSPL_{CT}$). A third measure for the LTL, based on the ratio of LTL cross-sectional area and spine length, was also derived ($ArSPL_{CT}$). Further details of how these measures were calculated are shown in Table 2. Each measure was multiplied by 10 so that all values obtained were greater than 1.

Data set 2

Correlations between the CT and dissection measures of muscularity could not be estimated using data set 1 as none of the lambs were slaughtered. However, CT, ultrasound and dissection information was available for a small number of lambs from each breed (50 Suffolk females, 50 Suffolk males, 40 Texel males and 20 Charollais males), with a similar range in ages to the lambs in data sets 1, from the trial previously described in Chapters 2 and 3.

The amount of data available for Charollais lambs was deemed too small to be considered separately and hence was not used. Correlations and phenotypic variances for the Charollais were assumed to be equal to those estimated for the Suffolks. This was considered appropriate since correlations and variance estimates were not significantly different between the Charollais and Suffolks in the previous analyses, reported in Chapters 2 and 3.

4.2.2 Statistical analyses

Parameter estimation; live weight, ultrasound and CT measures

The number of lambs with valid ultrasound, live weight and CT records in the data for each breed used in the analyses is shown in Table 2. The pedigree information for the Charollais, Texel and Suffolk breeds included 20330, 64712 and 67961 animals, respectively, of which 2371, 3550 and 4124, respectively, were directly related to lambs with CT information.

Possible deviation from a normal distribution is a concern when the ratio of two variables is considered as a trait in its own right (Koerhuis and Hill, 1996). Means and medians for the observed data were similar for each of the CT muscularity measures and the lean to bone ratio. Coefficients of skewness and kurtosis were also small relative to their standard errors. This suggests that any deviation from normality, even if present, would be small for each of the measures considered.

Model

A mixed-linear animal model was fitted to describe the CT, live weight and ultrasound measures. The model included fixed effects of contemporary group (which incorporated the combined effects of flock, year, birth season, sex, and management group), litter size reared (0 (artificially reared), 1, 2 and 3+) and dam age (1, 2, 3, 4-6, 7+). Age at scanning (ultrasound or CT as appropriate) was included as a linear covariate, along with the random effects of animal and residual. All variance components for these traits were obtained from univariate and bivarate analyses conducted within breed, using ASREML (Gilmour *et al.,* 1998).

Trait selection

Since only a limited amount of data were available to estimate correlations between the dissection muscularity measures and other traits, it was desirable to limit the number of traits that were to be included in a matrix of parameters that could be used for index development. Three CT measures of muscularity, one for each of the LTL, hind leg and whole carcass, were therefore chosen from those derived. The choice of measure for the LTL and hind leg was based on the magnitude of heritability estimates and coefficients of variation for the different measures (higher values being preferable for both), and the magnitude of their correlations with lean weight, fat weight and L:B. The magnitude of these correlations were considered due to the *a priori* supposition (Chapter 2) that useful measures of muscularity should be independent of fatness and positively associated with L:B. The three CT measures chosen based on these results were: $TMSPL_{CT}$, $BSPL_{CT}$ and WPL_{ISC}.

Parameter estimation; dissection muscularity measures

Three measures of muscularity, corresponding to the chosen CT measures were derived from the dissection information available in data set 2. The whole carcass measure (TMSL) was calculated as $(\sqrt{TM / SL^3})$ *1000, where TM is twice the total weight of lean in the left side of the carcass (kg), and SL is side length (cm). The hind leg measure (3MFL) was calculated as $(\sqrt{3M / FL^3})$ *10, where FL is the length (cm) of the femur and 3M is the combined weight (g) of the *M. semitendinosus, M. semimembranosus* and *M. gluteobiceps* which surround the femur. The LTL measure (BSL) was calculated as (B/SL)* 10, where B is the depth of the LTL muscle (mm) at the $12/13^{th}$ thoracic vertebra. Further details about how the individual measurements were obtained are given in Chapters 2 and 3.

Since dissection measures of muscularity were considered solely as selection objectives, only estimates of genetic variances and genetic covariances with the other traits were required to allow selection index calculations to be performed (Cameron, 1997). Given that dissection information was available for only a small number of lambs, a comprehensive genetic analysis could not be done. Therefore, correlation estimates were obtained from a phenotypic analysis and these were used as approximations of the genetic correlations with the dissection measures. The phenotypic correlations were calculated within breed as the correlation between residuals after fitting a linear regression on slaughter age for the Texels, and slaughter age and sex for the Suffolks.

Genetic variances for the dissection measures of muscularity were estimated using the residual variance from the phenotypic analysis (described above) and by assuming that heritabilities for these measures were 0.05 higher than that estimated for the corresponding CT muscularity measure. Genetic variances for the dissection measures in Charollais were calculated using the residual variances obtained for the Suffolks and heritability estimates that were 0.05 greater than that estimated for the corresponding CT measure in the Charollais data.

Residual variances obtained for each of the dissection measures of muscularity were 0.283, 0.043 and 0.073 for BSL, M3FL and TMSL, respectively, for the Suffolks and 0.483, 0.053 and 0.093, respectively, for the Texels.

Consistent sets of parameters

Eleven of the traits derived were selected to be included in the large parameter matrix for each breed. These included live weight, ultrasound measurements of fat and muscle depth, CT predictions of lean and fat weight, the three CT and three dissection measures of muscularity.

Residual and genetic variances for each of the CT, ultrasound and live weight measures were calculated as the mean of all estimates from the univariate and bivariate analyses. Genetic covariances for the dissection measures of muscularity were calculated from these mean genetic variances, the correlations estimated using data set 2 and the calculated genetic variances for the dissection measures.

When tested, the genetic and residual covariance matrices for each breed were found to be non-positive definite. Modified, positive definite matrices were obtained by setting negative eigenvalues to be $1X10^{-5}$, and then multiplying the eigenvectors of the original matrix by the new vector of eigenvalues.

4.3 Results

Summary statistics

Means and coefficients of variation (calculated using phenotypic variances from univariate analyses), for live weight, ultrasound and CT measures are shown for each breed in Table 2. Mean age at ultrasound scanning was similar across breeds and close to the intended target age of 150 days. Suffolks were heaviest at scanning and had the greatest depths of fat and muscle, whereas Texels were lightest and tended to have the smallest measurements of UFD. Coefficients of variation (CV) for both live weight and UMD were similar across breeds, being around 11 and 9% respectively. Estimates of CV for UFD were high in all breeds (>33%), and highest for the Texels (40%).

Mean ages for those lambs that were CT scanned were less consistent between breeds, but even so the differences were relatively small being greatest between the Texel and Suffolk breeds (9 days). Although lightest and youngest at scanning, Texels were intermediate in terms of average predicted lean weight and had the highest proportion of lean as a consequence of a lower fat weight and higher L:B than the other two breeds. Suffolks, in contrast, were the heaviest at scanning but had the lowest average lean weight. Fat weight for Suffolks was similar to predictions for the Charollais but L:B was lower suggesting that a greater proportion of live weight was accounted for by bone in the Suffolk lambs. Coefficients of variation for the predicted tissue weight were similar across breeds, except that fat weight had a higher CV for the Texels (28.3 *versus* 21.7 and 22.0). The CV for each of the linear dimensions was also similar across breeds, and ranged from around 4% for spine length to between 10 and 13% for LTL area.

Differences between the Suffolk and Charollais lambs in muscularity were fairly small, with means tending to be marginally higher for the Charollais. Texel lambs in contrast, had the highest values for all but one of the CT measures, WL_{ISC} for the hind leg, for which the mean was greatest for the Charollais lambs. However, since the Texels had a higher mean for WPL_{ISC} the change in ranking of means for WL_{ISC} is

Table 2 Means and coefficients of variation for live weight, ultrasound, linear measurements and CT measures of muscularity for Charollais, Texel and Suffolk lambs †

	Abbrev.	Charollais Mean	Charollais CV%	Texel Mean	Texel CV%	Suffolk Mean	Suffolk CV%
Live weight and ultrasound							
Number of lambs		18747		50673		49595	
Age (days)		152		150		148	
Scan live weight (kg)	SLW	50.4	10.9	45.9	11.7	56.6	10.9
LTL depth (mm) ‡	UMD	27.8	9.0	28.0	9.5	30.4	8.8
Fat depth (mm) ‡	UFD	3.5	33.8	2.5	40.0	3.7	33.0
CT scanning							
Number of lambs		922		941		944	
Age (days)		158		151		160	
Tissue predictions							
Lean weight (kg)	LEAN	14.01	9.4	13.44	10.9	13.03	9.6
Fat weight (kg)	FAT	6.59	21.7	4.22	28.3	6.27	22.0
Lean to bone (g /g)	L:B	3.47	6.1	4.17	6.7	3.10	6.2
Linear measurements							
Spine length (cm)	SPL	53.1	3.8	47.3	4.3	53.4	3.4
LTL width (mm) ‡	A_{CT}	80.2	5.3	75.6	6.0	78.6	6.1
LTL depth (mm) ‡	B_{CT}	35.2	9.1	34.6	10.1	35.9	8.6
LTL area (cm^2) ‡	Ar_{CT}	25.3	11.1	23.2	13.4	24.8	10.5
Muscularity §							
LTL	$ASPL_{CT}$	15.12	5.0	15.95	5.3	14.71	5.9
	$BSPL_{CT}$	6.63	9.2	7.28	10.0	6.72	8.9
	$ArSPL_{CT}$	9.46	5.7	10.12	6.3	9.29	5.4
Hind leg	WL_{ISC}	7.12	6.5	7.06	7.2	6.99	6.3
	WPL_{ISC}	6.25	8.6	6.36	9.3	6.09	8.9
Whole carcass	$TMSPL_{CT}$	9.16	5.6	11.19	5.7	9.19	5.0

† CV% were calculated using phenotypic standard deviations obtained after fitting the fixed effects in the model.

‡ Ultrasound measurements were taken at the 3rd lumbar and CT at the 5th lumbar vertebra positions.

Mean live weights for the CT scanned lambs were 51.6, 43.7 and 53.4 kg for the Charollais Texels and Suffolks respectively.

§ $ASPL_{CT} = (A_{CT}/SPL)*10$; $BSPL_{CT} = (B_{CT}/SPL)*10$; $ArSPL_{CT} = ((\sqrt{Ar_{CT}})/SPL)*10$; $WL_{ISC} = (W_{ISC}/L_{ISC})*10$, $WPL_{ISC} = ((W_{ISC}-P_{ISC})/L)*10$, where W_{ISC}, L_{ISC} and P_{ISC} are thigh width, length and thickness of the popliteal fat depot, respectively, measured on the ischium scan; $TMSPL_{CT} = (\sqrt{LEAN/(SPL^3)})*1000$. LTL is the *longissimus thoracis et lumborum* muscle.

likely the result of greater amounts of fat in the popliteal depot in the Charollais rather than greater hind leg muscularity for those lambs.

Coefficients of variation for each of the CT muscularity measures were fairly consistent across breeds, varying from 5 to 10% across measures. For the LTL measures CV's were higher for $BSPL_{CT}$ (9-10%) than for the other two measures. Similarly for the hind leg, CV's were marginally higher for WPL_{ISC} than for WL_{ISC} (9 *versus* 6-7%).

Table 3 Heritability estimates (s.e.) obtained from univariate analyses for each trait in the three breeds †

Trait	*Charollais* h^2	*Texels* h^2	*Suffolk* h^2
Tissue predictions			
L:B	0.52 (0.10)	0.24 (0.09)	0.40 (0.10)
Linear measurements			
SPL	0.50 (0.11)	0.46 (0.11)	0.43 (0.12)
A_{CT}	0.29 (0.10)	0.39 (0.10)	0.45 (0.11)
B_{CT}	0.48 (0.11)	0.37 (0.10)	0.38 (0.10)
AR_{CT}	0.51 (0.10)	0.33 (0.10)	0.48 (0.11)
Muscularity			
$ASPL_{CT}$	0.22 (0.09)	0.57 (0.10)	0.46 (0.11)
$BSPL_{CT}$	0.43 (0.11)	0.40 (0.11)	0.37 (0.11)
$ARSPL_{CT}$	0.45 (0.11)	0.46 (0.11)	0.45 (0.11)
WL_{ISC}	0.45 (0.11)	0.25 (0.10)	0.34 (0.09)
WPL_{ISC}	0.36 (0.10)	0.21 (0.10)	0.40 (0.09)
$TMSPL_{CT}$	0.35 (0.11)	0.48 (0.10)	0.31 (0.10)

† Abbreviations are defined in Table 2.

Parameter estimates

Heritability estimates for CT predictions of L:B, linear measurements and measures of muscularity obtained from univariate analyses are shown for each breed in Table 3. Univariate estimates of heritability for live weight, ultrasound measurements and CT predictions of lean and fat are not shown but multivariate estimates are given later.

Heritability estimates for all the linear dimensions were moderate to high (0.29-0.51) and tended to be fairly consistent across breeds. Where differences were present they were generally small relative to the standard errors for the individual estimates. The same was also true for L:B and each of the muscularity measures. Estimates for them ranged from 0.21 to 0.57, but most were around 0.40.

Phenotypic correlations (rp) between each of the CT muscularity measures and fat weight were positive, but estimates were generally small, being less than 0.28 (Table 4). The only exception was WL for the hind leg for which correlations were higher (0.31-0.40). Genetic correlations (rg) with fat tended to be lower than the phenotypic estimates and were not significantly different from zero.

Correlations between CT muscularity and the weight of lean in the carcass were all positive and higher in magnitude than those with fat weight. For the LTL measures, estimates were highest and similar for both $BSPL_{CT}$ and $ARSPL_{CT}$. Estimates of phenotypic correlations between lean weight and these two measures were around 0.40, and those for the genetic correlations ranged from 0.21 to 0.60. Estimates of similar magnitude were also found with the whole carcass measure ($TMSPL_{CT}$) and both CT measures for the hind leg.

Table 4 Estimates of genetic and phenotypic correlations (s.e.) between six CT measures of muscularity and lean weight, fat weight and lean to bone ratio (L:B) for each of the three breeds

		FAT			*LEAN*			*L:B*		
		Charollais	Texel	Suffolk	Charollais	Texel	Suffolk	Charollais	Texel	Suffolk
$ASPL_{CT}$	rp	0.06 (0.04)	0.14 (0.04)	0.10 (0.04)	0.22 (0.04)	0.32 (0.04)	0.25 (0.04)	0.19 (0.04)	0.29 (0.03)	0.21 (0.04)
	rg	*-0.24 (0.25)*	*-0.06 (0.18)*	*0.06 (0.19)*	*0.14 (0.22)*	*0.19 (0.17)*	*0.37 (0.17)*	*0.13 (0.23)*	*0.45 (0.18)*	*0.43 (0.17)*
$BSPL_{CT}$	rp	0.18 (0.04)	0.26 (0.03)	0.28 (0.04)	0.41 (0.03)	0.44 (0.03)	0.36 (0.03)	0.44 (0.03)	0.48 (0.03)	0.40 (0.03)
	rg	*0.11 (0.18)*	*0.17 (0.20)*	*0.28 (0.19)*	*0.60 (0.14)*	*0.30 (0.19)*	*0.32 (0.18)*	*0.73 (0.12)*	*0.78 (0.13)*	*0.38 (0.18)*
$ARSPL_{CT}$	rp	0.18 (0.04)	0.25 (0.04)	0.25 (0.04)	0.40 (0.03)	0.45 (0.03)	0.41 (0.03)	0.48 (0.03)	0.48 (0.03)	0.44 (0.03)
	rg	*0.11 (0.20)*	*0.04 (0.19)*	*0.11 (0.19)*	*0.47 (0.15)*	*0.21 (0.18)*	*0.44 (0.16)*	*0.65 (0.13)*	*0.63 (0.15)*	*0.51 (0.15)*
WL_{ISC}	rp	0.31 (0.04)	0.40 (0.03)	0.34 (0.04)	0.42 (0.03)	0.50 (0.03)	0.31 (0.04)	0.27 (0.04)	0.27 (0.03)	0.11 (0.04)
	rg	*0.35 (0.18)*	*0.39 (0.22)*	*0.08 (0.19)*	*0.56 (0.13)*	*0.25 (0.24)*	*0.29 (0.18)*	*0.69 (0.13)*	*0.62 (0.22)*	*0.23 (0.20)*
WPL_{ISC}	rp	0.08 (0.04)	0.23 (0.04)	0.16 (0.04)	0.29 (0.04)	0.37 (0.03)	0.24 (0.04)	0.15 (0.04)	0.12 (0.04)	-0.02 (0.04)
	rg	*0.15 (0.22)*	*0.24 (0.26)*	*-0.12 (0.18)*	*0.56 (0.16)*	*0.15 (0.27)*	*0.30 (0.17)*	*0.78 (0.15)*	*0.40 (0.28)*	*0.20 (0.20)*
$TMSPL_{CT}$	rp	0.04 (0.04)	0.09 (0.04)	0.21 (0.04)	0.36 (0.04)	0.34 (0.03)	0.46 (0.03)	0.42 (0.03)	0.45 (0.03)	0.43 (0.03)
	rg	*-0.17 (0.23)*	*-0.02 (0.19)*	*0.07 (0.22)*	*0.31 (0.18)*	*0.30 (0.17)*	*0.51 (0.17)*	*0.58 (0.15)*	*0.72 (0.14)*	*0.64 (0.17)*

† rp and rg are phenotypic and genetic correlations, respectively. Abbreviations for the traits are defined in Table 2.

Correlations between the CT muscularity measures and predicted carcass L:B were also all positive, but the magnitude of estimates varied between measures. Correlations with two of the measures for the LTL ($BSPL_{CT}$ and $ARSPL_{CT}$) and the whole carcass measure were similar and moderate to high (rp 0.40 to 0.48 and rg 0.38 to 0.73). The phenotypic association with L:B was, in contrast, weaker for $ASPL_{CT}$ and both measures in the hind leg (rp -0.02 to 0.29).

Consistent sets of parameters

Heritability estimates for the eleven selected traits along with the genetic and phenotypic correlations between them are shown for the Charollais, Texels and Suffolk breeds in Tables 5, 6 and 7 respectively. All parameters shown were derived from the positive definite covariance matrices.

Heritability estimates for all the eleven traits were moderate to high (0.29-0.54), and similar for the same trait across breeds. Estimates of phenotypic correlations were generally higher than those of genetic correlations between the same traits. Correlations between live weight, ultrasound measurements and the predicted lean and fat weights were similar across the three breeds. Scan live weight was highly correlated with both lean weight and fat weight (rg >0.73) and moderately correlated with UMD and UFD (rg 0.32 to 0.50). Correlations between lean weight and UMD and between fat weight and UFD were moderate to high (rg 0.40 to 0.64).

Each of the CT and carcass measures of muscularity was positively associated with UMD and lean weight. Most estimates of correlations were moderate to high (rg>0.26), with the highest being between UMD and $BSPL_{CT}$ (rg >0.64). Estimates between the muscularity measures and scan live weight were also positive or, in the few exceptions, not significantly different from zero. Correlations between muscularity and measures of fatness (UFD and FAT) were negative or low, genetic estimates tending to be less than 0.18, and not significantly different from zero. The only exceptions were two moderate positive correlations for the Texels, one of UFD with WPL_{ISC} (0.42), and the other of BSL with fat weight (0.37).

Correlations between the CT and dissection measures of muscularity were all positive and moderate to high across breeds, with all but one in the range 0.27 to 0.56. The highest estimate for each dissection measure was however, consistently across breeds, with the corresponding CT measure of muscularity (>0.41).

Correlations between the dissection measures for the whole carcass (TMSL) and for the loin (BSL) were high (0.52 to 0.62). Estimates between both measures and the dissection measure for the hind leg were also positive but lower, in the range 0.21 to 0.48. Genetic correlations between the CT measures of muscularity were similar in magnitude to those between the corresponding dissection measures for the Suffolks, but not for the other two breeds. Correlations between the hind leg measure and both whole carcass and loin CT measures were lower for the Texels and higher for the Charollias, but standard errors for these estimates were high.

Table 5 Genetic parameters (s.e) for the for live weight, ultrasound measurements, CT predictions of lean and fat weights, CT and dissection measures of muscularity for the Charollais breed †

	SLW	UMD	UFD	LEAN	FAT	$BSPL_{CT}$	WPL_{ISC}	$TMSPL_{CT}$	BSL	3MFL	TMSL
SLW	**0.38** (0.02)	0.48	0.42	0.86	0.82	0.22	0.16	0.09	NR	NR	NR
UMD	0.36 (0.04)	**0.30** (0.02)	0.28	0.50	0.39	0.53	0.27	0.25	NR	NR	NR
UFD	0.32 (0.04)	0.25 (0.04)	**0.34** (0.02)	0.16	0.58	0.05	0.03	-0.02	NR	NR	NR
LEAN	0.78 (0.04)	0.53 (0.10)	-0.11 (0.14)	**0.47** (0.09)	0.56	0.38	0.28	0.30	NR	NR	NR
FAT	0.72 (0.06)	0.42 (0.12)	0.41 (0.11)	0.42 (0.15)	**0.38** (0.09)	0.17	0.09	0.01	NR	NR	NR
$BSPL_{CT}$	0.14 (0.15)	0.74 (0.08)	0.01 (0.15)	0.57 (0.14)	0.10 (0.18)	**0.43** (0.11)	0.41	0.61	NR	NR	NR
WPL_{ISC}	0.14 (0.16)	0.40 (0.14)	-0.05 (0.16)	0.52 (0.16)	0.14 (0.22)	0.73 (0.14)	**0.36** (0.10)	0.28	NR	NR	NR
$TMSPL_{CT}$	-0.14 (0.17)	0.27 (0.14)	-0.06 (0.16)	0.28 (0.18)	-0.18 (0.23)	0.71 (0.20)	0.73 (0.16)	**0.35** (0.11)	NR	NR	NR
BSL	0.19	0.40	-0.01	0.31	0.02	0.41	0.29	0.33	**0.49**	NR	NR
3MFL	0.33	0.38	0.16	0.47	0.17	0.38	0.58	0.40	0.21	**0.41**	NR
TMSL	0.20	0.43	-0.01	0.39	-0.01	0.35	0.36	0.55	0.55	0.44	**0.40**

† Heritabilities are in bold on the diagonal, genetic correlations below the diagonal and phenotypic correalations are above. Standard errors for phenotypic correlation are all less than 0.04. BSL, 3MFL and TMSL are dissection measures of muscularity for the loin hind leg and whole carcass, respectively. The other abbreviations are defined in Table 2. Estimates of phenotypic and genetic variances for each trait can be derived form the results presented in Tables 2 and 3.

Table 6 Genetic parameters (s.e) for the for live weight, ultrasound measurements, CT predictions of lean and fat weights, CT and dissection measures of muscularity for the Suffolk breed †

	SLW	UMD	UFD	LEAN	FAT	$BSPL_{CT}$	WPL_{ISC}	$TMSPL_{CT}$	BSL	3MFL	TMSL
SLW	**0.30** (0.01)	0.55	0.50	0.91	0.85	0.33	0.30	0.34	NR	NR	NR
UMD	0.41 (0.02)	**0.32** (0.01)	0.31	0.48	0.40	0.57	0.30	0.33	NR	NR	NR
UFD	0.42 (0.02)	0.23 (0.03)	**0.35** (0.01)	0.25	0.60	0.18	0.13	0.10	NR	NR	NR
LEAN	0.92 (0.03)	0.53 (0.09)	0.14 (0.11)	**0.45** (0.09)	0.64	0.34	0.23	0.39	NR	NR	NR
FAT	0.70 (0.06)	0.31 (0.12)	0.64 (0.08)	0.46 (0.14)	**0.41** (0.09)	0.28	0.16	0.16	NR	NR	NR
$BSPL_{CT}$	0.23 (0.14)	0.89 (0.07)	0.17 (0.14)	0.31 (0.18)	0.28 (0.19)	**0.37** (0.10)	0.27	0.55	NR	NR	NR
WPL_{ISC}	0.22 (0.14)	0.21 (0.13)	-0.07 (0.14)	0.30 (0.17)	-0.13 (0.18)	0.17 (0.20)	**0.40** (0.09)	0.19	NR	NR	NR
$TMSPL_{CT}$	0.47 (0.14)	0.51 (0.13)	-0.06 (0.16)	0.54 (0.17)	0.10 (0.22)	0.54 (0.15)	0.34 (0.20)	**0.35** (0.10)	NR	NR	NR
BSL	0.19	0.41	-0.03	0.28	0.01	0.44	0.33	0.33	**0.42**	NR	NR
3MFL	0.33	0.38	0.12	0.38	0.15	0.39	0.58	0.27	0.21	**0.46**	NR
TMSL	0.20	0.43	-0.05	0.32	-0.03	0.37	0.39	0.44	0.55	0.44	**0.36**

† Heritabilities are in bold on the diagonal, genetic correlations below the diagonal and phenotypic correalations are above. Standard errors for phenotypic correlation are all less than 0.04. Abbreviations are defined in Tables 2 and 5. Estimates of phenotypic and genetic variances for each trait can be derived form the results presented in Tables 2 and 3.

Table 7 Genetic parameters (s.e) for the for live weight, ultrasound measurements, CT predictions of lean and fat weights, CT and dissection measures of muscularity for the Texel breed †

	SLW	UMD	UFD	LEAN	FAT	BSPL$_{CT}$	WPL$_{ISC}$	TMSPL$_{CT}$	BSL	3MFL	TMSL
SLW	**0.38** (0.01)	0.58	0.46	0.90	0.86	0.29	0.35	0.12	NR	NR	NR
UMD	0.50 (0.02)	**0.29** (0.01)	0.34	0.56	0.44	0.58	0.36	0.28	NR	NR	NR
UFD	0.40 (0.02)	0.25 (0.03)	**0.38** (0.01)	0.27	0.62	0.10	0.18	0.02	NR	NR	NR
LEAN	0.88 (0.03)	0.42 (0.10)	-0.02 (0.12)	**0.46** (0.09)	0.67	0.36	0.43	0.26	NR	NR	NR
FAT	0.73 (0.06)	0.24 (0.13)	0.58 (0.08)	0.48 (0.17)	**0.40** (0.09)	0.24	0.23	0.07	NR	NR	NR
BSPL$_{CT}$	0.05 (0.14)	0.64 (0.09)	-0.06 (0.14)	0.15 (0.19)	0.11 (0.20)	**0.42** (0.10)	0.29	0.62	NR	NR	NR
WPL$_{ISC}$	0.56 (0.13)	0.26 (0.15)	0.42 (0.17)	0.38 (0.27)	0.26 (0.26)	-0.06 (0.25)	**0.29** (0.10)	0.18	NR	NR	NR
TMSPL$_{CT}$	-0.09 (0.13)	0.10 (0.12)	-0.09 (0.13)	0.13 (0.17)	-0.06 (0.19)	0.59 (0.12)	-0.12 (0.24)	**0.48** (0.10)	NR	NR	NR
BSL	0.48	0.28	0.15	0.43	0.36	0.46	0.32	0.32	**0.45**	NR	NR
3MFL	0.27	0.24	0.18	0.29	0.06	0.33	0.52	0.32	0.48	**0.31**	NR
TMSL	0.30	0.40	0.01	0.32	0.01	0.38	0.17	0.51	0.62	0.41	**0.57**

† Heritabilities are in bold on the diagonal, genetic correlations below the diagonal and phenotypic correalations are above. Standard errors for phenotypic correlation are all less than 0.04. Abbreviations are defined in Tables 2 and 5. Estimates of phenotypic and genetic variances for each trait can be derived form the results presented in Tables 2 and 3.

4.4 Discussion

Parameters: CT measures

The moderate to high heritability estimates reported in this study for the CT measures of whole carcass and LTL muscularity were to be expected given that the estimates for each of the components used to derive them were also moderate to high. The high measurement accuracy achieved by using CT was reflected in the fact that the heritability estimates reported here were similar to those in the literature for measurements made directly on the carcass. Reported heritability estimates range from 0.23 to 0.38 for LTL depth, from 0.28 to 0.63 for width and 0.29 to 0.31 for area (Thorsteinsson and Bjornsson, 1982; Bennet *et al.*, 1991; Waldron *et al.*, 1992a; Pollott *et al.*, 1994; Thorsteinsson and Eythórsdóttir, 1998). No estimate of heritability for spine length measured on the carcass has been published, but the estimates reported in this study are similar to those for carcass measurements of body length (0.59) estimated by Thorsteinsson and Bjornsson (1982) and for carcass length (0.42) reported by Waldron *et al.* (1992a).

The heritability estimates for CT measured LTL depth were only marginally higher than those estimated for the corresponding ultrasound measurement in this and other studies (Young and Simm, 1990; Cameron and Bracken, 1992; Thorsteinsson and Eythórsdóttir, 1998). This is not surprising given the results reported in Chapter 3, where it was found that the CT measurements were only marginally better than ultrasound measurements as predictors of the corresponding carcass dimension. The benefit of using CT over ultrasound for measuring LTL width and area was, however, highlighted by the differences between the heritability estimates reported here for CT measurements and those in literature for ultrasound, which are typically less than 0.15 (see Fogarty, 1995 for a review).

The coefficients of variation reported in this study for the CT measures for the LTL, and the correlation estimates for them with lean weight, fat weight and L:B were in agreement with those reported by Waldron *et al.* (1992b) for similar measures on the carcass. The lower correlations estimated with fatness and L:B for the $ASPL_{CT}$

measure are in keeping with the view (Young, 1990) that the width of the LTL (A) is an earlier maturing dimension relative to its depth (B). The correlations with fatness were lowest with the $ASPL_{CT}$ measure, but they were also low for the other two measures for the LTL. Since the correlations with L:B were higher for these other two measures than with $ASPL_{CT}$, they were considered preferable to use where the aim (as was here) is to characterise the muscularity of the loin using a single measure. In this study the $BSPL_{CT}$ measure was used in preference to $ARSPL_{CT}$ since data were not available to derive a dissection measure that was equivalent to the latter. However, either would have provided an equally good measure for the loin.

The aim by using the ratio of two perpendicular measurements on each thigh on the ISC scan, was to develop a highly repeatable *in vivo* measure of muscularity for the hind leg that was robust to variations in leg position (Chapter 3). Whilst this was not formally tested, the moderate to high heritability estimates reported in this Chapter does suggest that the aim had been achieved.

As was suggested in Chapter 3, the WL_{ISC} CT measure for the hind leg, which ignores the thickness of popliteal fat, was positively associated with carcass fatness. This undesirable association was successfully reduced by using the alternative WPL_{ISC} measure. Measurement error and thus the residual variance were expected to be higher for the WPL_{ISC} in comparison to WL_{ISC} due to the additional measurement being taken. This was the case for two of the three breeds and resulted in the lower heritability estimates for the former measure. It is important to point out however, that there was no reduction in the amount of genetic variation present, as the total amount of phenotypic variance for WPL_{ISC} increased relative to WL_{ISC}. When considered along with the lower correlations with fatness, this indicates that the WPL_{ISC} would be the preferred CT measure for the hind leg.

The low phenotypic correlations between L:B and both the CT measures for the hind leg were unexpected. Two reasons may account for these estimates. The first, that the correlation between the dissection measure of muscularity and carcass L:B is also low. This may be expected if the length of the femur is a poor predictor of total bone weight in the carcass. Whether this is indeed the case is unclear since a correlation between a dissection measure for the hind leg and L:B has not been reported in any previous studies. The second and more likely reason is that, since the CT measures did not include a direct measurement of femur length, the phenotypic correlation with them was lower than would be found with the dissection measure. This reason would also account for the higher estimates of genetic correlations between these two CT measures and L:B. Further work will be required for this issue to be resolved.

Heritabilities for the total weights of lean and fat in the carcass and their correlations with live weight and ultrasound measures of muscle and fat depth have been estimated in relatively few previous studies, presumably as a result of the high cost associated with dissecting complete carcasses. Nonetheless, heritability estimates that have been reported are generally in the range of 0.40 for lean weight and 0.32 for fat weight, which are marginally lower than those reported for the predicted weights for each breed in this study (Waldron *et al.* 1992a; Fogarty, 1995, review). This does suggest that more accurate measures of composition can be obtained using CT than by dissection. This may well be true given the distinct possibility of measurement errors when a large number of carcasses are being dissected. The correlations of the tissue weights with live weight and the ultrasound measurements and between the latter three measures reported in this study, are very similar to those used by Simm *et al.* (1987) and subsequently by Simm and Dingwall (1989) for index calculations.

Consistency of parameters

Particularly given that some of the parameters used to form the initial variance covariance matrices were approximated from a phenotypic analysis, it is not surprising that these matrices were non-positive definite and required modification. Changes in parameters following modification of the matrices for the Charollais and Suffolks were small, being less than 0.05 for correlations estimates. However, the same was not true for the Texels, where some larger changes occurred, particularly the genetic correlations of WPL_{ISC} with $BSPL_{CT}$ and $TMSPL_{CT}$, and lean weight with $BSPL_{CT}$ and $TMSPL_{CT}$, which were reduced by around 0.10.

The approach used in this study to attain positive definite matrices had the benefits of being relatively simple. Unfortunately however, it did not take into account the differences in the reliability of some covariance estimates. This was an important issue in this study given that covariances used could be divided into three groups differing widely in reliability, from very high for those between the live weight and ultrasound measurements to low for the phenotypic approximations used for the dissection measures of muscularity. It was particularly true for the Texels given the small number of lambs for which dissection information was available, and problems with these estimates are likely to account for most of the inconsistencies present in the genetic covariance matrix for this breed. Whilst more complex methods of attaining consistent parameters have been proposed in the past, such as 'bending' by Hayes and Hill (1981), no method, to the authors knowledge, has been developed that would allow different weightings to be applied to the estimate in the three groups. If such a method does become available then it would be useful to apply it the original parameters estimated in this study to investigate if differences would occur.

Previous genetic analyses of muscularity in sheep have been limited to the one study by Waldron *et al.* (1992b), which considered only dissection measures in the loin; therefore there is little opportunity to compare the parameters obtained in this study for the dissection measures of muscularity. Nevertheless, one of the measures used by Waldron *et al.* (1992b) was similar to the BSL measure defined in this study, and they estimated a heritability of 0.43 and genetic correlations with lean and fat weight of 0.32 and –0.06, respectively. These results are very similar to those reported here for the BSL measure in each breed, the only exception being the correlation with fatness for the Texel lambs, which was higher (0.36).

Ideally, a further trial should be conducted to obtain improved estimates of correlations between the dissection measures of muscularity and the other measures, particularly for the Texels and Charollais. In the meantime the greater uncertainty surrounding some of the correlations estimates should be accounted for if these parameters are used for index calculations. This could be done by investigating the effect of fairly large changes in the correlation estimates in the sensitivity analyses when deriving index coefficients.

Prospects for incorporating muscularity into selection programmes

The results of this study suggest that measures of muscularity could be incorporated into a selection programme that included increasing lean weight and reducing or restricting fat weight amongst its selection objectives, without large detrimental effects on current responses. Given the parameters reported, small correlated improvements in muscularity would be expected by simply selecting for increased lean weight. However, higher responses could be achieved by including muscularity in the selection objective and using the CT measures as selection criteria.

Correlations between the different dissection measures of muscularity were positive but not high. This implies that if improving muscularity in different parts of the carcass is considered important, more than one measure (e.g. loin and leg) may need to be included amongst the selection objectives and consequently more than one CT measure used as selection criteria.

Conclusion

The results of this study show that good *in vivo* measures of muscularity can be obtained using CT scanning, and these measures plus those for *in vivo* predictions of lean and fat weight are moderate to highly heritable in the Charollais, Suffolk and Texel breeds. Incorporation of CT predictions of lean and fat weights into current selection programmes would result in higher responses in improving lean growth. Moreover, given the parameters reported, measures of muscularity could also be incorporated into these selection programmes, without large detrimental effects on current responses.

The parameters reported in this study can now be used to develop selection programmes for the Charollais, Suffolk and Texel breeds of sheep that make best use of CT technology to improve lean composition and muscularity.

Chapter 5

Market requirements for lamb

5.1 Introduction

One way of obtaining selection indices that are directly related to market requirements and price signals for lamb would be to develop economic indices (Chapter 1). For this to be achieved, meaningful economic values for the objective measures would need to be obtained. These values cannot be calculated unless the requirements of markets for lamb and the prices paid for carcasses are known. Since the benefits of genetic improvement are gradually accumulated with continued selection over a number of years, the requirements of likely future markets as well current markets also need to be considered. This is particularly true where market requirements were likely to change and ignoring the likely requirements of future markets could well have detrimental effects on returns achieved in the long term. Unfortunately, all this information is not widely available, particularly the likely requirements of future markets.

Recent information about requirements of current markets is generally confined to overviews produced by the Meat and Livestock Commission (MLC) (e.g. MLC, 1999a and 2000). In these, requirements are defined broadly in terms of the MLC carcass classification scores for fatness and conformation, which are widely used by the industry as a measure of carcass quality. Fatness is scored, based on a subjective assessment, as 1, 2, 3L, 3H, 4L, 4H or 5, where 1 has least and 5 most fat, and conformation is scored as E, U, R, O or P, where E has the best and P the worst conformation. The general requirements are seen as fat class 1, 2 or 3L and conformation E, U, or R. More detailed information about the relative economic value of different classifications and carcass weights preferred by different markets is not given.

Kilkenny (1990) indicated that largest domestic markets preferred a carcass weight range of 16-20 kg, conformation R or higher and fat classes 2 or 3L, with increasing preference for fat class 2. Conformation was seen as the least important aspect of carcass specifications. Kilkenny (1990) and Richardson *et al.* (1990) also indicated a growing demand, for heavier, lean carcasses, to supply the growing boneless and processed lamb markets, due to the potential for lower boning cost per kg of lean meat. If demand for boneless lamb products continues to grow this will have important consequences on the requirements of future markets. The conclusion drawn by Kilkenny (1990), that conformation is of comparatively lower importance, is also interesting and requires further investigation since it would affect the relative importance placed on improving carcass shape in any selection index.

The main aims of this study were to establish: (i) the current carcass specifications required by different markets, (ii) the relative importance of bone-less product in current markets (iii) the relative importance of higher conformation in current markets and (iv) the likely carcass specifications required for future markets.

5.2 Methods

Two questionnaires were designed and sent out in September of 1999, one to abattoirs and the other to domestic retail companies (Appendices 2 and 3, respectively). Retail companies were targeted since they formed the largest market for UK produced lamb in 1998, accounting for 59% (household purchases; MLC, 1999a).

Representatives from companies similar to those targeted were consulted during the design phase. This consultation was used mainly to minimize the number of questions that may be considered commercially sensitive and were therefore unlikely to be answered. Both questionnaires were sent out to the largest companies in their respective sectors. This approach allowed a large proportion of the lamb sold in each sector to be accounted for, and the number of companies involved was sufficiently small to allow contact by telephone to encourage a higher return rate for the questionnaires.

The abattoir questionnaire was sent out to the 46 abattoirs in the UK which slaughtered more than 100,000 lambs between April 1998 and March 1999 (MLC, unpublished). The retailer questionnaire was sent out to the 13 retail companies in the UK that each accounted for more than 0.5% of household purchases of lamb (fresh and frozen) in 1998 (MLC, unpublished).

Each questionnaire focused on three main areas: (i) buying lamb; (ii) selling lamb; and (iii) the likely future market requirements for lamb. A further two smaller sections were also included, one focused on the importance of higher conformation and the other on buying and selling of boneless lamb. In the abattoir questionnaire, questions relating to selling lamb were split into two sections, domestic and export. Domestic sales were further split into four categories, retail, catering, wholesale butchers and other; the first three categories were expected to define the main market outlets for lamb based on the initial consultations with abattoir representatives.

The main emphasis when asking abattoirs how they bought lambs was in relation to dead weight purchasing (payments for the assessed carcass). Most abattoirs purchase both live lambs (through auctions) and on dead weight, but only in the latter is purchase price related to carcass weight and subjective assessments of fatness and conformation. This information is therefore most useful for establishing the relationship between carcass quality and price. The carcass classification scores are also frequently used in specifications given by customers, and so having this information allows the relationship between customer requirements and payments to producers to be assessed.

To ensure that a good overview of the lamb market had been achieved, once the replies had been obtained, a summary of the findings was produced and this was sent back to each of the respondents for confirmation.

5.3 Results

5.3.1 Abattoir Sector

Responses were obtained from 20 of the abattoirs contacted. These collectively accounted for 44% of the total UK lamb kill in the year 1998/99.

<u>Buying lambs</u>

The majority of abattoirs bought lambs both on a dead weight basis and through live auctions. All but five purchased most of their lambs (>60%) on a dead weight basis.

The preferred carcass weight range for lambs bought dead weight was generally 16-21 kg. Deviations from this range were small (+/- 1 kg). Only two abattoirs extended their preferred range further (8-21 kg and 13-22 kg). Carcasses lighter than the lower limit of the preferred weight range were discounted (10-50 p/kg). The upper limit was the maximum weight for which payment was made.

Payments made to producers were a combination of a base price per kg with premiums and penalties paid depending on fat and conformation classifications. Base prices changed either on a weekly or daily basis. The national average live auction price, competitors price and throughput rate were all indicated as factors influencing the base price and abattoir set. When throughput rate was below maximum, the base price paid was frequently inflated to try to increase the number of lambs sold to the abattoir.

Carcass classification using the MLC scores was performed in nearly all abattoirs, both for lambs bought on a dead weight basis and through live auctions. Only in one abattoir was the MLC scale not used. In this case producers were not paid on the basis of a carcass classification.

The abattoir's preferences for specific carcass classifications are best characterised by the premiums and penalties paid for each grade (conformation and fat class combination), frequently shown as a price grid. The price grid currently used for producer payments was obtained from 12 abattoirs. The average price grid, over these twelve abattoirs is shown in Table 1.

Fatness was more important than conformation with differences in premiums/penalties between adjacent fat classes tending to be greater than between conformation classes. Only carcasses classified as fat class 2, 3L and conformation E, U consistently received premiums, with no differentiation made in terms of premiums between the two fat classes. Carcasses in fat class 1 and 4L-5 were penalised but considerable variation existed in the penalties imposed ranging, for the extreme fat classes, from -5 to -100 p/kg for fat class 1, and between -20 and -100 p/kg for fat class 5.

Table 1 Premiums and penalties paid to producers for carcasses in each grade (p/kg carcass weight) averaged over the 12 abattoirs that supplied their price grid.†

	1	2	3L	3H	4L	4H	5
E	-22.5 (10)	+14.6 (12)	+14.6 (12)	+3.3 (12)	-16.4 (11)	-36.5 (10)	-51.7 (9)
U	-24.3 (10)	+9.8 (12)	+9.8 (12)	+0.33 (12)	-18.2 (11)	-36.5 (10)	-51.7 (9)
R	-26.3 (10)	+3.0 (12)	+2.4 (12)	-4.3 (12)	-20.0 (11)	-36.5 (10)	-51.9 (8)
O	-32.5 (8)	-5.2 (12)	-4.3 (12)	-12.8 (12)	-30.4 (12)	-41.8 (11)	-51.9 (8)
P	-64.3 (7)						

† The number of values used to calculate the mean is shown in brackets. Where this number is less than 12 the remaining abattoirs paid a realisation price for that grade of carcass, which was ignored in the calculation of the cell mean. The realisation price is not fixed and is a reflection of the price obtained when the carcass is sold to a third party.

Within fat class 2/3L, five abattoirs did not differentiate between classes U and E in terms of the premiums paid. Price differences between adjacent conformation classes in other fat classes tended to be small. With the exception of the poorest class (P), price differences were frequently not present between conformation classes within the most extreme fat classes (4H and 5).

Choice of premiums and penalties

Understanding how premiums and penalties are chosen should give some indication of how stable these are likely to be over time. Four main factors that affected the choice of premiums and penalties were identified. These were:

1) Customer requirements

Carcass grades specified by the abattoirs main customers effected which grades received premiums. Whether stable markets were available for carcasses outside this range affected the magnitude of penalty imposed.

2) Previous distribution of carcasses over the classification grid

Where a high proportion of carcasses had fallen outwith the desired range, higher penalties and premiums were usually used in order to encourage a shift in the classifications of carcasses on offer to the abattoir. The frequency with which price grids were changed differed between abattoirs. For the majority the price grid was changed annually, but three abattoirs changed their price grid seasonally as the carcass quality of the lambs available generally change.

3) Differences in yield between different classes

Eleven abattoirs had undertaken in-house trials to quantify the differences in saleable meat yield between carcasses in different fat and conformation classes and the economic value of these differences.

4) Competition for lambs available

Seven abattoirs indicated that the differentials used were not a true reflection of the value of different carcass grades. Penalties for over-fat carcasses were usually less than should be imposed if trimming and marketing costs were to be recovered. True costs were not passed on in fear that producers may sell their lambs to other abattoirs where penalties are less, or through live auctions.

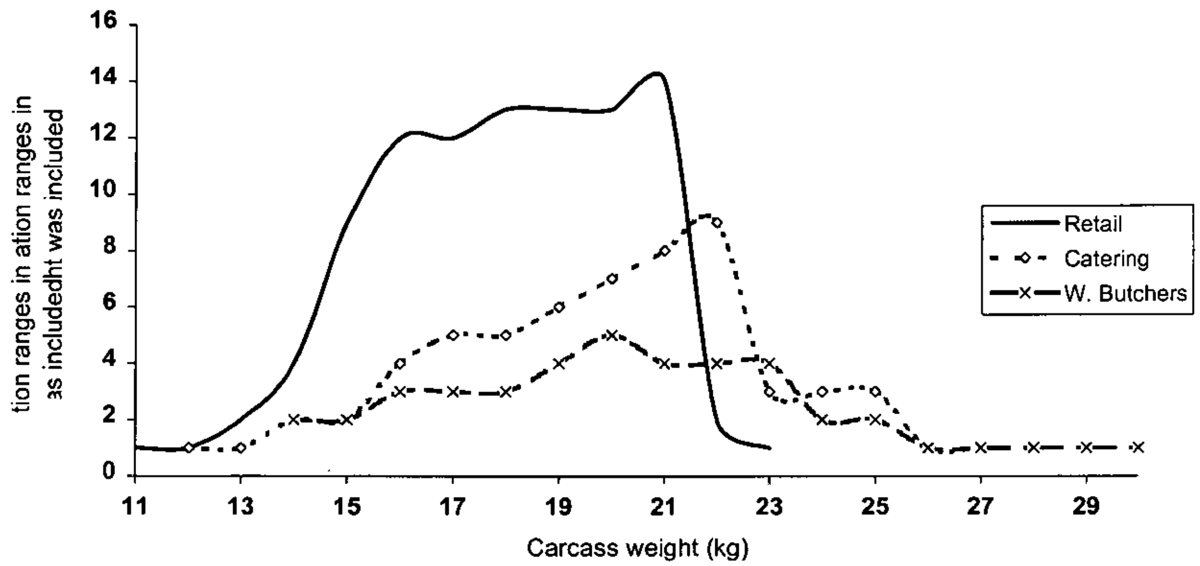
Selling Lamb

The majority of the abattoirs supplied both the export and domestic markets, the highest proportion tending to be destined for the latter. Only six abattoirs exported more than 50% of their lamb output and two abattoirs supplied only the domestic market.

Domestic Market

The frequency with which specific carcass weights, conformation classes and fat classes were included in the specification ranges for retail, catering and wholesale butcher customers are shown in Figures 1 to 3. Distributions are based on information given by abattoirs supplying the retail (16 abattoirs), catering (8 abattoirs) and wholesale butcher (7 abattoirs) trades.

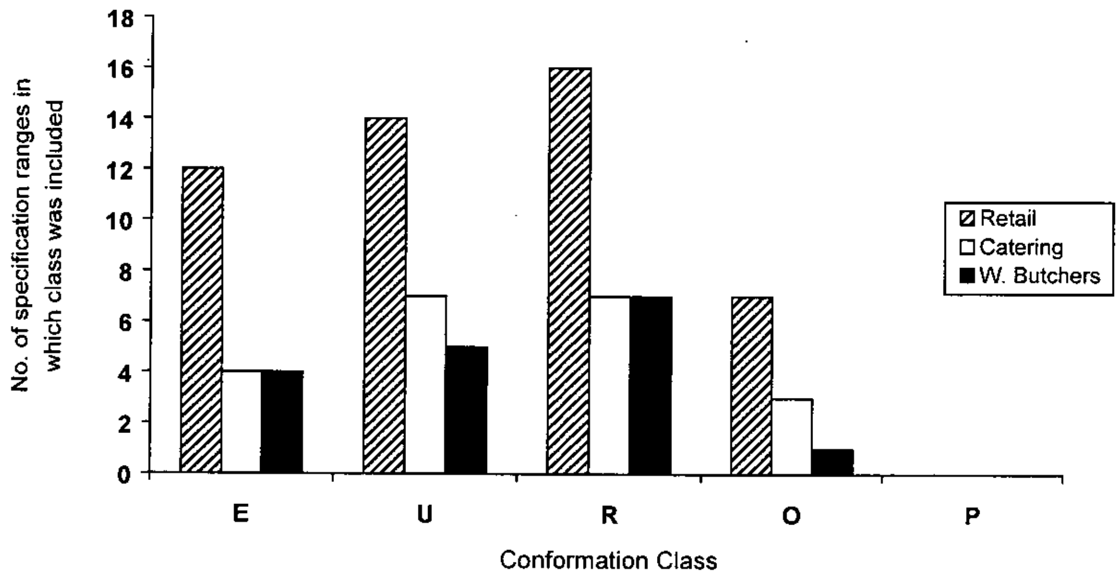
Figure 1 Frequency distribution for carcass weights included in specification ranges given by each domestic customer type



1) Retail

Although carcasses supplied to the retail trade ranged from 11-23 kg, the supply of 16 to 21 kg carcasses was most common. Similarly, for conformation a range of E-R was most common, but some large retailers allowed a small proportion classified as O where sufficient numbers of EUR carcasses could not be supplied. A greater preference for classes U and R was evident. The range specified for fat classes was most frequently 2 to 3H, with fat class 3L tending to be preferred.

Figure 2 Frequency distribution for conformation classes included in specification ranges given by each domestic customer type



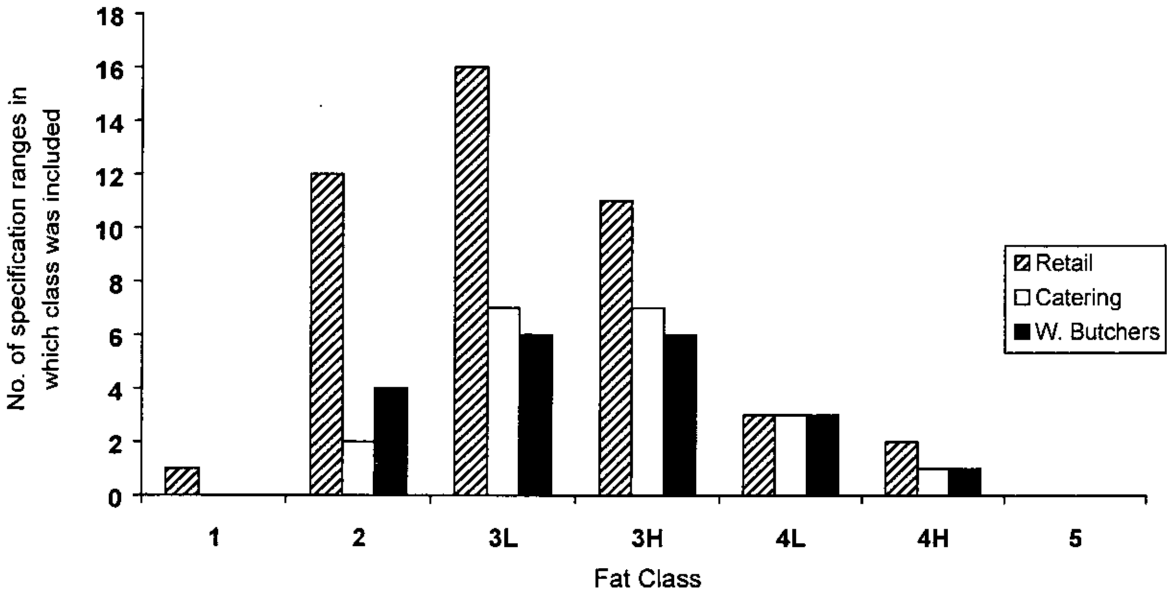
2) Catering

The upper limit for carcass weight specified tended to be higher for the catering sector than for retailers, typically 22-25 kg. Specifications given for conformation and fat classes were very similar to those of retailers, although a greater preference for fat classes 3L and 3H was evident.

3) Wholesale butchers

Wholesale butchers are a common customer for most abattoirs. However, the carcasses purchased are frequently sold on to catering or retail trades. The similarities between specifications given by wholesale butchers and those given by retailers and caterers are therefore unsurprising.

Figure 3 Frequency distributions for fat classes included in specification ranges given by each domestic customer type



Export

The largest proportions of exports were accounted for by sales to customers in France, Germany and Belgium. French customers accounted for the largest proportion, typically 60-90% of most abattoirs total exports. Some abattoirs also exported to Portugal, Spain, Italy, Greece, Switzerland and Austria but these generally accounted for a small proportion of their export and, with the exception of sales to Switzerland and Austria, consisted of only carcasses weighing less than 14kg.

Carcass weights, conformation and fat classes preferred by French customers were similar to retail customers in the UK (16-20 kg, fat class 2, 3L and conformation E, U, R). As for domestic retailers, ranges for conformation and fatness were often extended to include O and 3H scores. Carcass weights and conformation classes specified by German customers tended to be lower, being typically 13-18 kg and R-O. Belgian customers preferred carcasses of higher conformation E and U. Fat class 2 tended to be preferred in both of the latter markets.

The ideal carcass for current markets (Domestic and Export)

In the questionnaire respondents were asked to identify a single weight, conformation and fat class that was most suitable for the current domestic and export markets. The answers received were very consistent with only a range of 2 kg for the carcass weight. The ideal carcass for the current domestic market was generally seen as 18 kg, conformation R/U and fat class 3L. For the export market, a carcass weight of 18 kg, conformation U/E and fat class 2 was considered most suitable.

Value of higher conformation

Most abattoirs indicated that their domestic customers did not pay premiums for carcasses of higher conformation (E versus U, U versus R). One abattoir indicated that premiums were available from some retail butchers, but this is likely to be a very small market. Numerous respondents indicated that premiums were available for E class carcasses in some export markets providing they were sufficiently lean (fat class 2 or 3L).

Bone-less lamb

Sixty five percent (13) of the abattoirs that replied were de-boning lamb. Bone-less lamb constituted on average 25% of their lamb sales (range 5-50%). Each company predicted that the proportion sold as bone-less would increase with future production expected to be 46% (range 30-75%). Only seven of these companies predicted that the upper limit to their preferred carcass weight range would increase as the bone-less output increased. Even then, a carcass weight of 24-25 kg was seen as a limit to which the range could be extended. Three limitations were suggested to affect the weight of carcass that could be routinely used for de-boning:

1) Risk of increasing carcass fatness

Carcasses to be de-boned need to be sufficiently lean (fat class 2 or 3L). The extent to which carcass weights could be increased would depend on the carcasses not becoming too fat.

2) Size of boneless cuts

As carcasses become heavier, the size of certain boneless cuts, such as steaks (chump/leg steaks) also increases. Size specifications given by customers with regards to these cuts, may limit the size and weight of carcass that could be used.

3) Continuity of supply

Heavier carcasses would need to be available in sufficient numbers throughout the year to justify changing the current practice of using carcasses from the 16-21 kg range. Currently larger carcasses were only available for relatively short periods during the year, and thus did not justify changing the current practice.

Future market for lamb

Most abattoirs did not foresee a change over the next 10-15 years in the carcass specifications being given by customers. However, two respondents did anticipate a narrowing in their customer's specifications. One of these respondents anticipated the development of two distinct markets for lamb. These included a market for medium weight lambs to produce bone-in joints and cuts, and a market for heavier lambs to be used for producing bone-less lamb.

5.3.2 Retail sector

Responses were obtained from eight of the 13 companies from the retail sector that were contacted. These eight companies accounted for 57.3% of the lamb sold through retail outlets in 1998 (MLC, unpublished), and consisted of seven supermarkets and one retail butcher chain.

<u>Buying lamb</u>

For most of the supermarkets, lamb was bought either as primal cuts/joints or as retail packs. Only one supermarket and the retail butchers bought a proportion of their lamb supply as whole carcasses for in-house butchering. As a result, specifications given by supermarkets were usually for retail packs or specifications for primal joints. Ranges for carcass weights and grades were given to their suppliers but served mainly as a guide to the weight and grade of carcass that were most suitable to obtain cuts that met these specifications.

Carcass weight ranges given by supermarkets were generally 16-21 kg, with only one supermarket chain specifying a narrower weight range of 16-18 kg. For the retail butcher lighter carcasses were preferred (13 to 16 kg). A range of E-R were given for conformation classes, with some supermarkets allowing a small proportion of carcasses classified as O, in order to achieve continuity of supply. Similarly, for fat score a range of 2-3L was preferred, with some allowance by supermarkets for a small proportion of selected 3H carcasses in order to achieve sufficient supply.

Primal and retail pack specifications

Where lamb was bought in only as primal joints and retail packs, specifications for fat depths over the joint were also given. The maximum fat depths specified ranged from 5 to 8 mm with variation between different joints in some cases i.e. less than 6 mm for the loin and less than 8 mm for the shoulder. Minimum fat depths were not specified, being determined by carcass fat class. Other specifications such as the presentation and weight of retail packs were also given. These were chosen largely on the basis of feedback from consumer panels/ listening groups that were organised by the retail company.

<u>Selling lamb</u>

The majority of lamb was sold through retail outlets as bone-in roasting joints (44-57%) and a further 19 to 28% sold as bone-in cuts (i.e. loin chops). Bone-less products generally accounted for 10 to 33% of total sales for supermarkets, consisting mainly of roasting joints, steaks and mince.

Ideal carcass

As in the abattoir questionnaire, respondents were asked to indicate their ideal carcass specifications. Supermarket respondents generally indicated that their ideal carcass was 18 kg, conformation U/R and fat class 3L. A single specification was not obtained for the butcher chain.

The value of higher conformation

Carcasses of higher conformation were perceived to produce cuts with greater muscle depths and a better lean to bone ratio, which increased the aesthetic value of cuts. The cuts and joints in which these attributes were most important were loin chops, the leg and cutlets.

Cuts and joints from E class carcasses were considered frequently too big or too heavy by supermarkets to meet their retail pack specifications. A high proportion of E conformation carcasses was therefore considered undesirable, and carcasses classed as U and R were generally preferred. Premiums were not paid for carcasses of higher conformation (E *versus* R).

Some supermarket respondents suggested that the benefits conveyed by high conformation carcasses could justify the development of a separate product line for cuts from these carcasses which could be marketed at a premium. However, the development of such product lines could not be justified currently due to the small and inconsistent supply of E class carcasses that were available commercially.

Bone-less lamb

All but one company expected the proportion of lamb sold as bone-less products to increase; the proportion anticipated in the future was 40 to 50%.

Separate carcass weight ranges were not given to suppliers for carcasses to be used for de-boning. Relatively few respondents were able to suggest an upper limit to the carcass weights that could be used. However, where given, upper limits were seen as 22-23 kg, based on concerns of over fatness and unit size of cuts such as steaks.

Future market for lamb

Most respondents expected little change in carcass specifications given to suppliers over the next 10-15 years. However, four supermarket respondents suggested that the range given for carcass weights, conformation and fat classes were likely to be reduced, with the aim of increasing the uniformity of the lamb products sold. None of these companies speculated what the future specifications were likely to be.

5.4 Discussion

Current market requirements

Carcass specifications required by the largest markets for lamb (domestic retail, catering and exports to France) were similar, preferring carcass weights of 16-21 kg, conformation class R or higher and fat class 2 or 3L. These results are in agreement with those indicated by Kilkenny (1990), suggesting that specifications being given have changed little over the last 10 years, despite perceived changes in consumer requirements and marketing methods.

The increasing preference for carcasses of fat class 2 indicated by Kilkenny (1990), although present for some export markets, was not apparent for the UK domestic market. Carcasses of fat class 3L tended to be preferred by retailers and classes 3L and 3H by caterers. The reasons for this domestic preference were unclear, although two of the retail respondents suggested that more uniform fat cover over different joints were obtained from 3L carcasses. Whether this claim is justified may require further verification. Presumably caterers perceive that the higher fat content of these carcasses confers some benefit during cooking, although there is little evidence to support this view. This preference for fatter carcasses may partly explain why heavier carcasses tended to be used for catering versus retail, the higher fat content of a heavier carcass being more readily accepted.

Carcasses of conformation class R were considered adequate for the majority of markets. Premiums for higher conformation carcasses were generally not paid to abattoirs, with the exception of relatively few export customers. Opportunities for obtaining premiums for higher conformation from the largest market (domestic supermarkets) seem small. Although the development of a separate product line was indicated as one possibility, only 0.7% of the carcasses classified by the MLC within the 16-22 kg weight range were classified as being E, 2/3L in 1998-99 (Appendix 4). Since these carcasses are also in demand for some export markets, large increases in the amount available would be needed before such developments could even be considered.

Bone-less lamb

The increasing importance of lamb sales in a bone-less form was emphasised in these results. However, the increasing tendency to use of heavier carcasses within the range 20-24 kg to supply this market, as indicated by Kilkenny (1990), was not apparent. Bone-less products continued to be produced from carcasses within the range of 16-21 kg. The attraction of lower de-boning costs per kg of lean seem to be out-weighed by concerns about the supply and fatness of heavier carcasses and the increasing size of some bone-less cuts.

The degree of fatness is likely to be the main barrier to the routine use of heavier carcasses since costs associated with reduced yields and trimming when carcasses are too fat may well be greater than any advantage of reduced de-boning costs. Recent reports have shown that the concerns about the fatness of heavy carcasses currently available, are justified (MLC, 1997 and 1999). In 1998, approximately 50% of carcasses classified by the MLC within the range of 22-24 kg were considered over-fat (>3L), and this proportion was even higher in heavier weight categories.

Numerous respondents did express a wish to use heavier carcasses to produce bone-less lamb in the future. It therefore seems reasonable to propose that a market would develop for them if lean heavy carcasses (21 kg+) could be produced in reasonable numbers. If these improvements were achieved, other concerns such as the size of some cuts may be overcome by the development of alternative cutting techniques.

Payments to producers

The pricing system used by abattoirs to pay lamb producers reflected market requirements in so far that the carcass grades and weights preferred received premiums. However, for fatness in particular, price differences between classes did not reflect their true market value. An abattoir's need to maintain throughputs (so that overheads cost per carcass are kept low) often led to higher base prices and lower penalties for over-fat carcasses than should be used to truly reflect product value. This problem of inconsistency between market demands and payments to producers has been flagged in past (Simm, 1998) and is likely to be a consequence of the over-capacity that has been shown to still exist in the British abattoir sector, particularly for the slaughter of lambs (MLC, 1999b).

Future market requirements

No clear forecast of likely requirements for future markets was obtained from the questionnaire responses. This may partly be due to the potential commercial sensitivity of such information, but may also reflect the lack of clear communication between different sectors of the sheep industry.

A number of respondents, particularly from abattoirs, anticipated little or no change to their desired specification ranges in the future. For abattoirs that supply a number of different customers, this view is not unexpected since a relatively broad range of specifications may be needed to meet all their requirements. However, numerous abattoir and supermarkets respondents also indicated problems in finding a sufficient supply of lambs that met their current specifications. These problems are likely to be reflected in the answers given. Under current conditions, even if desired, any narrowing in the range of carcass specifications would likely result in greater supply problems, and thus would be considered impractical in the long term.

This problem of achieving sufficient supply of lambs within the desired grades is not surprising given that only 56% of carcasses classified in 1998-99 by the MLC in the weight range of 16-22 kg met the criterion of EUR conformation and fat class 2/3L (Appendix 2). The proportion of carcasses that meet target specifications has changed little over the last ten years (e.g. MLC 1991 and 2000), illustrating that the industry has been slow to react to market needs. This situation has persisted despite technology (selection indices) being available that could help ensure improvement. The fact that a large proportion of lambs are sold through live auctions, where the link between quality and price are less clear, and that relatively small economic incentives to improve the quality of carcasses are available for those producers selling dead weight, have likely contributed to this slow reaction. Large increases in the proportion of carcasses meeting these requirements are therefore unlikely on a national scale if this situation continues.

The recent development and increased popularity in the UK of producer groups and partnerships between producers, abattoirs and supermarkets does provide an opportunity for effecting more rapid change (Fearne, 1998). All producers within these schemes are obliged to sell dead weight. The closer links between the different levels of the supply chain also allows the supermarkets wishes to be conveyed directly to producers and stronger economic incentives instituted to encourage the supply. The carcass specifications supermarkets would wish to obtain are likely to be those indicated in some of the answers reported here.

Numerous supermarket respondents indicated a desire to reduce the range of carcass specifications they give to suppliers in order to increase the uniformity of the product they sell. The range desired was not explicitly given, but presumably would focus around the perceived ideal for the current market of 18 kg, U/R, 3L. This lower carcass weight is in contrast with the view that heavier carcasses will increasingly be used to produce bone-less lamb. However, the weight of carcass from which bone-in joints are produced is more important than for bone-less lamb and therefore this specification is more likely to reflect that desired for producing bone-in lamb.

The anticipated development of two distinct domestic markets for lamb expressed by one abattoir respondent, one for medium weight carcasses to produce bone-in joints and cuts and a separate market for heavier lambs to be used for producing bone-less lamb does follow the suggestions put forward by the supermarket respondents. Particularly, if the supermarkets share of the domestic retail lamb market continues to grow [60.4% in 1998 from 31.7% in 1988 (MLC, 1999a)], this should be considered seriously as a possible future development.

Implications for breeding schemes and new index development

Given current requirements and economic incentives, the aim for producers should be to produce lambs with a carcass weight of 20-21 kg, fat class 3L and conformation R+. Aiming for a carcass weight at the upper end of the preferred weight range would increase the unit value of the carcass produced, but lambs that could not attain a fatness equivalent to fat class 2 until their carcass weight was greater than 21 kg would be considered undesirable.

If two separate markets do develop, with different specifications, this poses distinctly different challenges. Following current suggestions, one market would require a carcass weight of 18 kg, fat class 3L and conformation R+, and the other a carcass weight of 21 kg+, fat class 2/3L and conformation R+. This implies that two different types of lamb would need to be produced. Some variation may be achieved by the use of different dam breeds, but the development of two sire types could also be needed. From a breeding perspective, this would suggest the adoption of two different selection indices. These could be used either within different breeds, with a view of using different breeds to meet the different requirements, or within a breed with a view of developing two separate lines.

Conformation and carcass shape is important in so far as it does have some economic value and should be at least considered in the development of any new index. But, the incentive to produce lambs of conformation score higher than R was relatively small and is unlikely to be large in the future. A strong emphasis on improving shape in any new selection index cannot be justified simply on the results of this study. Nevertheless, possible positive impacts on the uptake of the selection technology by including shape measure in the index should also be considered when deciding on its relative importance.

Conclusions

The results of this survey provide a valuable insight into the current markets for lamb and those likely in the future. This information can now be used to help calculate economic values for traits of interest, and as a basis for theoretical investigation of suitable selection indices.

The inconsistency between market demands and payments to producers does raise questions over the value of using market prices as a basis for choosing long-term selection decisions, however these prices do provide a useful starting point for theoretical investigations.

Chapter 6

A bio-economic model for estimating the economic value of unit changes in lean or fat weight at a fixed age for terminal sire breeds of sheep

6.1 Introduction

Bio-economic models have increasingly been used over recent years as a method for calculating economic values for traits included in the objective for livestock breeding programmes. The approach has been used for pigs (Tess *et al.*, 1983a, b; de Vries, 1989; Skorupski *et al.*, 1995a, b), beef cattle (Hirooka *et al.*, 1998a, b; Amer *et al.*, 1997), dairy cattle (Groen, 1989a, b) and sheep (Wang and Dickerson 1991; Conington, 2000). Models of this type are a method of effectively describing typically complex livestock production systems, taking into account genetic, nutritional, management and economic factors. Importantly, once the model is developed the effects on the system of changes in any of these factors can easily be investigated. As a result they provide a very good tool for estimating the economic value of genetic changes in various traits, and also to investigate the robustness of these values to changes in nutrition, management and market prices.

A model for deriving economic values for objective traits for terminal sire breeds of sheep has not previously been reported. Past studies for sheep have focused on pure-breeding production systems and the life cycle of both dams and their offspring have been modelled (Wang and Dickerson 1991; Conington, 2000). For terminal sire breeds the main outputs from pedigree flocks are rams that are sold to commercial producers as sires of crossbred lambs that are slaughtered for meat production. Demand for these rams, and hence the price obtained, is dependent on their ability to produce lambs that give good returns to the commercial producer. Consequently, when considering the breeding objective for terminal sire breeds the main interest is in growth and carcass traits and in particular on the effects of genetic changes in them on the performance of commercial offspring. Since few of these offspring are kept as breeding females, only the life cycle of lambs from birth to slaughter needs to be considered when developing a bio-economic model.

Selection within the majority of current breeding programs for terminal sire breeds in the UK is based on values for the lean growth index (Simm and Dingwall, 1989). The objective for the index includes lean and fat weights at a fixed age of 150 days. The relative economic weights for these objective measures (+3 and –1 respectively) were chosen, following an investigation using a desired gains approach, so as to achieve near maximum selection responses in lean weight whilst minimizing increases in fat weight. Market prices in the UK are typically unstable, varying with season and between years, and this has partly contributed to the desired gains approach being preferred. Nevertheless no attempt has previously been made to estimate actual economic values for these objective measures under UK commercial conditions. Given its flexibility, a bio-economic model would provide the ideal tool for doing this.

The aim of this study was to develop a bio-economic model that described a typical production system for crossbred slaughter lambs in the UK, and to use it to derive economic values for lean and fat weights at 150 days. The sensitivity of these values to typical fluctuations in market prices was also investigated.

6.2 Materials and methods

6.2.1 Production system modelled

The production system considered was a lowland sheep unit producing crossbred lambs for meat production, with lambs being finished outdoors, mainly off grass with some supplementary concentrate feeding when grazing is in short supply. All lambs are sold for slaughter on a dead weight basis with the value of the carcass depending on its weight, and subjective scores for subcutaneous fat proportion and conformation. The finer details of the system were based on that reported by Lewis *et al.* (1996), and are described later.

The model was programmed using the Mathcad software package (Mathsoft, 1995).

6.2.2 Underlying growth model

The underlying model developed for the prediction of the biological variables was based mainly on the approach of Amer *et al.* (1997), which uses the interspecies model described by Emmans (1988). Only a brief description of the principles used to develop the underlying model is given here.

The degree of maturity in body protein (P) at time *t*, was described using a form of the Gompertz (1825) growth equation, as:

$$u_t = \exp(-\exp(G_0 - B.t)$$

where *B* is a general rate parameter and G_0 is the initial condition. For animals grown under non-limiting conditions the scaling rule of Taylor (1980) suggests that the rate parameter (*B*) would be inversely proportional to mature size raised to the power of 0.27. A further multiplier (M_x, which takes a value in the range of 0 to 1), was incorporated to allow for limiting conditions. The actual rate parameter was calculated as:

$$B = \frac{0.023}{P_m^{0.27}} M_x$$

where P_m is the weight of protein at maturity and 0.023 is the interspecies value of the scaled constant (Emmans, 1997). The initial condition considered was that at birth, and the value of G_0 was calculated as:

$$G_0 = \ln(-\ln(P_0 / P_m))$$

where P_0/P_m is the degree of maturity in protein at birth. The value of P_0/P_m was assumed to be constant across all genotypes at the value of 0.062 (Amer *et al.,* 1997).

The fleece free empty body was considered composed of three chemical components - water, lipid and lipid-free dry matter. The lipid-free dry matter was assumed to contain constant proportions of protein and ash. Emmans (1988) showed that, where the value *B* is the same for all chemical components, the degree of maturity (*u*) in any one chemical component can be predicted as a power function of the degree of maturity in any other. Using this principle, the weights of protein (P_t), lipid (L_t) and water (H_t) in the empty body at time *t* were calculated as:

$$P_t = u_t \,.\, P_m, \quad L_t = u_t^{bL} \,.\, Q \,.\, P_m \text{ and } H_t = u_t^{bH} \,.\, R \,.\, P_m \qquad (1)$$

where Q and R are the ratios of the weights of lipid and water, respectively, to protein weight at maturity, and b_H and b_L are exponents relating the degree of maturity in water and lipid, respectively, to the degree of maturity in protein. Values for b_H and R were assumed constant (Table 1). Values for Q and b_L were assumed to depend on the genotype and production system being modelled.

Following from the above equations daily retentions of protein, lipid and water in the body were calculated as:

$$\frac{dP}{dt} = B \,.\, P_m \,.\, u_t \,.\, \ln(1/u_t)$$

$$\frac{dL}{dt} = B \,.\, Q \,.\, P_m \,.\, u_t^{bL} \,.\, \ln(1/u_t^{bL})$$

$$\frac{dH}{dt} = B \,.\, R \,.\, P_m \,.\, u_t^{bH} \,.\, \ln(1/u_t^{bH}) \qquad (2)$$

By assuming that the lipid-free dry matter was 0.8 protein, empty body weight (EBW) and live weight (LW) were calculated as:

$$EBW_t = 1.25.P_t + L_t + H_t \text{ and } LW_t = (1 + GF + WL) \,.\, EBW_t$$

where GF and WL are gut fill and wool, respectively, as a proportion of empty body weight. Values for GF and WL were assumed constant at all stages of maturity (Table 1).

Carcass weight and subcutaneous fat

Given a value for killing out proportion (KO), carcass weight (CW) was calculated as:

$CW_t = KO_t . LW_t$

The proportion of the carcass that was subcutaneous fat (SFe) was calculated from a prediction of the weight of subcutaneous lipid. Following from equations 1 and 2, the weight, and daily retentions of subcutaneous lipid were calculated as:

$$LS_t = u_t^{bLS} . S . P_m$$

$$\frac{dLS}{dt} = B . S . P_m . u_t^{bLS} . \ln (1/u_t^{bLS})$$

where S in the weight of subcutaneous lipid as a ratio of protein weight at maturity, and b_{LS} is an exponent relating the degree of maturity in subcutaneous lipid to degree of maturity in protein. The value of S was assumed to vary linearly with the value of Q, with a relationship of $S = Q.k_{SF}$, and the value of k_{SF} was assumed constant for sheep (Table 1). The value of b_{LS} was considered to vary linearly with the value for b_L, with a relationship of $b_{LS} = b_L.k$, and the value of k was assumed constant (Table 1).

Assuming that subcutaneous fat is composed of lipid and water in the ratio of 9:1, SFe was calculated from the above predictions as:

$$SFe = (1.1 * LS_t) / CW_t$$

Conformation was predicted from values for carcass weight and fatness as described later.

Table 1 Constants used in the biological model

Description	Symbol	Value	Units	Source
Constants				
Energy cost of maintenance (kg^{-1} $P_m^{0.75}$)	Z_M	1.63		Emmans (1994)
Energy cost per kg of protein retained	Z_P	50		Emmans (1994)
Energy cost per kg of lipid retained	Z_L	56		Emmans (1994)
Water on protein maturity exponent†	b_H	0.855		Kotarbinska (1969)
Ratio of water to protein in the mature body	R	3.20	kg kg^{-1}	Emmans (1988)
Subcutaneous lipid as proportion of total lipid at maturity	k_{SF}	0.29		Butterfield (1988)
Exponent relating maturity in sub fat to maturity in lipid‡	k	1.2		Amer *et al.* (1997)
Gut fill as a proportion of empty body weight		0.27		
Wool weight as a proportion of empty body weight		0.03		
Mature protein weight	P_m	0.14*MW		
Proportion of lean weight accounted for by protein	P_{Lean}	0.20		
Proportion of lean weight accounted for by water	H_{Lean}	0.80		
Proportion of fat weight accounted for by lipid	L_{Fat}	0.90		
Proportion of fat weight accounted for by water	H_{Fat}	0.10		
Mature weights				
Females	MW	75.0	kg	
Castrates	MW	82.5	kg	

† Assumed equal to that for pigs
‡ Assumed equal to that for cattle

Energy requirements

Daily energy requirement was estimated from a calculated requirement for energy needed for maintenance, wool growth, activity and the retention of body protein and lipid. Maintenance requirement on day t (MR_t, MJ) was calculated as:

$$MR_t = Z_M \,.\, P_m^{0.73} \,.\, u_t$$

where Z_M is the energy cost of maintenance (MJ.(kg^{-1} $P_m^{0.73}$ day)). Requirements for wool growth and activity were assumed to be an additional 20% of that required for maintenance.

Total feed energy requirement on day t (FE_t, MJ day^{-1}) was calculated as:

$$FE_t = \frac{dP}{dt}.Z_P + \frac{dL}{dt}.Z_L + (MR_t.1.20)$$

where Z_P and Z_L are the energy cost of protein and lipid retention respectively (MJ kg^{-1}). The values of Z_M, Z_P and Z_L were assumed constant (Table 1), and their value was defined using the effective energy scale (EE), and hence FE(t) was in units of EE (Emmans and Fisher, 1986; Emmans, 1994). To avoid double counting, food wastage was not directly considered in the calculation of requirements, but was incorporated into the calculation of feed costs.

6.2.3 Between animal variation

The underlying model, described above, predicts biological variables and values for each trait at different points over time for an individual average animal. In order to be extended to represent a group of lambs, typical variation between lambs at an age needed to be incorporated.

Variation between lambs at any age for carcass weight, SFe and cumulative feed intake (CFI) was incorporated using stochastic simulation. A group size of 1000 lambs was simulated. Deviations for each lamb from the mean value for each of the three traits at each of a series of fixed points in time (weekly intervals from two weeks prior to weaning in this case, see later) were simulated. In doing so, the relationships between the three traits and between values at successive time intervals were taken into account. The latter was incorporated to give a more realistic representation of the growth of lambs over time.

The simulated values were obtained by first sampling initial deviation values for each trait and time point for each lamb from a random normal distribution with mean zero and standard deviation of one. Actual deviations from the mean for each trait were then obtained by multiplying through a large variance covariance matrix that represented the relationships between the three traits and between values at successive time points. This matrix was derived using a given set of correlations between traits and between values at successive time points, and standard deviations calculated using given coefficients of variation for each trait (described later).

Once simulated, carcass weight, fat score and cumulative feed intake for each lamb at each time point were obtained by adding the animals deviation to the mean for each trait at that time as determined by the underlying model.

The correlation between carcass weight and SFe was estimated from data available, as were coefficients of variation for both traits. Since CFI is not readily recorded, an assumed value 0.80 was used for the correlation of CFI with both carcass weight and SFe, respectively. The coefficient of variation for CFI was assumed equal to the value for food intake for sheep (0.10), reported by Kyriazakis and Oldham (1993). The correlation between values for a trait at successive points in time (1 week apart) was assumed constant across the three traits with a value of 0.80.

Conformation (CONF) was predicted for each carcass from its weight and SFe, using a prediction equation derived from available data (shown later). Although reasonable, the accuracy of prediction was not high (R^2~50%). To account for this, residual deviations for each lamb were sampled from a random normal distribution with mean zero and a standard deviation equal to an estimate of the residual standard deviation for the prediction, and this deviation was then added to the predicted value.

6.2.4 Incorporating experimental results into the model

To be typical of that found commercially in the UK, the finer details of the system were based on that described by Lewis *et al.* (1996), and data collected as part of that trial were used to adapt the biological model. A brief description of the trial and the data collected is given here.

As part of the trial 11 high index and 11 low index rams (lean growth index; Simm and Dingwall, 1989) were chosen in each of 1986, 1987 and 1988, and mated in single sire paddocks with 18 to 20 Scottish Mule [Bluefaced Leicester (BFL) X Scottish Blackface (SB)] ewes in October of that year. Following mating, ewes were managed as one flock and were housed in mid January. Within 1 day of birth the weight and sex of each lamb were recorded. Ram lambs were castrated within 24 hrs of birth. Over the three years 94% of ewes gave birth to two or more lambs and most lambs were reared as twins (90%) with the remainder reared as singles or artificially. Within sire families, lambs were allocated at random within sex to one of three target live weight groups for slaughter (35.5, 41.5 or 47.0 kg). Lambs, and their dams prior to weaning, were maintained on mixed grass sward of predominantly perennial ryegrass (*Lolium perene L.*) until they reached slaughter weight. Weaning occurred when lambs were approximately 12 weeks of age and live weights at weaning were recorded. When swards were grazed down to less than 4 cm (by Mid October or November), lambs were supplemented with concentrates.

Slaughter measurements

All lambs were weighed unshorn before transport for slaughter. The carcasses were chilled overnight and their weight recorded. All carcasses were scored for subcutaneous fat (seven-class scale) and conformation (five-class scale) by a classifier from the Meat and Livestock Commission (MLC). In 1988 and 1989, the MLC classifier also assessed conformation on a 15 point scale and made a direct visual assessment of the proportion of subcutaneous fat on the carcass.

Data analysis

In the model SFe and conformation are considered as continuous variables. Records for SFe and conformation recorded on the extended scale were therefore more appropriate to consider. Since assessments of these scales were done only in 1988 and 1989, the data used was restricted to those collected during these two years. A further restriction of data to only lambs born and reared as twins was also done since the numbers of lambs in other birth/rearing number classes were small.

The growth of the lambs described by Lewis *et al.* (1996) can be considered as being in three phases: (1) pre-weaning, (2) weaning to beginning concentrate feeding and (3) the period of autumn concentrate feeding. In order to adapt the biological model in an appropriate way, mean live weights for both females and castrates at the beginning of each phase were required, as were measures of mean fatness for each sex at two different ages to allow values for Q and b_L to be estimated.

Birth and weaning weights were available for all lambs. As some variation in weaning age was present, least square means were calculated using analysis of variance (Genstat, 1998), after fitting sex and linear regression on age in the statistical model. The effects of sire line and year were also investigated but were found not to be significant and hence were not included in the final model fitted.

The mean birth date for lambs in the data was day 95 of the year (5^{th} April), and the mean age at weaning for both sexes was 81 days. Concentrate feeding in autumn was assumed to start on 15^{th} October, which corresponded to 193 days of age for these lambs. Least squares means for live weight and SFe at 193 days were obtained by considering only lambs slaughtered at 193 +/-15 days of age, and fitting the effect of sex and age as a linear covariate in the statistical model. Few lambs were slaughtered around weaning, so a mean age of 109 days (around which more lambs were slaughtered) was used to obtain the second mean for fatness at an age. Again, the data were restricted to lambs slaughtered at 109 +/- 15 days of age and least squares means were obtained after fitting sex and age as a linear covariate in the statistical model.

An estimate of the killing out proportion (KO) at a given live weight and the change in KO with changes with live weight were obtained by first calculating KO for all lambs, using carcass weights and live weights before transport to slaughter, and then fitting a linear regression of KO on live weight. The difference between sexes was small and a common estimate was derived. Coefficients of variation for carcass weight (CW) and SFe was obtained using the least-squares means and residual variances obtained after fitting slaughter age as a linear covariate for both traits, in turn. Again, differences between the two sexes were small and a common estimate was used.

A prediction equation for conformation was derived using multiple linear regression, fitting CW and SFe as predictors. The effect of sex was found not to be important ($P>0.05$) and hence was not included in the model.

Estimates of P_m

The only other input required for the model was an estimate of protein weight at maturity (P_m) for both sexes. Direct estimates of P_m for different genotypes are not readily available, so P_m was assumed to be 0.14 of estimated mature weight for sheep kept under commercial conditions. The mature weight for the crossbred ewes was taken as the mean of estimates for ewes in the two parent breeds. McEwan *et al.* (1988) reported live weights of 81.8 kg for mature Suffolk ewes out at grazing (>3.4 years old), and the mean pre-mating weight for 216 four-year-old Scottish Mule ewes that were weighed as part of another study at SAC was 69.0 kg (A. van Heelsum, personal communication). A mature weight of 75 kg was therefore used for females in this study. The mature weight for castrates was assumed to be 10% higher than that for females (Table 1).

Estimation of values for the biological variables

The values of M_x for period one, M_x for period two, Q and b_L were simultaneously derived. The model was forced to predict the mean live weights at birth, 81 and 193 days of age and the mean SFe at 109 and 193 days of age, that were obtained from the analysis of the experimental data. This was done iteratively using the Levenberg-Marquardt numerical search method, which is incorporated in the Mathcad software.

Since most lambs were slaughtered prior to about 250 days of age, a good estimate of live weights at older ages could not be obtained from the available data. As a result a value of the M_x multiplier for period three could not be estimated. A live weight for each sex at 350 days of age was therefore chosen which corresponded to a M_x value of 0.75 when the values for Q and b_L were those estimated using the above method.

6.2.5 Genetic changes in lean and fat weights

Genetic changes in the weight of lean and fat in the body at 150 days of age was assumed to be the result of a fixed change in the daily retentions of the corresponding chemical components. Daily retention of protein, lipid water and subcutaneous lipid following genetic changes were calculated as:

$$\frac{dP}{dt} = B \cdot P_m \cdot u_t \cdot \ln(1/u_t) + \frac{\Delta Lean.P_{Lean}}{150}$$

$$\frac{dL}{dt} = B \cdot Q \cdot P_m \cdot u_t^{bL} \cdot \ln(1/u_t^{bL}) + \frac{\Delta Fat.L_{Fat}}{150}$$

$$\frac{dH}{dt} = B \cdot R \cdot P_m \cdot u_t^{bH} \cdot \ln(1/u_t^{bH}) + \frac{\Delta Lean.H_{Lean}}{150} + \frac{\Delta Fat.H_{Fat}}{150}$$

$$\frac{dLS}{dt} = B \cdot S \cdot P_m \cdot u_t^{bLS} \cdot \ln(1/u_t^{bLS}) + \frac{\Delta Fat.(L_{Fat}.k_{SF})}{150}$$

where ΔLean and ΔFat are the change in weight of lean and fat (at 150 days), respectively, P_{Lean} and H_{Lean} are the proportions of lean weight accounted for by protein and water respectively, L_{Fat} and H_{Fat} are the proportions of fat weight accounted for by lipid and water respectively. Each proportion was assumed to have a constant value (Table 1).

Any changes in retentions were assumed not to affect the proportion of maturity for each chemical component at time t (u_t) as they were small. Similarly, correlated changes in P_m and Q with genetic increases in lean and fat weights were assumed sufficiently small not to effect maintenance requirements.

6.2.6 Drafting and carcass value

The inspection of lambs for possible drafting for slaughter was started two weeks before weaning (approximately 11th of June) and thereafter on a weekly basis. Two criteria for drafting were used; a value for SFe of greater than 10 or a carcass weight of 21 kg. These criteria were chosen following the results of Chapter 5. A value for SFe of 10 forms the boundary between fat classes 2 and 3L (on the seven-class scale), which were considered the preferred fat classes for commercial lambs. A carcass weight of 21 kg was usually the maximum weight for which payments were made when lambs were sold on a dead weight basis. Once drafted, the weight of each carcass was rounded down to the nearest 0.5 kg, to represent commercial practice, before the commercial value of the carcass was calculated.

The commercial value of the carcass was determined by its weight, and subjective assessments of estimated subcutaneous fat proportion (SFe) on a seven-class scale and conformation on a five-class scale. The price obtained was a combination of a base price per kg carcass weight and premiums or penalties depending on the fat and conformation score assigned.

The continuous scales used to model SFe and conformation were translated into seven and five classes respectively, using appropriate thresholds. For conformation, each class on the five-class scale was assumed to incorporate three on the 15-class scale. Thresholds for SFe were chosen following the approach of Kempster *et al.* (1986), whereby class 1 is <6%, class 2 is 6-9.99%, 3L is 10-11.99%, 3H is 12-13.99%, 4L is 14-15.99%, 4H is 16-18.99% and 5 is >19% subcutaneous fat. The premiums and penalties paid for each carcass grade were assumed fixed, and equal to the average values reported in Chapter 5.

In the results of Chapter 5 it was shown that the base price chosen by an abattoir for dead weight purchases, was influenced strongly by the national weekly average live auction price. Therefore the base price per kg carcass weight was calculated using national weekly averages for live weight sales (MLC, unpublished), and the killing out proportion calculated from the available data. Over the last few years the seasonal fluctuations in national averages from live weight sales in the UK have varied considerably (Figure 1). National weekly averages from 1995 to 2000 were used in turn, to investigate the sensitivity of economic values for lean and fat weights to seasonal fluctuations in base price.

Following the results of Chapter 5, the base price was paid only up to a carcass weight of 21 kg, and carcasses weighing less than 16 kg were discounted by 20 p/kg.

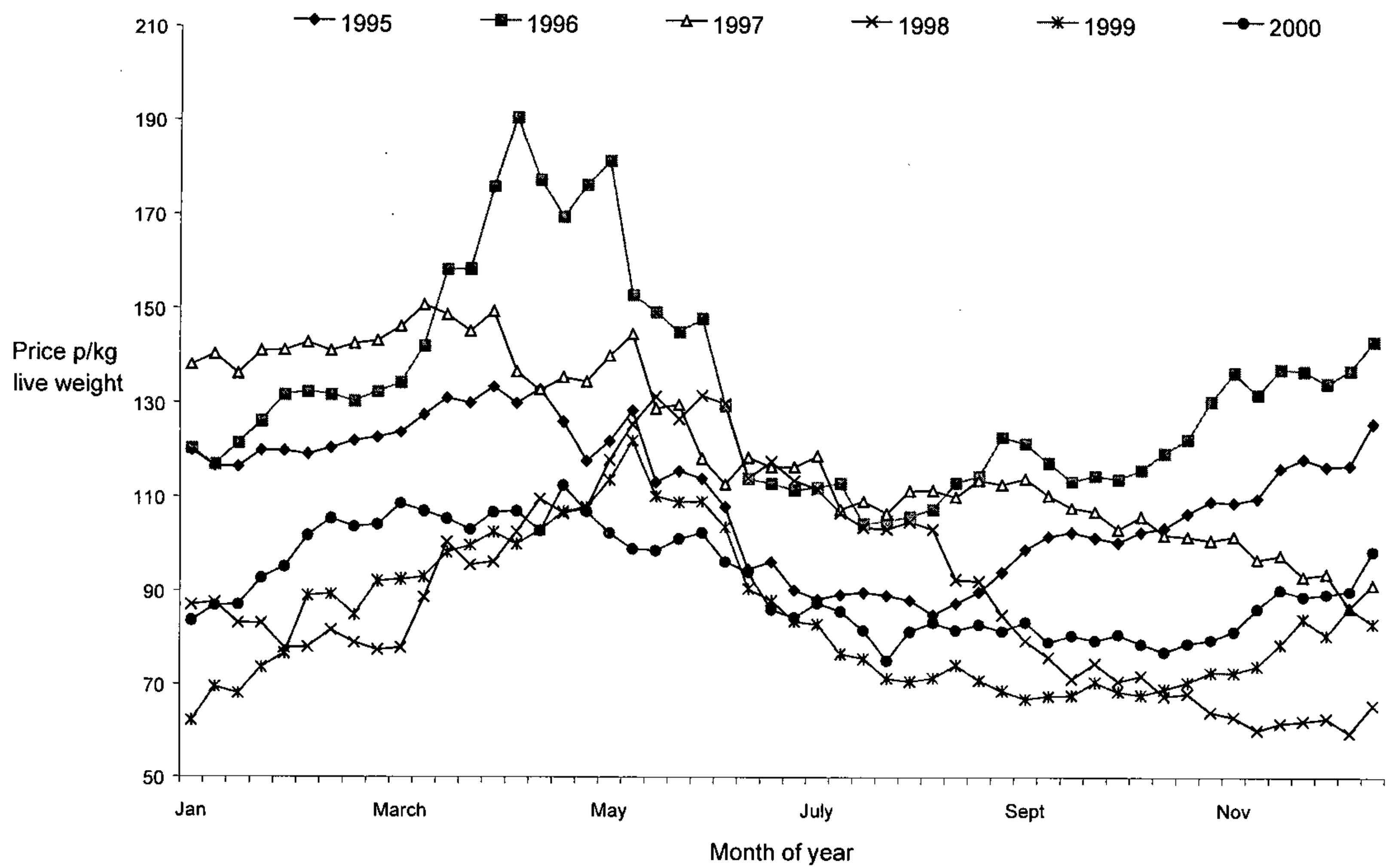
6.2.7 Economic values and calculation of feed costs

The economic values for lean and fat weight were estimated as the change in average marginal profit or loss per lamb (marginal return – marginal cost) resulting from a 1 kg increase in the mean weight of the respective tissue in the body for a group of 1000 lambs (the simulated number) at 150 days of age. These values were obtained by first running the program for the unchanged group, then for the genetically changed lamb groups, and calculating the difference in profit between them. Hereafter the unchanged, genetically fatter and leaner groups will be referred to as the Base, Fat and Lean groups respectively.

Economic values for each of the two sexes were estimated separately. Within sex, separate estimates were also derived using the national weekly average prices from each of the six different years (Figure 1). A total of 10 separate runs were conducted for each scenario and the average of these runs was used.

It was assumed that the only production cost that differed between the groups was that for lamb feed. Genetic changes in the lambs potential to deposit lean or fat was assumed not to affect litter size or the feed requirements for the dam. It was also assumed that no lamb mortality occurred in any of the lamb groups.

Figure 1 Seasonal fluctuations in weekly national averages from live auctions in the UK, across years from 1995 to 2000



Any increases in energy requirements for the genetically changed lambs were assumed supplied by the increased consumption of available feed. Similarly, any decrease in requirements was assumed to result in a reduction in feed consumption and thus feed costs. Changes in feed intake in the first and third growth periods (birth to weaning and autumn concentrate feeding), were assumed to be solely changes in the consumption of concentrates, whilst changes in period two (grazing period) were assumed to be changes in the consumption of pasture.

As part of the model, energy requirements were calculated in units of effective energy (EE), and therefore feed costs needed to be calculated in corresponding units. The effective energy yield of a food for ruminants was estimated (Emmans, 1994) as:

$$\text{EE kg}^{-1}\text{ DM} = 1.15\text{ ME} - 3.84 - 4.67\text{ DCP}$$

where ME is the metabolisable energy (MJ) per kg of food dry matter, and DCP is the digested crude protein kg kg^{-1} of food dry matter.

Cost of energy from pasture

The costs of pasture and concentrate energy were calculated using approaches proposed by P. Amer (personal communication). The cost of pasture energy (p/MJ EE) was calculated as:

$$= \frac{\text{Fertilizer cost Ha}^{-1} \text{ / increase in DM yield Ha}^{-1}}{\text{Proportion of pasture utilized} * \text{EE kg}^{-1}\text{ pasture DM}} * 100\text{p/kg}$$

In SAC (2001) it was indicated that for every 125 kg of nitrogen that is applied, dry matter yield increases by 1700 kg per hectare (vigorous grass/clover sward). Straight nitrogen fertilizer was assumed to cost £0.35 per kg and contractor application cost was £6.25 per Ha (SAC, 2001). It was assumed that 80 % of the pasture available is utilized by sheep (Sibbald *et al.*, 1987) and the ME content of grazing was 13.0 MJ kg DM and the DCP content 13.0% (Amer and Emmans, 1998). Therefore following from above:

$$= \frac{[(125*0.35)+6.25]/1700}{0.80*10.5}*100 \quad = 0.35 \text{ p /MJ EE}$$

Cost of energy from Concentrates

The cost of energy from concentrates was calculated as:

$$= \frac{\text{cost kg}^{-1} \text{ wet weight}}{\text{Proportion utalized} * (\text{EE kg}^{-1} \text{ DM} * \text{proportion DM kg}^{-1})} *100 \text{ p/kg}$$

The cost of lamb concentrates was assumed to be £130 /tonne wet weight and the DM content of the feed was assumed to be 90%, with a ME content 13.0 MJ/kg DM and DCP content 16%. The proportion of feed wasted was assumed to be 5%. Therefore following from above:

$$= \frac{0.13}{0.95*(10.36*0.90)} *100 \quad = 1.47 \text{ p MJ}^{-1} \text{ EE}$$

6.3 Results

Analysis of the experimental data

Least squares means for live weights at birth, 81 and 193 days of age, and estimated fat scores at 109 and 193 days estimated from the data for females and castrates are shown in Table 2, along with the number of records from which each mean was calculated.

Castrates were heavier at each age, but differences in live weight between the two sexes were relatively small being less than 0.5 kg at both 81 and 193 days. Females were fatter than castrates and the difference between them in mean SFe increased with age.

Estimated killing out proportion across sexes was 450 g/kg at a mean live weight of 42 kg, and changes with live weight were 0.1 g/kg. Across-sex estimates of coefficients of variation for carcass weight and SFe at a fixed age were 0.13 and

0.25, respectively, and the correlation estimate between residuals for both variables after fitting a linear regression on slaughter age was 0.68.

Table 2 Least squares means for live weight at two different ages and estimated fat proportion (SFe) at two different ages for female and castrate male lambs †

	Birth	81 days	109 days	193 days
Females	n = 343	n = 343	n = 92	n = 68
Live weight (kg)	4.62	30.87	-	46.53
SFe	-	-	11.30	13.66
Castrates	n = 385	n = 385	n = 91	n = 54
Live weight (kg)	4.92	31.34	-	46.78
SFe	-	-	10.41	11.73

† n = number of records used to calculated each mean

The equation derived for the prediction of conformation (on the 15 class scale) from linear regressions on carcass weight (CW) and estimated fat score (SFe) was:

$$CONF = -0.636 + 0.268*CW + 0.442*SFe$$

The coefficient of determination (R^2) for the prediction was 54%, with a residual standard deviation of 1.69.

Estimation of values for the biological variables

The estimated values for the limiting conditions multiplier for period one (M_x1), period two (M_x2) and values for Q and b_L for each sex are shown in Table 3. Values for M_x in both periods were similar for both sexes. Those for period one were close or equal to one, indicating that conditions prior to weaning were non-limiting and that potential growth was being attained. In contrast, values for period two were low (0.27 and 0.28) indicating that the energy derived from grazing was much less than that required to sustain the growth potential.

Estimated values for Q and b_L differed between sexes, the former tending to be higher and the latter lower in females. Given these estimates females were expected to have more fat relative to protein at maturity than castrates and the rate with which they matured in fatness was higher.

Table 3 Estimated values for limiting conditions multipliers (M_x), ratio of fat to protein at maturity (Q) and degree of maturity in fatness parameter (b_L) for female and castrated male lambs

	M_x1	M_x2	Q	b_L
Females	1.0	0.28	5.36	2.13
Castrates	0.99	0.27	5.06	2.23

Effects of genetic changes on: Numbers and carcass weights for drafted lambs

The number of lambs drafted each week from the Base, Fat and Lean groups and the mean carcass weight for those drafted are shown in Figures 2 and 3 respectively for females, and in Figures 4 and 5 respectively for the castrated males. All results shown are the mean of the 10 repeated simulation runs for each scenario.

Females

For the female Base group 350 lambs reached the desired fatness, and thus were drafted, before weaning. After weaning the number of lambs being drafted each week reduced dramatically corresponding with the reduction in quality of the feed available. The majority of the lambs were drafted by 158 days of age (approx. 10th September), and all lambs were drafted before 215 days of age.

Mean carcass weights for drafted lambs increased with age. Nonetheless mean carcass weights for lambs drafted at young ages were low and did not exceed the desired weight (16 kg) until day 102, by which time 553 lambs had been drafted and sold.

Figure 2 Mean number of female lambs drafted at each age from the base and genetically changed groups

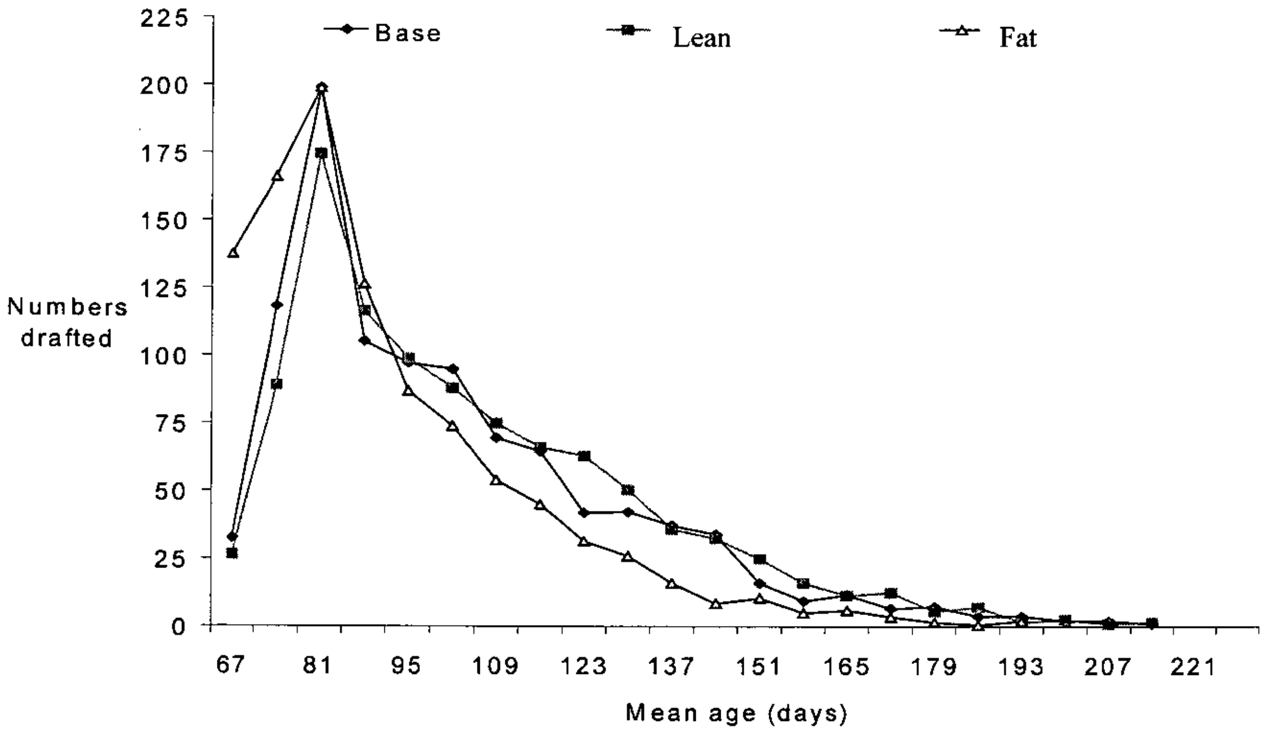
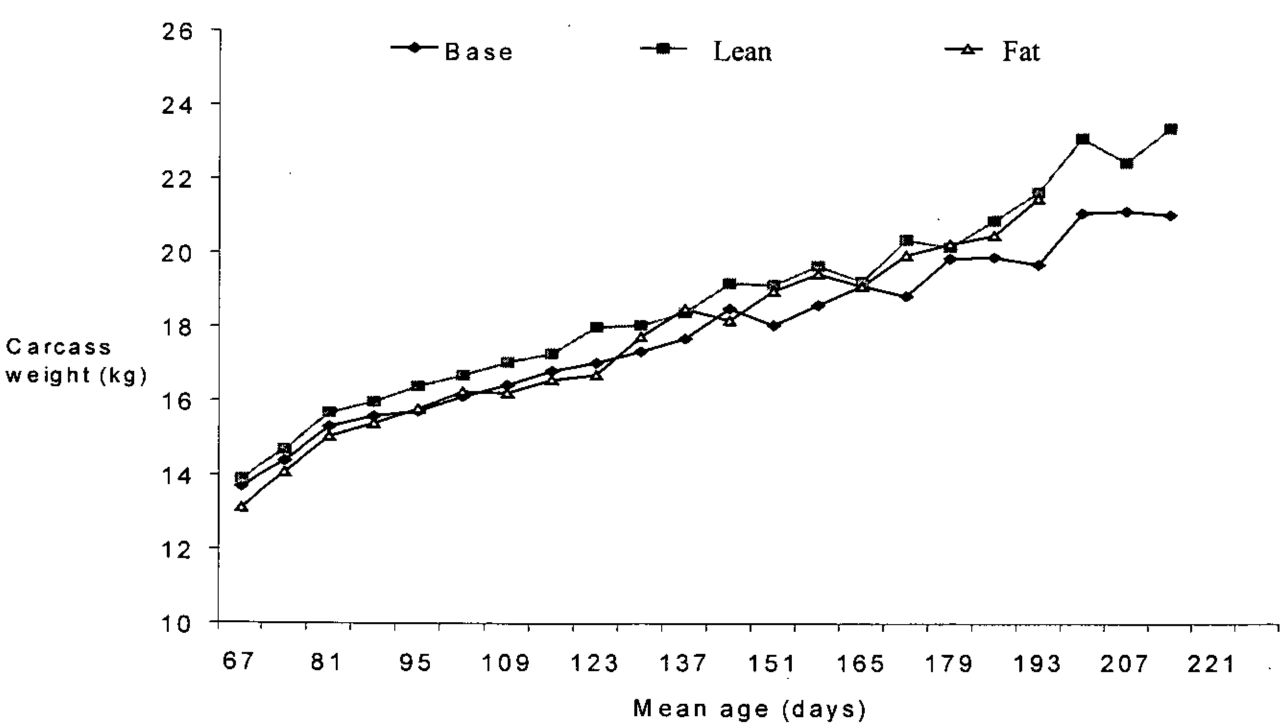


Figure 3 Mean carcass weight of female lambs drafted at each age from the base and genetically changed groups



By increasing the rate of fat deposition (Fat group) the number of lambs being drafted at early ages, as a result of attaining the desired fatness, increased. Five hundred and three lambs were drafted before weaning and a total of 716 were drafted before the mean weight exceeded 16 kg at 102 days. All lambs from the Fat group were drafted by 194 days of age.

When the rate of lean deposition was increased (Lean group) the number of lambs sold at young ages with a low carcass weight was reduced and the mean carcass weight at each draft also increased. Only 290 lambs were sold before weaning and only 407 were sold before day 95 when the mean carcass weight exceeded 16 kg. As with the base females all lambs were sold before 215 days of age.

Castrates

As expected given the lower estimates for the Q and b_L parameters, fewer of the castrated male lambs attained the desired fatness at early ages in comparison to females. For the Base group only 79 lambs were drafted before weaning (*versus* 350 for the Base females). Mean carcass weights at each draft were also higher with only 10 of the Base group castrates being sold at weights below 16 kg.

As for females, the number of castrated lambs drafted each week dropped after weaning, but then numbers gradually increased with each subsequent week to a peak at 116 days of age. The majority of lambs were sold by 207 days of age, and all lambs were sold by 228 days of age.

By increasing the rate of fat deposition (Fat group) the number of lambs drafted before weaning increased to 225, with 75 being sold at low carcass weights (<16 kg). The majority of lambs from the genetically fatter group were drafted by 186 days of age but some lambs still remained until 228 days of age.

Similar to females, the effect of increasing the rate of lean deposition (Lean group) was that the carcass weights for lambs drafted at each age were higher and fewer lambs were drafted at early ages. None of the lambs drafted had a carcass weight of

Figure 4 Mean number of castrate lambs drafted at each age for the base and genetically changed groups

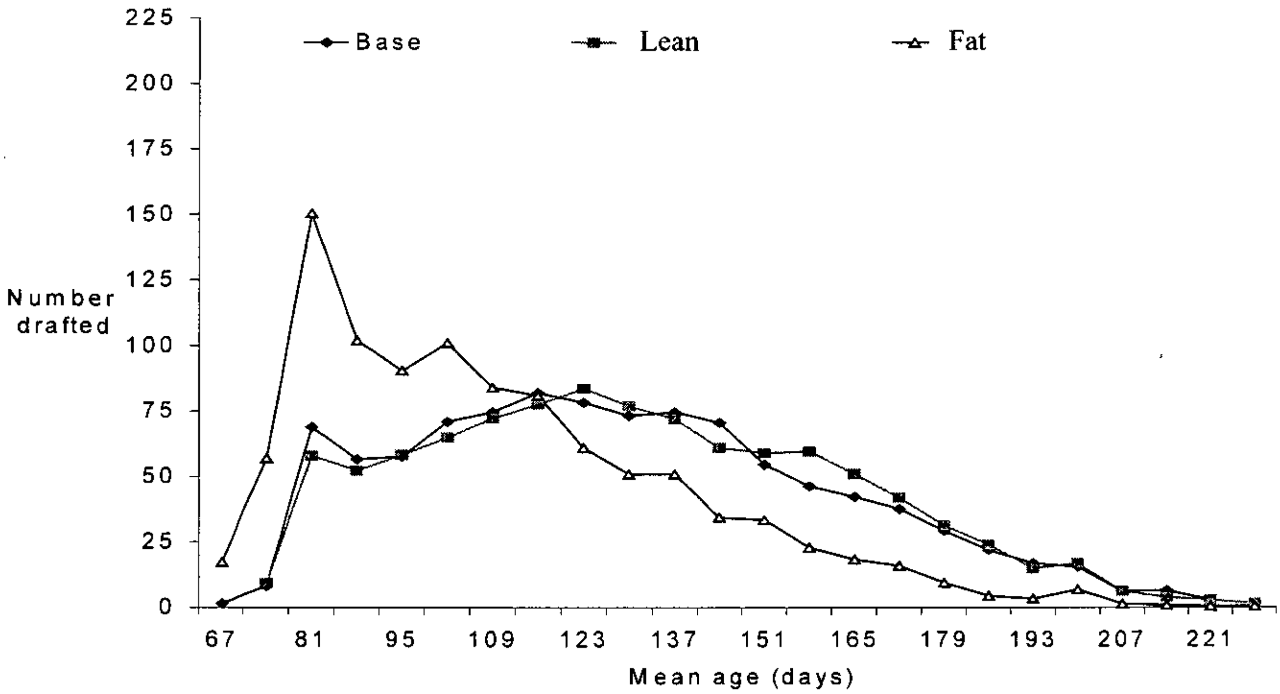
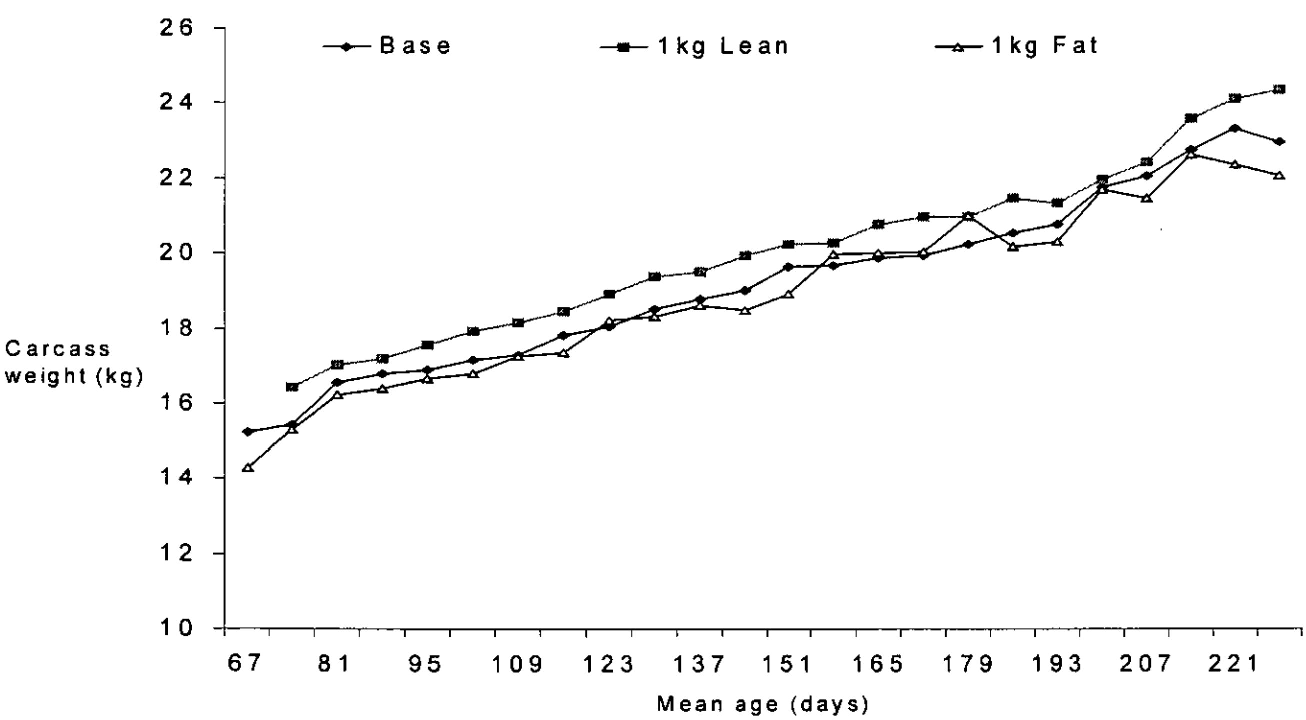


Figure 5 Mean carcass weights for castrate lambs drafted at each age from the base and genetically changed groups



less than 16 kg. As with the base group the majority of lambs were drafted by 207 days of age and all lambs were drafted by an age of 228 days.

The overall differences in mean carcass weight for each of the groups in both sexes are summarised in Table 4.

Energy requirements

For both males and females energy requirements were highest for all groups in the period prior to weaning (period one; Table 4). Despite more females lambs being sold at early ages in comparison to castrates, the total energy requirements for that period were higher for females as a consequence of the increased energy demand for the higher rate of fat deposition. The lower energy requirements for females relative to castrates in the second period (grazing) reflected the fact that fewer female lambs remained by this time, and similarly for period three.

Table 4 Mean carcass weights (CW) and total units of effective energy units (EE) utilized in each of the three growth period by the 1000 female or castrated male lambs in the Base, Fat and Lean groups

		CW (kg)	EE utilized (K units) †		
			Period 1	Period 2	Period 3
Females	Base	16.05	619.831	182.352	1.208
	Fat	- 0.78	- 0.093	- 66.021	- 1.208
	Lean	+ 0.72	+ 7.845	+ 25.608	+ 0.056
Castrates	Base	18.40	601.402	383.506	9.598
	Fat	- 1.07	+ 23.769	- 138.612	- 7.093
	Lean	+ 0.81	+ 6.169	+ 21.059	- 0.877

† Values for the Lean and Fat groups in each period are expressed as deviations from values for the Base group

As a general rule the energy required in each period was lowest for the Fat group and highest for the Lean group. This was largely as a result of the different numbers of lambs remaining at any given age for each group. There were, however, two exceptions to this general rule, both for castrates. The first, that the energy requirements for the Fat group was higher in period one than for the Base group. This occurred since Fat group lambs had higher daily energy requirements relative to the base group due to the increased rate of fat deposition. But, in contrast to the females, the rate of deposition was not sufficiently high for a large number of the lambs to be drafted so that the overall requirements for the group in period one was lower. The second exception to the general rule was that the requirements for the Lean group in period three was lower than for the Base group. This was the result of a number of the Lean group lambs being drafted earlier, before reaching the desired fatness, because they were heavier than the upper carcass weight threshold of 21 kg.

Economic values for the genetic changes

The economic value per lamb of increasing the weight of lean or fat at 150 days, using national weekly prices from each of 1995 to 2000 in turn, are shown in Table 5, separately for each sex and across sexes. Within sex values for lean weight were consistently positive and those for fat weight negative, with only one exception (castrates 1998). Even so, the actual values calculated for both tissue weights differed between sexes and with price year. As a general rule (with only the one, same exception) the magnitude of EV's for both tissues were smaller for females than for castrates.

Economic values of fat weight tended to be more variable between years than those for lean weight. Differences between years for EV for both tissues generally depended on how prices changed over the selling period for the lamb groups (June to October). The magnitude of EV's tended to be highest when prices were relatively stable or increased over this period, as in 1995, 1996 and 1997 (Figure 1), and lowest when prices continued to reduce substantially over these months, as occurred in 1998 and 1999 (Figure 1). The positive EV for fat weight for castrates in 1998 resulted since prices plummeted during August and September in that year.

Table 5 Economic values (£/lamb) for a 1 kg increase in mean lean and fat weights at 150 days of age for females, castrated male and across sexes, calculated using national average weekly prices from six different years

		Year					
		1995	1996	1997	1998	1999	2000
Females	Lean	1.83	1.75	1.91	1.45	1.04	1.32
	Fat	-0.51	-0.82	-1.81	-0.42	-0.04	-0.85
Castrates	Lean	1.66	1.93	1.90	1.53	1.16	1.39
	Fat	-2.24	-2.60	-2.05	0.69	0.00	-1.26
Across sexes	Lean	1.75	1.84	1.90	1.49	1.10	1.35
	Fat	-1.37	-1.70	-1.93	0.13	-0.01	-1.06

6.4 Discussion

Biological variables

The underlying growth model used as part of this study was based largely on the model reported by Amer *et al.* (1997), which was used to estimate economic values for meat production and slaughter traits in beef cattle. In their study the model was used to describe the growth and development of different crossbred types grown in one of two production systems, one where cattle were sold for slaughter at 16 months and the other where they were sold at 24 months of age. Although each of the production systems considered had a number of growth phases (rearing, grazing and finishing for the 16 months system and an additional winter store period after rearing in the 24 month system), only one estimate of M_x for the whole period was used in the model. In addition, the value for the ratio of lipid to protein at maturity (Q) was assumed fixed and only the value of b_L predicted.

In this study, as a further development to the original approach, it was recognised that the degree to which conditions are limiting may differ between phases where the animals considered are fed different diets that range in quality. A separate M_x value was fitted for each of the three growth phases being considered, with two of these being directly estimated by the model. A fixed value for period three was only used because of the limited amount of information that was available for lambs older than 250 days. As a further development to the model of Amer *et al.* (1997) it was also recognised that the phenotypic value of Q can vary between production systems and with genotype, and therefore was simultaneously estimated along with the two values of M_x and that for b_L.

The two values of M_x estimated in this study differed between the rearing and grazing periods. Despite the data being limited to only those reared as twins, conditions for the lambs prior to weaning were estimate to be non-limiting for growth ($M_x1 \approx 1$). This is not unexpected given that the breed/cross of the dams in this study (mules) is renowned for its milking ability and good quality grass would have been in plentiful supply for these ewes since the timing of parturition (early April) would have corresponded with the onset of spring grass growth (Orr *et al.*, 1988). The low value M_x for period two underlined the fact that conditions are more limiting under grazing conditions since the bulky nature and low dry matter content of grazing, in comparison to milk and concentrates, has a major constraining effect on the energy intake for the lambs.

As for the values of M_x, it is only useful to predict values for Q and b_L if those obtained are sensible. Estimates of Q for sheep have generally not been directly reported in the literature. However, Blaxter *et al.*, (1982) did report the weights of protein and lipid in the carcass for a number of castrated males ranging in slaughter age from one to five years. For the five sheep with greater than 10 kg of protein (expected to be at or close to maturity), the ratio of lipid to protein ranged from 4.2 to 5.7. This range encompasses the values presented here for both sexes. As far as the author is aware the only published estimate of b_L for sheep is 2.2 that was reported by Emmans (1988), which is again similar to the estimates presented in this study. Emmans (1988) derived his estimate by considering results from three other published studies, the largest amount of information coming from the results of

Blaxter *et al.* (1982). It is therefore not surprising that the value is most similar to that predicted here for castrates.

Estimates of differences between sexes for values of Q and b_L have not been reported for sheep. Whilst caution should be used in comparing actual values for other species, it is worth noting that Emmans (1988) reported a lower estimate of b_L for female pigs in comparison to castrates, which is similar to that seen in this study. However, both Emmans (1988) and Knap (2000) reported a lower estimate of Q for females in comparison to castrates, which is contrary to the results reported here. Whether this is a true difference between species or a function of the data and model assumptions used in this study is unclear. Further within sex estimates for sheep, where the animals have been reared under similar conditions, will be required for this issue to be resolved.

Comparisons of approach with previous studies

Previous attempts to derive EV's for lean and fat weights at a fixed age have focused on market conditions in New Zealand (Simm *et al.*, 1987; Waldron *et al.*, 1991). In both studies, changes in marginal returns with unit changes in the tissue weight were derived from the relevant partial coefficient when both lean and fat weights were regressed on carcass price. Values for each of the three variables (lean weight, fat weight and carcass price) were predicted from measures of carcass weight and GR fat depth (the criteria used commercially in NZ to assess carcass quality). Actual data for a group of lambs was used by Waldron *et al.* (1991), whereas Simm *et al.* (1987) used values derived from a population of lambs simulated to represent the national kill. In the study by Simm *et al.* (1987) the values obtained were then adjusted for anticipated average feed requirements for growth in the relevant tissue, so as to represent changes in profit.

The approach presented here provides a number of advantages in comparison to these previous studies. For instance, the flexibility to investigate the effects of drafting lambs on various criteria, and the ability to account for seasonal fluctuations in market prices. In both these previous studies the price obtained for each 'grade' and weight of carcass was assumed fixed within a year. As was shown in Figure 1, unless all lambs were sold on the same day, such an assumption cannot be used for the UK scenario.

In this study average returns and hence economic values for both tissue weights varied between years and differences tended to depend on how prices changed over the season. The economic value for fat weight was most sensitive to these changes. This is because, given the drafting criteria, changes in the rate of fattening had a greater effect on the timing of drafting than did the rate of lean deposition. This is can be seen in Figures 2 and 4.

The tendency for EV's for both tissues to be lower within a year for females in comparison to castrates was also a consequence of the pattern in seasonal changes in market prices. The majority of females were sold early in the season when weekly reductions in market prices were greatest. Therefore, when the rate of fattening was increased and carcass weights reduced a greater compensation of carcass value occurred through earlier marketing than was achieved later in the season when the majority of castrates were sold.

Other benefits of the approach presented here, in comparison to that used by Simm *et al.* (1987) and Waldron *et al.* (1991), include a more implicit accounting for the feed requirements of individual animals and the ability to account for seasonal fluctuations in feed costs. In their calculation of energy costs Simm *et al.* (1987) assumed that all energy was derived from grazing. Whilst this can be justified when considering a production system in New Zealand where the grazing season is long, it cannot be assumed for UK systems were the grazing season is shorter and supplementary feeding is frequently required. The approach presented here allowed the differences in costs between energy derived from grazing and concentrates, which was in excess of fourfold, to be accounted for. Only three different feeding phases were considered as part of this study, but the model could be adapted to account for up to weekly changes in feed costs.

Sensitivity to assumptions and market prices

Values for a number of the biological parameters used in this model were assumed rather than known (i.e. b_H, R, k and P_m, Table 1). Many of these values were assumed equal to published estimates for other species, and thus are good starting points. Nevertheless it is possible that differences between species may exist. The sensitivity of the model to small changes to these assumed values should be investigated. If the sensitivity to changes in any parameter is high then obtaining a more accurate estimate for sheep should be seen as a high priority for further research.

The most appropriate EV's to consider when deriving a selection index would be those estimated across sexes. Even the across sex values calculated in this study were sensitive to differences between years in market prices and changes over the season. This does create problems in deciding which values should be used for deriving a selection index. The best approach is likely to be to use an average value across years, either all years for which data is available, or excluding the most extreme years if they are considered atypical. For example, in this study data for 1998 could be excluded given that market prices continued to drop sharply during the latter part of the year whilst increases in prices during this time are more typical. Once an index was derived the more extreme economic values could be used to test its sensitivity to changes in market prices.

Comparison of estimates with previous studies

Simm *et al.* (1987) used the average market price for only one year and estimated economic values of NZ$ 5.65 per kg and NZ$ -4.12 for lean and fat weight respectively. Waldron *et al.* (1991) in contrast showed that estimates for both tissues varied when average prices from different years were used. Their estimates ranged from NZ$1.27 to 3.36 per kg for lean and from NZ$ -0.53 to 0.66 per kg for fat. Much of the difference between the estimates reported in both studies were likely due to the differences in mean carcass weight and fatness between the two populations of lambs being considered, which was also shown to have an important effect by Waldron *et al.* (1991). Mean carcass weight and GR were 13.64 kg and

8.03 mm respectively in the Simm *et al.* (1987) study and 14.59 kg and 6.84 mm in the Waldron *et al.* (1991) study.

Due to the differences in currency being used and the difference in mean weights in particular between the populations being considered, care should be made in directly comparing the results presented here with those in these two previous studies. Nevertheless, it is interesting to compare the relative values for both tissues in each study. For comparisons between values for different years, Waldron *et al.* (1991), calculated the ratio of the value of lean weight relative to fat weight when the later is set to –1. If we use the same approach here, the relative value for lean weight is 1.37 for the Simm *et al.* (1987) study and ranges from 0.92 to 1.69 in the study by Waldron *et al.* (1991). The mean value across years and sex in this study was 1.59 if all six years are considered, or 1.31 if values for 1998 are excluded. Both values are broadly similar to those presented in the two previous studies.

Other uses for the model

The UK sheep industry is characterized by a diverse range of breeds and crosses, many of which are mated to terminal sire breeds to produce slaughter lambs. These lambs are also grown under a range of different conditions. It is important to recognize that the results presented in this study are specific to the one breed-cross and production system considered and values may differ for other scenarios. Before a suitable selection index could be derived, economic values for at least the most diverse scenarios should be calculated and then used as part of the sensitivity analyses for the index.

Many of these different scenarios could be investigated relatively easily by adapting this model. Different drafting policies, such as drafting at a fixed weight or at a greater fatness than was used here, could be investigated just by changing the drafting criteria. If a different production system or breed-cross was to be described the model could be adapted using phenotypic data for a relatively modest number of lambs of the breed/cross of interest, grown under the required conditions, and slaughtered, ideally, over a range of ages. The experimental data used in this study to adapt the model were not ideal in so far that the lambs were not slaughtered over a series of ages. However, three features of the experimental design ensured that the data was suitable to use. These were: (1) all lambs were weaned at a fixed age and weighed at that time, (2) all lambs were randomly allocated within sex to each slaughter group, and (3) the range in live weights considered was fairly diverse.

In previous studies for beef cattle, both Amer *et al.* (1994) and Amer *et al.* (1997) used a bio-economic model to determine the optimum slaughter point for different breeds and crosses so as to maximise profit. A similar approach for slaughter lambs could be done using this model. When drafting at a fixed predetermined fatness (as was done here), the premiums and penalties paid for different fat classes has little effect on carcass value since the variation in fatness at drafting is low. However, if lambs were drafted at a fixed live weight, or the model was used to determine the optimum 'economic' slaughter point, then the price differentials between the different classes would have an important effect. Concern that the premiums and penalties being paid commercially by abattoirs in the UK do not fully reflect market demands has been expressed before (Simm and Dingwall, 1989; Simm, 1998), and were supported by the results presented in Chapter 5 of this thesis. A preliminary investigation using this model (results not shown) further suggested that, generally, where carcass were lighter than the maximum threshold, the penalties currently imposed on over fat carcasses were not sufficiently high to offset the financial benefits of increasing carcass weights. This means that for most producers, given current economic incentives, returns would be higher if lambs were drafted when over-fat. This model could be used to investigate what price differentials need to be imposed for this not to be the case, and more specifically for the optimum 'economic' slaughter point to correspond with the desired fat classes of 2 and 3L.

Improvements to the model

No model of a complex system is ever complete, and the one presented here is no exception. If further development was to be done, two areas in particular warrant further attention.

Accounting for gut fill. In the current model gut fill was considered as a fixed proportion of empty body weight (EBW, 27%) throughout the lamb's life. Whilst providing a useful first approximation, a more detailed description would be desirable. In ARC (1980) it was suggested that not only does gut fill, when expressed as a proportion of EBW, change as ruminants mature, but also changes with diet. The proportion is lowest when the diet consists solely of milk, increases for concentrates, further for grazing, and is highest for dried grass and silage. As an added complexity, the diet of lambs in the production system considered in this study would consist only of one food type very early on in the lambs life (milk), and thereafter consist of two or even three just prior to weaning. Developing a better way of accounting for gut fill given these conditions was considered beyond the scope of this current study.

Number of lambs drafted. At present, all lambs were drafted when they exceed the threshold for fatness or weight. No consideration is given to the number of lambs that are drafted at any one time. In practice this is unlikely to be the case since it would not be economical to transport a small number of lambs to the abattoir. Thus, lambs may not be sold unless more than a certain number can be drafted. Similarly, when the number of lambs remaining is small, they are all likely to be sold together, when a majority exceed the drafting thresholds. This practical consideration should be accounted for if further development of the model is to be undertaken.

Conclusions

The bio-economic model presented in this Chapter provides a very good tool for estimating economic values for increases in lean and fat weights at a fixed age in the progeny of terminal sire breeds of sheep. In contrast to previous approaches the model presented here can: (i) account for seasonal fluctuations in market prices for lamb carcasses; (ii) be easily adapted to accommodate different drafting criteria; (iii) implicitly account for the feed requirements of individual lambs, and (iv) account for seasonal variations in feed costs.

Economic values specific to one breed-cross type and production system were derived. Rams from terminal sire breeds are, however, typically mated to a range of different dam breeds and the resulting progeny are grown under a variety of conditions. The aim now should be to use this model to derive economic values for the most diverse scenarios in which progeny would need to perform. The most extreme values derived can then be used as boundaries for the range of economic values that needs to be investigated as part of the sensitivity analyses for the index.

Chapter 7

General Discussion

7.1 Introduction

The five studies described in this thesis were conducted to meet two overall aims. The first was to develop the means to incorporate measures of muscularity into selection indices for sheep. This was the focus of the first three studies (Chapters 2 to 4). The second aim was to develop a bio-economic model that could be used to estimate economic values for lean and fat weights for terminal sire sheep breeds in the UK. To achieve this information was first collected regarding the requirements of markets for UK lambs and market prices (Chapter 5). This information was then used to help develop a bio-economic model that gave a good description of a typical production system (Chapter 6).

The results presented in the preceding Chapters provide a valuable source of information that can be used to help develop new selection indices for terminal sire sheep breeds in the UK that would: (i) directly consider carcass shape, and (ii) be directly related to the market prices and signals for lamb. Both of these have been identified as improvements that are desired by breeders and development of these indices could help maintain and even increase the uptake of index selection methods amongst breeders in the UK (Chapter 1).

A detailed investigation of the different index possibilities is not included in this thesis. However, in this Chapter the intention is to provide a synthesis of the main points from the preceding Chapters and to discuss them in the context of how best to utilise the information in developing new indices (breeding programs). Practical issues to consider and areas in which further research would be desirable are also highlighted.

7.2 Incorporating measures of muscularity into a selection index

The results in Chapter 2 showed that a comprehensive assessment of the muscularity through the carcass could not be achieved by using a single measure. It was therefore proposed that the main focus should be on measures of muscularity in the loin and hind leg, as they are the most economically important joints. A further measure of whole carcass muscularity was also developed. This provided a useful general measure of carcass muscularity as correlations between it and measures in both loin and leg were moderate. On the basis of these results *in vivo* measures of muscularity for the hind leg, loin and whole carcass were developed (Chapter 3) and genetic parameters estimated for them and the corresponding carcass measures (Chapter 4).

The results presented in Chapter 4 provide a number of ways in which muscularity could be incorporated into a selection index. For example, one or both of the measures in the loin and hind leg, or the whole carcass measure, could be incorporated into the selection objective (as was suggested in Chapter 3) and one or more of the *in vivo* measures included amongst the selection criteria as appropriate. At first sight it may not be entirely clear which approach should be used.

The choice of measures will be influenced largely by the importance of improving muscularity in both the loin and leg (the choice of weighting for muscularity measures in a selection index will be discussed later). If the importance is high for both, then measures in each joint should be included in the selection objective and the corresponding CT measures included among the selection criteria. If the importance is only moderate for both, or lower for one *versus* the other, then including one measure would be preferable for practical reasons, such as ease of index development and of explaining the measures and results to breeders. Where the importance of improving muscularity in both the loin and leg is only moderate, then selection on the whole carcass measure may well be preferred.

The aim now should be to investigate different index options and record the expected correlated responses in each of the muscularity measures. These results could then be used as the main basis for further discussion as to the best approach to use. As part of these discussions some consideration will also need to be given to the practicalities of incorporating these measures into selection programmes. Many of these issues will be highlighted in subsequent sections of this Chapter.

7.3 Incorporating CT measures into two-stage selection programmes

Due to the high cost associated with CT scanning its cost-effective use is only likely to be achieved as part of a two-stage selection programme (Chapter 4). Following the completion of preliminary research (Young *et al.,* 2001a), two-stage selection programmes have recently been established within the SRS's for the Suffolk, Charollais and Texel sheep breeds in the UK. Within these programmes, CT is currently used solely to facilitate the accurate prediction of lean and fat weights. This is achieved by using information from three tomogram scans taken at the TV8, LV5 and ISC positions (Young *et al.,* 1999; Chapter 3). A topogram scan is also taken to help position these scans.

The linear measurements used to derive the *in vivo* measures of muscularity in Chapter 4 were taken on these same scans. The only additional cost therefore of deriving the muscularity measurements would be that of taking the linear measurements on scans. This cost should be comparatively small.

Within each of the SRS's, the time between ultrasound scanning (at 21 weeks of age) and mating is relatively short (< 2 months). The success of the two-stage selection programmes depends on the ability to CT scan candidates, analyse images, conduct the BLUP analyses and select reference sires for the following mating season, within that time. Rapid image analysis is therefore very important.

Since data collection was completed for the studies described in Chapters 3 and 4, automated procedures for determining tissue areas in the three reference scans (TV8, LV5, ISC; Chapter 4) have been developed (Young *et al.,* 2001a; M. Young, personal communication). These new procedures substantially reduce the time required for image analysis. The linear measurements taken as part of the studies described in Chapters 3 and 4 were taken manually, and this process was slow. Before the *in vivo* measures of muscularity could be incorporated effectively into two stage selection programmes, automated procedures for taking these measurements would be required. These procedures are not available at present and would need to be developed. If achieved this would further reduce the cost of obtaining the measures.

Given their importance, any potential difficulties in the development of the automated procedures may have a profound influence on the choice of muscularity measure to use as part of a breeding programme. Discussions with software developers will be an important part of the decision process. It is worth noting that one of the biggest problems to overcome is likely to be the measurement of spine length. Whilst all the other linear measurements used are taken on a single scan, spine length is the combination of two separate measurements taken on the overlapping topogram scans. At present the accuracy of the combined measurement depends on the operator's ability to assess the degree of overlap that has occurred. Changes to the scanning protocol or method may be needed before an accurate automated procedure for taking the measurements can be developed.

Methods of assessing muscularity on farms

Estimates of the correlation between the ultrasound measurement of muscle depth and each of the *in vivo* and carcass measures of muscularity were all positive (Chapter 4). This suggests that some information about an animal's muscularity would be gained at the first stage of the two-stage selection programme from an ultrasound measurement. However, few of these correlation estimates were high, with most being less than 0.45, particularly for the hind leg and whole carcass measures. If improving muscularity was considered sufficiently important then greater genetic progress could be achieved by developing more informative methods of assessing muscularity on farms.

The use of more practical and less costly methods of assessing muscularity on the live animal has been investigated in very few studies. Wolf *et al.* (2001) and van Heelsum *et al.* (1999) used a visual linear score for hind leg conformation on the live animal for Texel and Bluefaced Leicester sheep respectively. In the phenotypic study by Wolf *et al.* (2001), higher leg conformation scores tended to be associated with higher hind leg, loin and whole carcass muscularity measures that were similar to those used in Chapter 2 of this thesis, but the magnitudes of correlations between them were not estimated. In the genetic analysis by van Heelsum *et al.* (1999) the hind leg score was found to be moderately heritable (h^2 0.20, s.e. 0.04). Correlations with carcass measures of muscularity could not be estimated since none of the animals considered were slaughtered; however, undesirable positive genetic and phenotypic correlations of 0.39 and 0.35, respectively, were estimated with an ultrasonic measurement of fat depth above the third lumbar vertebra. Whether this positive correlation would be different in other breeds is unknown, nevertheless it does cast some doubt over the potential value of a visual score for assessing muscularity as part of a breeding programme. Estimates of correlations with the carcass measures of muscularity and with fatness in other breeds would be needed before the value of using this subjective score could be ascertained.

In the study by van Heelsum *et al.* (1999), a single assessor did the assessments of the hind leg. More than one assessor would be required if the scoring method was to be used as part of a large breeding programme. It would therefore be important also to determine the repeatability of the hind leg score across different assessors. A low repeatability would undermine the assessments potential value.

It is worth pointing out that, even if found to be useful, use of the hind leg scoring method as part of current breeding programmes may also have practical problems. In the study by Wolf *et al.* (2001) all lambs were sheared prior to assessment. If this requirement was not overcome then commercial breeders may not readily accept the use of this method.

In addition to assessing the hind leg, it may also be possible to derive an on farm measure of loin muscularity, similar to the *in vivo* measure used in Chapter 4, by dividing an ultrasound measurement of muscle depth by a measure of body length. Although used by Wolf *et al.* (2001), the value of such a measure as a predictor of the carcass measure has not been assessed and would need to be investigated further. As was highlighted in Chapter 3, the main difficulty is likely to be obtaining highly repeatable measures of body length.

Interpreting the measures of muscularity

The successful incorporation of any new measures into a selection programme is greatly dependent on the measures and the resulting EBVs (for the *in vivo* measures in this case) being easily interpreted by breeders. Because of the way in which they are derived, muscularity measures do not generally lend themselves to straightforward interpretation. Some thought is therefore required as to how best to present and describe these measures before they are incorporated into breeding programmes.

Three possible approaches are described here. The first possible approach is to describe the value obtained as being the thickness of muscle per unit length of bone (M. Young, personal communication). For example, consider the CT measure for the loin ($BSPL_{CT}$, Chapter 4), for a muscle depth measurement of 35 mm and a spine length measurement of 50 cm ($BSPL_{CT}$ = (35/50)*10 = 7.0). This value could be described as a muscle thickness of 7 mm per 10 cm of bone length. It is important to recognise that the wording of the interpretation is directly linked to the choice of scaling factor used. For instance, for the above measure it may desirable to further scale the values by 10 so that the EBV's would more likely be greater than one. The interpretation would then become a muscle thickness of 70 mm per 100cm of bone length. The EBVs would be interpreted as increases or decreases in muscle thickness at a fixed bone length of 100 cm.

The above approach would be best suited for those measures that are based on the ratio of two linear measurements that are taken in one region of the body, such as the CT measures for the loin or the hind leg ($BSPL_{CT}$ and WPL, Chapter 4). It could also be used to interpret values for the whole carcass measure, but the interpretation would be more difficult to relate to the overall form of the body.

A second possible approach is to report the phenotypic muscularity values as a score with a predetermined mean, such as 100. The disadvantage of this approach is that the value has no direct biological interpretation, nevertheless the score would be relatively easy to explain to breeders.

The third option is simply to express the EBVs in terms of standard deviation units. Scaling the values by a factor of 10 could be used to increase the range in values. As with option two, this approach has the disadvantage that the EBVs would not have a 'biological' interpretation, moreover care would need to be taken in choosing how to express the phenotypic values so as to avoid confusion. The main advantage of this approach would be that an animal's relative merit within the population could be easily determined.

Deciding on which of these (or other) approaches to use would be an important part of discussions prior to the muscularity measures being incorporated into a selection programme.

Correlated changes in vertebra number

In Chapter 3 it was shown that variation in the number of lumbar and thoracic vertebra existed between animals within each of the three breeds considered. At present, no information is available regarding the nature in which vertebrae number is inherited or its association with other traits.

By selecting on measures of muscularity that include spine length as a denominator, such as the loin and whole carcass measures, there is a danger that selection may tend towards those animals with a lower number of vertebra in one or both regions of the spine. This may lead to a correlated decrease in the frequency of animals within the national population with the higher number of vertebra.

Whether the number of vertebra in either of these regions of the spine is of economic importance to today's retailers, and thus whether this potential shift should be of concern, is presently unclear. Even so, unless it can be shown that the number of vertebra is unimportant, then it is important to determine the relationships between the different muscularity measures and vertebra number so it can be established whether this potential shift in number would occur. These results need to be available before any of the measures of muscularity are incorporated into a selection programme. If the correlated reduction is found to be likely, then methods of restricting this change may need to be developed.

7.4 Economic values

Muscularity

Economic values for measures of muscularity were not derived as part of the bio-economic model presented in Chapter 6. The main reason for this was that information about the relationships between the measures of muscularity and conformation (which has commercial value) were not available. Even so, it does not seem appropriate to derive economic values for 'better' measures of carcass shape based on the relationships with an assessment that is widely accepted as having undesirable attributes. Ideally, methods of objectively assessing carcass muscularity at abattoirs could be developed and payments to producers would be directly linked to these assessments. Only then could useful economic values for muscularity measures be estimated.

To the authors knowledge no study into practical methods of objectively assessing the muscularity of a carcass at abattoirs has been conducted. However, considerable research has been and continues to be focused on developing practical objective methods of assessing carcass composition at abattoirs (see Standford *et al.*, 1998 for a review). Some success has been achieved but as yet there is no method available that is sufficiently useful to use commercially (Standford *et al.*, 1998). If a useful method of accurately determining the weight of lean in a carcass could be developed then it may be possible to derive a measure of whole carcass muscularity relatively simply by also measuring carcass length (length from the gambrel to the bottom of the neck). Moxham and Brownie (1976) have already shown that carcass length could be measured on a slaughter line.

Until methods of assessing carcass muscularity at abattoirs are developed and useful economic values can be derived for measures of muscularity there seems little option but to use a desired gains approach to weight these measures in a selection index. This approach could be used in conjunction with actual economic values for lean and fat weights. Given the results in Chapter 5 (indicating the relatively low importance of conformation) a high weighting for improving muscularity and thus carcass shape at the expense of improvements in the other traits of interest cannot be justified. How much emphasis can be put on improving muscularity without having large detrimental effects on selection responses in lean and fat weights will become apparent only when the investigation of different index option is conducted.

Lean and Fat weights

The bio-economic model presented in Chapter 6 provides a very good tool for calculating the economic value of increases in lean and fat weights at a fixed age in the progeny of terminal sire rams. Given the model's flexibility it can be adapted relatively easily to account for different market condition and production systems (Chapter 6).

The economic values presented in Chapter 6 were specific to the requirements and prices of current markets for UK produced lambs (Chapter 5). For selection on an index to be effective in the long term, the relative economic values used also need to be relevant for likely future markets. The robustness of any derived index to likely changes in the economic values, if and when markets change, should therefore be investigated.

Detailed information about the requirements of likely future markets is not available. However, a valuable insight into likely changes was obtained as part of the study described in Chapter 5. The development of two distinct markets was indicated as a possibility, one for medium sized lambs with a carcass weight of 18 kg, fat class 3L and conformation R+ and a second market for heavy lambs with a carcass weight of 21 kg +, fat class 2/3L and conformation class R+.

Approximate estimates of the economic values of increasing lean and fat weights under both these likely markets could be obtained simply by changing the two thresholds for carcass weights in the bio-economic model (below and above which different payments were made) and then re-running the model. For instance, the heavy lamb market could be represented by increasing the lower weight threshold to 20 kg and removing the upper threshold. The market for the medium sized lambs could be represented by reducing the upper weight threshold to 19 kg. Since the predicted fatness and conformation ranges desired in both these likely future markets were similar to that required by current markets, it seems reasonable to assume that the same premiums and penalties for the different carcass grades could be used.

Customised indices

If both these markets were to develop, then it implies that two distinct types of lambs would need to be produced. Some variation may be achieved by using different dam breeds but the development of two sire types would also be needed. From a breeding perspective, this would suggest the adoption of two different selection indices. These could be used either within different breeds, with a view to using different breeds to meet the different requirements, or within a breed with a view to developing two separate lines. The use of indices customised to suit the different production circumstances is already commonplace within the UK sheep industry in so far as a total of eleven indices are in use for selection within different breeds (Collins, 1999). However, only one index (lean growth index) is currently used for selection in all terminal sire breeds.

Given the differences in characteristics between the different terminal sire breeds, some would be better suited than others to meet the requirements of the two different markets (Chapter 2). For example, the slower growth and greater development of carcass shape at younger ages associated with the Texel suggest that it would be best suited to produce lambs to supply the medium sized lamb market. Similarly, the high growth associated with the Suffolk suggests that it would be best suited to supply the large lamb market. However, breeders are unlikely to respond positively to being told which market their breed should focus on supplying. A better response would likely be achieved by developing more than one index for possible use within each breed and affording breeders the choice of which to use.

In the UK a choice of index is currently available only for hill breeds (Collins, 1999). For these breeds a choice of two indices is available, one for extensive conditions where lambs are sold as stores, and the other for intensive conditions where lambs are sold for slaughter. A choice of indices for selection within breeds is more common in Australia, where a range of index options are available for selection within terminal sire breeds of both sheep and beef cattle (Banks, 1994; Barwick, 1994). A choice of five indices is available for use in terminal sire sheep breeds as part of the LAMBPLAN. Developed using a desired gains approach, each index differs in the emphasis placed on changing growth, fatness and muscle depth (Banks, 1994). For beef cattle the customised index approach has been extended to a computerised procedure (BreedObject) where the relevant production system and target market can be specified and bulls are ranked on an appropriate index. Since economic indices are used, the index values are expressed in terms of the progeny's expected relative profitability. As part of LAMBPLAN and BreedObject, the same range of indices are available for all terminal sire breeds.

The main advantage of developing more than one index is the likely greater adoption and commitment to use of the index technology by breeders (Barlow, 1989). A possible disadvantage, however, is slower overall genetic progress, particularly where breeders choose to use a number of very different indices. The best approach is likely to be the provision of the choice of a relatively small number of different indices.

At present all slaughter lambs in the UK are produced to meet the same range of market requirements (Chapter 5). The development of more than one index for selection within a specific terminal sire breed is unlikely to be justified, the only exception being when rams from that breed were being used for mating to very different dam breeds. Whether the economic values for increasing lean and fat weight were sufficiently different in the most diverse breed-cross types to justify the development of separate indices would need to be investigated. A similar investigation could also be conducted to establish whether the development of separate indices for use in the different terminal sire breeds was warranted.

If the two separate markets, suggested in Chapter 5, were to develop then the development of two separate indices within each breed may well be required. Even then any groups of breeders, such as those in the Sire Referencing Schemes, should be encouraged to choose a single index for use so that the rate of genetic progress is not compromised.

Conclusions

This thesis does not provide all the information that is required to directly develop the most suitable index/indices to use as a basis for selection in terminal sire breeds of sheep in the UK. For example, uncertainty still exists over the economic value for improvements in carcass shape, and over the requirements of likely future markets. Even so, this thesis does provide sufficient information to allow the development of a range of possible selection indices that include measures of carcass shape amongst the selection objectives. Once developed the relative merits of these various index options can then be compared theoretically. Given the uncertainty associated with likely future markets in particular, decisions regarding which of these indices would be most useful to use can only be made following discussions with different sectors of the industry. Clarifying the likely requirements of future markets would be an important part of these discussions. The results presented in Chapter 5 would provide a very useful base on which to develop these discussions.

The aim now should be to conduct these theoretical investigations and develop a range of possible indices that can be presented to the industry.

References

Abdullah, A.Y., Purchas, R.W., Davies, A.S. and Kirton, A.H. 1993 Relationships between objective and subjective measurements of carcass muscularity. Proceedings of the New Zealand Society of Animal Production 53: 397-402

Abdullah, A.Y., Purchas, R.W. and Davies, A.S. 1998 Patterns of change with growth for muscularity and other composition characteristics of Southdown rams selected for high and low backfat depth. New Zealand Journal of Agricultural Research 41: 367-376

Agricultural Research Council (A.R.C) 1980 The nutrient requirements of ruminant livestock. Technical review by an ARC working party. Commonwealth Agricultural Bureaux, Farnham Royal, UK.

Allen, P. and Vangen, O. 1984 X-ray tomography of pigs – some preliminary results. In: In Vivo Measurement of Body composition in Meat animals (ed. D. Lister), pp 52-66. London: Elsevier

Amer, P.R., Kemp, R. A., Buchanan-Smith, J. G., Fox, G. C. and Smith, C. 1994 A Bioeconomic model for comparing beef cattle genotypes at their optimal economic slaughter end point. Journal of Animal Science 72: 38-50

Amer, P.R., Emmans, G.C. and Simm, G. 1997 Economic values for carcase traits in UK commercial beef cattle. Livestock Production Science 51: 267-281

Amer, P.R. and Emmans, G.C. 1998 Predicting changes in food energy requirements due to genetic changes in growth and body composition of growing ruminants. Animal Science 66:143-153

Banks, R.G. 1994 LAMBPLAN: Genetic evaluation for the Australian lamb industry. Proceedings of the 5th World Congress on Genetics Applied to Livestock Production 18: 15-18

Barlow, R. 1989 Breeding objectives - current state of knowledge. In: Proceedings A.P.C. Committee Workshop on Beef Cattle breeding (ed. S. Newman), Mt. Gambier, South Australia.

Barwick, S. A., Henzell, A. L. and Graser, H.U. 1994 Developments in the construction and use of selection indexes for genetic evaluation of beef cattle in Australia. Proceedings of the 5th World Congress on Genetics Applied to Livestock Production 18: 227-230

Bass, J.J., Butler-Hogg, B.W. and Kirton, A.H. 1990 Practical methods of controlling fatness in farm animals. In: Wood, J.D. and Fisher, A.V. (Eds), Reducing Fat in Meat Animals, Elsevier, London, pp145-200

Bennet, G.L., Johnson, D.L., Kirton, A.H. and Carter, A.H. 1991 Genetic and environmental effects on carcass characteristics of SouthdownXRomney lambs: II. Genetic and phenotypic variation. Journal of Animal Science 68: 1864-1874

Binnie, D.B., Farmer, R.J. and Clarke, J.N. 1995 Ultrasonic scanning of lamb carcasses for non-destructive carcass quality measurements. Proceedings of the New Zealand Society of Animal Production 55: 111-113

Blaxter, K. L., Fowler, V.R. and Gill, J.C. 1982 A study of the growth of sheep to maturity. Journal of Agricultural Science, Cambridge 98: 405-420

Brascamp, E.W. 1984 Selection indices with constraints. Animal Breeding Abstracts 25 (9): 645-654

Brascamp, E.W., Smith, C and Guy, D.R. 1985 Derivation of economic weights from profit equations. Animal Production 40: 175 – 180

Butterfield R.M. 1988 New concepts in sheep growth. Griffin Press Ltd, Marion Road, Netley, South Australia.

Cameron, N.D. 1997 Selection indices and the prediction of genetic merit in animal breeding. CAB International, Wallingford, Oxon

Cameron, N.D. and Bracken, J. 1992 Selection for carcass lean content in a terminal sire breed of sheep. Animal Production 54: 367-377

Cameron, N.D. and Drury, D.J. 1985 Comparison of terminal sire breeds for growth and carcass traits in crossbred lambs. Animal Production 40: 315-322

Collins, M.E. 1999 Genetic evaluation and selection of purebred sheep in the UK. A technical report for Signet, PO Box 603, Winterhill, Milton Keynes.

Conington, J.E. 2000 The genetic improvement of carcass and maternal traits in Scottish Blackface sheep. PhD thesis, University of Edinburgh.

Cuthbertson, A., Harrington, G. And Smith, R.J. 1972 Tissue separation - to asses beef and lamb variation. In: Symposium on aspects of carcass evaluation. Proceedings of the British Society of Animal Production, pp. 113-122

Davies, A.S., Garden, K.L., Young, M.J. and Reid, C.S.W. 1987. An atlas of X-ray tomographical anatomy of the sheep. Science Information Publishing Centre, DSIR: Bulletin No. 243. Wellington, New Zealand. 118 p.

De Boer, H., Dumont, B.L., Pomeroy, R.W. and Weniger, J.H. 1974 Manual on E.A.A.P. reference methods for the assessment of carcass characteristics in cattle. Livestock Production Science 1: 151-164

Dekkers, J.C.M. 2001 Economic aspects of applied breeding programs. Notes for a summer short course, University of Guelph, June 9-13.

de Vries, A.G. 1989 A model to estimate economic values of traits in pig breeding. Livestock Production Science 21: 49-66

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

Ellis, M., Webster, G.M., Merrell, B.G. and Brown, I. 1997 The influence of terminal sire breed on carcass composition and eating quality of crossbred lambs. Animal Science 64: 77–86

Emmans, G.C. and Fisher, C. 1986 Problems of nutritional theory. In: Nutritional requirements and nutritional theory (eds Fisher, C. and Boorman, K.N.). Butterworth, London

Emmans, G.C. 1988 Genetic components of potential and actual growth. In: Animal Breeding Opportunities, British Society of Animal Production No. 12, 153-181

Emmans, G.C. 1994 Effective energy: a concept of energy utilisation applied across species. British Journal of Nutrition 71: 801-821

Emmans, G.C. 1997 A method to predict the food intake of domestic animals from birth to maturity as a function of time. Journal of Theoretical Biology 186: 189-199

Faerne, A. 1998 Building effective partnerships in the meat supply chain: Lessons from the UK. Canadian Journal of Agricultural Economics Vol 46, 4 pp 491-518

Fogarty, N.M. 1995 Genetic parameters for live weight, fat and muscle measurements, wool production and reproduction in sheep: a review. Animal Breeding Abstracts 63: 3, 101-143

Fortin A. and Shrestha, J.N.B. 1986 In vivo estimation of carcass meat by ultrasound in ram lambs slaughtered at an average live weight of 37 kg. Animal Production 43: 469-475

Genstat 5 Release 4.1 (PC/Windows NT). 1998. Genstat 5 Committee, Lawes Agricultural Trust (Rothamsted Experimental Station).

Gibson, J.P. and Kennedy, B.W. 1990 The use of constrained selection indexes in breeding for economic merit. Theoretical and Applied Genetics 80: 801

Gilmour, A.R., Cullis, B.R., Welham, S.J. and Thompson, R. 1998 ASREML user's manual, October 1998. New South Wales Agriculture, Orange Agricultural Institute, Orange, NSW, Australia.

Gompertz, B. 1825 On the nature of the function expressive of the law of human mortality and on a new method of determining the value of life contingencies. Phil. Trans. Roy. Soc., 513-585

Groen, A.F. 1989a Economic values in cattle breeding. I Influences of production circumstances in situations without output limitations. Livestock Production Science 22: 1-16

Groen, A.F. 1989b Economic values in cattle breeding. II Influences of production circumstances in situations with output limitations. Livestock Production Science 22: 17-30

Hammond, J. 1932 Growth and development of mutton qualities in the sheep. Oliver and Boyd, London.

Harrington, G. and Kempster, A.J. 1989 Improving lamb carcass composition to meet modern consumer demand. In: Reproduction, Growth and Nutrition in Sheep (ed. O.R. Dyrmundsson and S. Thorgeirsson), pp79-90

Harris, D.L. and Newman, S. 1994 Breeding for profit: Synergism between genetic improvement and livestock production (a review). Journal of Animal Science 72: 2178-2200

Hayes, J.F. and Hill, W.G. 1981 Modification of estimates of parameters in the construction of genetic selection indices ('Bending'). Biometrics 37: 483-493

Hirooka, H., Groen, A.F. and Hillers, J. 1998a Developing breeding objectives for beef cattle production 1. A bio-economic simulation model. Animal Science 66: 607-621

Hirooka, H., Groen, A.F. and Hillers, J. 1998b Developing breeding objectives for beef cattle production 2. Biological and economic values of growth and carcass traits in Japan. Animal Science 66: 623-633

Holloway, I.J., Purchas, R.W., Power, M.T. and Thomson, N.A. 1994 A comparison of the carcass and meat quality of Awassi-cross and Texel-cross ram lambs. Proceedings of the New Zealand Society of Animal Production 54: 209-213

Hopkins, D.L., Pirlot, K.L., Roberts, A.H.K. and Beattie, A.S. 1993 Changes in fat depths and muscle dimensions in growing lambs as measured by real-time ultrasound. Australian Journal of Experimental Agriculture 33: 707-712

Hopkins, D.L. 1996 The relationship between muscularity, muscle:bone ratio and cut dimensions in male and female lamb carcasses and the measurement of muscularity using image analysis. Meat Science 44: 307-317

Hopkins, D.L., Fogarty, N.M. and Menzies, D.J. 1997 Differences in composition, muscularity, muscle to bone ratio and cut dimensions between six lamb genotypes. Meat Science 45: 439-450

Houghton, P.L. and Turlington, L.M. 1992 Application of ultrasound for feeding and finishing animals: a review. Journal of Animal Science 70: 930-941

Huxley, J.S. 1932 Problems of relative growth. Methuen, London. pp 276

Jackson, T.H. and Mansour, Y.A. 1974 Differences between groups of lamb carcasses chosen for good and poor conformation. Animal Production 19: 93-105.

James, J.W. 1982 Economic aspects of developing breeding objectives: General considerations. In: Future developments in genetic improvement of animals (ed. Barker, J.S.F., Hammond, R., McClintock, A.E.)

Jones, H.E., Simm, G., Dingwall, W.S. and Lewis, R.M. 1999 Genetic relationships between visual and objective measures of carcass composition in crossbred lambs. Animal Science 69: 553-561

Jopson, N.B., McEwan, J.C., Dodds, K.G. and Young, M.J. 1995 Economic benefits of including computer tomography measurements in sheep breeding programmes. Proceedings of the Australian Association of Animal Breeding and Genetics Vol 11: 194-197

Jopson, N.B., McEwan, J.C., Fennessy, P.F., Dodds, K.G., Nicoll, G.B. and Wade C.M. 1997 Economic benefits of including computer tomography measurements in a large terminal sire breeding programme. Proceedings of the Association for the Advancement of Animals Breeding and Genetics Vol 12: 72-76

Kempster, A.J., Croston, D. and Jones, D.W. 1981 Value of conformation as an indicator of sheep carcass composition within and between breeds. Animal Production 33: 39-49

Kempster, A.J., Cook, G.L. and Grantley-Smith, M. 1986 National estimates of the body composition of British cattle, sheep and pigs with special reference to trends in fatness. A review. Meat Science 17:107-138

Kempster, A.J., Croston, D., Guy, D.R. and Jones D.W. 1987 Growth and carcass characteristics of crossbred lambs by ten sire breeds, compared at the same estimated carcass subcutaneous fat proportion. Animal Production 44: 83-98

Kilkenny, J.B. 1990 Changes in quality specifications for different markets. In: Slade, C.F.R. and Lawrence, T.L.J. (Eds.), New Developments in Sheep Production, Occasional Publication No. 14, British Society of Animal Production 1990, pp 109-114

Kirton, A.H., Woods, E.G. and Dunganzich, D.M. 1983 Comparison of well and poorly muscled lamb carcasses as selected by experienced meat industry personnel. Proceedings of the New Zealand Society of Animal Production 43: 111-113

Knap, P.W. 2000 Time trends of Gompertz growth parameters in 'meat type' pigs. Animal Science 70: 39-49

Koerhuis, A.N.M. and Hill, W.G. 1996 Predicted response in food conversion ratio for growth by selecting on the ratio or on linear component traits, in a (sequential) selection programme. British Poultry Science 37: 317-327

Kotarbinska, M. 1969 [An investigation into the transformation of energy in growing pigs.] Institut Zootechniki, Wydewnictwa Wlasne, nr. 238, Wroclaw.

Kyriazakis, I. and Oldham, J.D. 1993 Diet selection by sheep: the ability of growing lambs to select a diet that meets their crude protein (nitrogen õ 6.25) requirements. British Journal of Nutrition 69: 617-629

Lawrie, R.A. 1991 Meat science, 5th ed. Pergamon Press plc. Oxford. Ch 7 pp 122

Lewis, R.M., Simm, G., Dingwall, W.S. and Murphy, S.V. 1996 Selection for lean growth in terminal sire sheep to produce leaner crossbred progeny. Animal Science 63: 133-142

Lewis, R.M. and Simm, G. 2000 Selection strategies in sire referencing schemes in sheep. Livestock Production Science 67: 129-141

Leymaster, K.A. and Jenkins, T.G. 1993 Comparison of Texel-sired and Suffolk-sired crossbred lambs for survival, growth and compositional traits. Journal of Animal Science 71: (4) 859-869

Maniatis, N. and Pollott, G.E. 1998 The dynamics of genetic resources at national level-the British sheep industry as a case study. Proceedings of the 6th World Congress on Genetics Applied to Livestock Production, Armidale, Australia. Vol 27: 219-222

Mathsoft 1995 Mathcad 6.0 User's Guide. Mathsoft, MA, USA.

McEwan, J.C., Clarke, J.N., Knowler, M.A. and Wheeler, M. 1989 Ultrasonic fat depths in Romney lambs and hoggets from lines selected for different production traits. Proceedings of the New Zealand Society of Animal Production 49: 113-119

McEwan, J.C., Hanrahan, J.P. and Fitzsimons, J.M. 1988 Growth and carcass traits of pure bred Texel and Suffolk sheep. Proceedings of the New Zealand Society of Animal Production 48: 41-48

MLC 1991 Sheep Year Book 1991. Meat and Livestock Commission, Milton Keynes, UK.

MLC 1999a Sheep Year Book 1999. Meat and Livestock Commission, Milton Keynes, UK.

MLC 1999b The Abattoir and Meat Processing Industry in Great Britain, 1999 edition. Meat and Livestock Commission, Milton Keynes, UK.

MLC 2000 Sheep Year Book 2000. Meat and Livestock Commission, Milton Keynes, UK.

Moav, R. 1973 Economic evaluation of genetic differences. In: Agricultural Genetics. Selected Topics (ed Moav, R.) John Wiely and Sons, New York, pp 319-352

Moxham, R.W. and Brownlie, L.E. 1976 Sheep carcass grading and classification in Australia. Wool technology and sheep breeding 23(2):17-25

Orr, R., Parsons, A.J., Treacher T.T., and Penning P.D. 1988 Seasonal patterns of grass production under cutting and continuous stocking management. Grass and Forage Science 43: 199-207

Palsson, H. 1939 Meat qualities in the sheep with particular reference to Scottish breeds and crosses. I. Journal of Agricultural Science, Cambridge 29: 544-626

Pálsson, H. 1940 Meat qualities in the sheep with special reference to Scottish breeds and crosses. II Journal of Agricultural Science, Cambridge 30: 1-63

Parratt, A.C. and Simm, G. 1987 Selection indicies for terminal sires to improve lean meat production from sheep in the United Kingdom. Animal Production 45: 87-96

Pollot, G.E., Guy, D.R. and Croston, D. 1994 Genetic parameters of lamb carcass characteristics at three end-points: fat level, age and weight Animal Production 58: 65-75

Purchas, R.W., Davies, A.S. and Abdullah, A.Y. 1991 An objective measure of muscularity: Changes with animal growth and differences between genetic lines of Southdown sheep. Meat Science 30: 81-94

Purchas, R.W. and Wilkin, G.H. 1995 Characteristics of lamb carcasses of contrasting subjective muscularity. Meat Science 41:3, 357-368

Richardson, R.I., Taylor, A.A. and Jolley, P.D. 1990 Added value products for lamb. In: Slade, C.F.R. and Lawrence, T.L.J. (Eds.), New Developments in Sheep Production, Occasional Publication No. 14, British Society of Animal Production 1990, pp 55-70

SAC 2001 The Farm Management Handbook 2001/02. SAC, West Mains Road, Edinburgh EH9 3JG.

Sehested, E. 1984 Computerised Tomography in sheep. In: In Vivo Measurement of Body composition in Meat animals (ed. D. Lister), pp 67-74. London: Elsevier

Sibbald, A.R., Grant S.A., Milne, J.A. and Maxwell, T.J. 1987 Heather moorland management - a model. In: Agriculture and Conservation in the Hills and Uplands (eds M. Bell and R.G.H. Bunce). ITE, Grange-over-Sands, pp 107-108.

Simm, G. 1987 Carcass evaluation in sheep breeding programmes. In: New techniques in sheep production (ed. I.F.M. Marai and J.B. Owen), pp. 125-144. Butterworths, London.

Simm, G. 1994 Developments in improvement of meat sheep. Proceedings of the 5th World Congress on Genetics Applied to Livestock Production, Guelph, Ontario, Canada. Vol 18: 3-10

Simm, G. 1998 Genetic improvement of cattle and sheep. Farming Press, Miller Freeman UK Ltd, Wharfedale Road, Ipswich, UK.

Simm, G. 1992 Selection for lean meat production in sheep. In: Progress in sheep and goat research (ed. Speedy A.W.). CAB International, Wallingford, Oxon, UK, pp 193-216

Simm, G, Amer, P.R. and Pryce, J.E. 1997 Returns from genetic improvement of sheep and beef cattle in Britain. SAC Animal Science Research Report 1997, Scottish Agricultural College, Edinburgh, pp 12-16

Simm, G. and Dingwall, W. S. 1989 Selection indices for lean meat production in sheep. Livestock Production Science Vol 21, pp 223-233

Simm, G., Lewis, R.M., Collins, J.E. and Nieuwhof, G.J. 2002a Use of sire referencing schemes to select for improved carcass composition in sheep. Journal of Animal Science (in press)

Simm, G., Young, M.J. and Beatson, P.R. 1987 An economic selection index for lean meat production in New Zealand sheep. Animal Production Vol 45, pp 465-475

Simm, G., Lewis, R.M., Grundy, B. and Dingwall, W.S. 2002b Responses to selection for lean growth in sheep. Animal Science 74: 39-50

Simm, G. and Murphy, S.V. 1996 The effects of selection for lean growth in Suffolk sires on the saleable meat yield of their crossbred progeny. Animal Science 62: 255-263

Simm, G., Smith, C. and Prescott, J.H.D. 1986 Selection indices to improve the efficiency of lean meat production in cattle. Animal Production 42: 183- 193

Skorupski, M.T., Garrick, D.J., Blair, H.T. and Smith, W.C. 1995a Economic values of traits for pig improvement. I. A simulation model. Australian Journal of Agricultural Research 46: 285-303

Skorupski, M.T., Garrick, D.J., Blair, H.T. and Smith, W.C. 1995b Economic values of traits for pig improvement. II. Estimates for New Zealand conditions. Australian Journal of Agricultural Research 46: 305-318

Smith, G.C., Dutson, T.R., Hostetler, R.L. and Carpenter, Z.L. 1976 Fatness, rate of chilling and tenderness of lamb. Journal of Food Science 41: 748-756

Smith, C., James, J.W. and Brascamp, E.W. 1986 On the derivation of economic weights in livestock improvement. Animal Production 43: 545-551

Sorensen, M.T. 1984 Computerized tomography of goats during pregnancy and lactation. In: In Vivo Measurement of Body composition in Meat animals (ed. D. Lister), pp 75-83. London: Elsevier

Standford, K., Jones, S.D.M and Price, M.A. 1998 Methods of predicting lamb carcass composition: A review. Small Ruminant Research 29: 241-254

Tallis, G.M., Turner, H.N. and Brown, G.H. 1964 The relationship between live measurements and edible meat in Merino weathers. Australian Journal of Agricultural Research 15: 446-452

Taneja, G.C. 1955 Mutton qualities in Australian Merino sheep. Australian Journal of Agricultural Research 6: 882-890

Taylor, St. C.S. 1980 Genetic size scaling rules in animal growth. Animal Production 30: 161-165

Tess, M.W., Bennett, G.L. and Dickerson, G.E. 1983a Simulation of genetic changes in lifecycle efficiency of pork production. I A bioeconomic model. Journal of Animal Science 56: 336-353

Tess, M.W., Bennett, G.L. and Dickerson, G.E. 1983b Simulation of genetic changes in lifecycle efficiency of pork production. II Effect on components of efficiency. Journal of Animal Science 56: 354-368

Thorgeirsson, S. 1982 Growth and development of Scottish Blackface and Icelandic sheep. PhD, Edinburgh.

Thorsteinsson, S.S. and Bjornsson, H. 1982 Genetic studies on carcass traits in Iceland twin ram lambs 1. Estimates of genetic parameters on carcass traits, live weight at weaning and carcass weight. Livestock Production Science 8: 489-505

Thorsteinsson, S.S. and Eythórsdóttir, E. 1998 Genetic parameters of ultrasonic and carcass cross-sectional measurements and muscle and fat weight of Icelandic lambs. Proceedings of the 6th World Congress on Genetics Applied to Livestock Production, Armidale, Australia. Vol 24: 149-152

van Heelsum, A.M., Lewis, R.M., Jones, D.W., Haresign, W. and Davies, M.H. 1999 Genetic parameters for live weight, ultrasonic measurements and conformation in Bluefaced Leicester sheep. Proceedings of the British Society of Animal Science 1999 pp 122

Waldron, D.F., Clarke, J.N. and Rae, A.L. 1991 Analysis of lamb schedules and relative economic values for lean and fat. Proceedings of the New Zealand Society of Animal Production 51: 405- 409

Waldron, D.F., Clarke, J.N., Rae, A.L., Kirton, A.H. and Bennett, G.L. 1992a Genetic and phenotypic parameter estimates for selection to improve lamb carcass traits. New Zealand Journal of Agricultural Research 35:287-298

Waldron, D.F., Clarke, J.N., Rae, A.L. and Woods, E.G. 1992b Expected responses in carcass composition to selection for muscularity in sheep. Proceedings of the New Zealand Society of Animal Production 52: 29-31

Wang, C.T. and Dickerson, G.E. 1991 Simulation of life-cycle efficiency of lamb and wool production for genetic levels of component traits and alternative management options. Journal of Animal Science 69: 4324-4337

Ward, B.G., Purchas, R.W. and Abdullah, A.Y. 1992 The value of ultrasound in assessing the leg muscling of lambs. Proceedings of the New Zealand Society of Animal Production 52: 33-36

Weller, J.I. 1994 Economic aspects of animal breeding. Chapman and Hall, 2-6 Boundary Row, London.

Wiener, G. and Hayter S. 1974 Body size and conformation in sheep from birth to maturity as affected by breed, crossbreeding, maternal and other factors. Animal Production 19: 47-65

Wolf, B.T., Smith, C. and Sales, D.I. 1980 Growth and carcass composition in the crossbred progeny of six terminal sire breeds of sheep. Animal Production 31: 307-313

Wolf, B.T. 1982 An analysis of the variation in the lean tissue distribution of sheep. Animal Production 34: 257-264

Wolf, B.T., Jones, D.A. and Owen, M.G. 2001 Carcass composition, conformation and muscularity in Texel lambs of different flock, sex and leg shape score. Animal Science 72: 465-476

Young, M.J. 1988 Bone and muscle growth in sheep. PhD thesis, University of Canterbury, New Zealand.

Young, M.J. 1990 Developmental changes in muscularity and selection to alter body composition. Proceedings of the 8th Conference of the Australian Association of Animal Breeding and Genetics pp 553-554

Young, M.J., Garden, K.L. and Knopp, T.C. 1987 Computer aided tomography – comprehensive body compositional data from live animals. Proceedings of the New Zealand Society of Animal Production 47: 69-71

Young, M.J., Lewis, R.M., McLean, K.A., Robson, N.A.A., Fraser, J., Fitzsimons, J., Donbavand, J. and Simm, G. 1999 Prediction of carcass composition in meat breeds of sheep using computer tomography. Proceedings of the British Society of Animal Science 1999: 43

Young, M.J., Lewis, R.M., Simm, G., Glasbey, C.A. and McLean, K.A. 2001a Incorporating x-ray computer tomography into selection programmes to improve the quality of sheep meat. Scottish Agricultural College final report for the Department of Environment, Food and Rural Affairs (DEFRA).

Young, M.J., Nsoso, S.J., Logan, C.M. and Beatson, P.R. 1996 Prediction of carcass tissue weight in vivo using live weight, ultrasound or X-ray CT measurements. Proceedings of the New Zealand Society of Animal Production 56: 205-211

Young, M.J. and Simm, G. 1990 Genetic parameters for in vivo body measurements in Suffolk sheep. Proceedings of the New Zealand Society of Animal Production 50: 403-406

Young, M.J., Simm, G. and Glasbey, C.A. 2001b Computerised tomography for carcass analysis. Proceedings of the British Society of Animal Science 2001: 250-254

Zar, J.H. 1996 Biostatistical Analysis. Prentice-Hall International Inc., Simon and Schuster, Upper Saddle River, N.J. Chapter 18, pp 371-406

Appendix 1 Intercepts (α) and coefficients (β) for each breed-sex for the regression of each composition and lean distribution variable on live weight (adjusted) †

	Suffolk Males α (s.e.)	*Suffolk Females* α (s.e.)	*Charollais Males* α (s.e.)	*Texel Males* α (s.e.)	*Suff/Char* β (s.e.) ‡	*Texels* β (s.e.)	diff §
Composition							
Lean (g / kg)	588.34 (6.31) [b]	563.55 (5.64) [a]	610.37 (7.56) [c]	681.12 (8.10) [d]	-2.56 (0.20) ***	-2.50 (0.44) ***	ns
Fat (g / kg)	207.47 (7.40) [a]	251.27 (6.61) [b]	197.01 (8.86) [a]	126.68 (9.49) [c]	3.97 (0.24) ***	4.18 (0.51) ***	ns
L:B	3.00 (0.07) [a]	3.26 (0.06) [b]	3.37 (0.08) [b]	3.86 (0.09) [c]	0.01 (0.00) ***	0.02 (0.01) ***	ns
Lean distribution							
Leg (g / kg)	293.76 (2.14) [b]	303.376 (1.91) [c]	285.34 (2.56) [a]	307.01 (2.75) [c]	-0.31 (0.07) ***	-1.00 (0.15) ***	***
Loin (g / kg)	117.79 (1.49) [c]	116.225 (1.33) [c]	111.86 (1.79) [b]	101.92 (1.91) [a]	0.04 (0.05) ns	0.46 (0.10) ***	***
Best end (g / kg)	60.01 (0.74) [c]	59.346 (0.67) [bc]	57.91 (0.89) [b]	51.74 (0.96) [a]	-0.08 (0.03) **	0.15 (0.05) **	***
Shoulder (g / kg)	198.66 (1.73) [a]	196.587 (1.54) [a]	210.26 (2.07) [b]	208.50 (2.22) [b]	-0.15 (0.06) **	-0.34 (0.12) **	ns

† Live weights were adjusted such that intercepts represent values at the mean weight at 14 week for each breed-sex, which were 41.7, 36.7, 38.1 and 30.0 kg for the Suffolk males, Suffolk females, Charollais males and Texel males respectively.

[a,b,c,d] Within rows, intercepts with different superscripts differ ($P<0.05$)

‡ Superscripts indicate the significance of differences from zero. Standard errors indicated as 0.00 are positive but less than 0.005

§ Significance of the difference between the two regression coefficients

Appendix 2

Abattoir/Cutting plant questionnaire

All answers given to any part of this questionnaire will be treated as confidential.

Please answer each questions in the space provided (underlined), or tick the appropriate box (shaded) where required.
Please give any additional comments that you feel would be useful/important in the space provided at the end of the questionnaire.

Name of company: ______________________ Telephone: ____________

Name of respondent: ______________________

Position in the company: ______________________

Does your company:

Slaughter lambs? Yes ☐ No ☐

Cut lamb carcasses into primal joints? Yes ☐ No ☐

Do retail packing of lamb? Yes ☐ No ☐

1. Buying Lambs

1(a).
Approximate number of lambs killed per year? ______________________

Of all lambs slaughtered what % is bought in: %
On a dead weight basis? ______
Through live/electronic auctions? ______

1(b). Dead weight buying (if none please move on to section **1(c)**.)

Carcass classification

In addition to weight, are prices paid based on a classification grade given to a carcass?
Yes ☐ No ☐

If yes, what is the scale/method used for carcass grading?
MLC (EUROP, conformation, 1-5, fatness) ☐ Other ☐

If other, please specify______________________

For the pricing grid you currently use, please specify premium/penalties for each cell of the grid.

If the MLC classification is not used please modify the categories as required.
Please attach your price grid on a separate sheet if more convenient.

MLC classification

	1	2	3L	3H	4L	4H	5
E							
U							
R							
O							
P							

On what basis are these premiums and penalties decided?______________________

____

____

____

____

Have you undertaken any studies/trials to work out the actual value to you, when cutting, of carcasses in different:

Fat class Yes ☐ No ☐

Conformation class Yes ☐ No ☐

If yes, please give details______________________

____

____

Are the premiums/penalties used a true reflection of costs/value of each grade to you?

Yes ☐ No ☐

If no, why not?______________________

____

____

Are premiums/penalties constant over the year/season or changed periodically?

Constant ☐ Changed ☐

If changed, what changes are made and when?______________________

____

Why?______________________

Carcass Weight

What is the preferred carcass weight range?______________________

Why is this range preferred?______________________

What discount are applied to carcasses outside this range?______________________

____

____

What is the base price (onto which premiums/penalties are added) paid by you based on (i.e. GBSQQ or other), please give details?______________________

____

____

How are carcasses outside of the desired fat/conformation grades and weight range sold?

Over weight______________________ Under weight______________________

Too lean______________________ Too fat______________________

Poor conformation______________________

1(c). Live Auctions (if none please move on to section **2.**)

General specifications outlined to buyer:

Live weight ______________________

Other______________________

Are some breeds preferred and, if yes, which?____________________

Reasons for this preference? ____________________

Do you pay more per kg for lambs from these breeds? Yes ☐ No ☐

After slaughter are carcasses graded using an MLC or similar system? Yes ☐ No ☐

2. Selling Lamb

2(a).

What % of your total output is sold to a:

Domestic market:______________ % ____ Export market:______________ % ____

2(b). Domestic Market

What % of your output is supplied to each outlet type, and what carcass specifications are outlined by them?

			Carcass specification	
	% of domestic sales	Carcass weight	Conformation	Fat class
Retailers	______	______	______	______
Caterers	______	______	______	______
Wholesale butchers	______	______	______	______
Other (please specify)	______	______	______	______

Who are your main customers?____________________

If you are cutting or retail packing, is fatness also specified in terms of a maximum depth of fatness over specific joints? If so what depth and which joints/cuts?____________________

Do you receive a premium from your customers for lambs of higher conformation?
(E vs U, U vs R) Yes ☐ No ☐

If yes, please give details____________________

What are the benefits of a carcass with higher conformation:

For you?____________________

For you customers?____________________

Could conformation be adequately measured by focusing on one or two joints?

Yes ☐ No ☐

If yes, which joints?____________________

If no, why not?____________________

2(c). Export Market (if none please move on to section **3.**)

Main countries supplied?	% of total export	Carcass specification: Weight	Conformation	Fat class
________	________	________	________	________
________	________	________	________	________
________	________	________	________	________
________	________	________	________	________

Are there any other specifications that are outlined?________________________________

____

Is conformation and fat score more important for export than for the domestic market?
Conformation Yes ☐ No ☐
Fat score Yes ☐ No ☐

If yes, why is this?________________________________

____

____

Do you receive a premium for higher conformation carcasses when exporting?
(E vs U, U vs R grades etc.) Yes ☐ No ☐

If yes, please give details________________________________

____

3. Cutting and Processing Lamb

3(a). Boning

*What % of your total output is sold as bone-less product?*________________

Do you expect this proportion to increase in the future? Yes ☐ No ☐

If yes, what proportion do you expect in future? ________________

If you expect your bone-less product output to increase, would you be looking to extend your preferred carcass weight range so as to obtain larger carcasses for boning? Yes ☐ No ☐

*If yes, what carcass weight range would you expect to allow?*________________

Do you see a limit to the carcass weight that could be used, if so what? ________________

____

____

3(b). Retail packing (if you do not retail pack please move to section **4.**)

Do you pack lamb supplied from other abattoirs/cutting plants? Yes ☐ No ☐

Is New Product Development (NPD) for lamb, undertaken by:
You ☐ Customer ☐ None undertaken ☐

4. Lamb marketing overview

If all lambs could fall into a narrow weight range/single conformation and fat class, what carcass weight, fat and conformation classification would be the ideal lamb for the:
Domestic market?____________________
Why?____________________
Export market?____________________
Why?____________________

Over the next 10-15 years would you expect this preferred lamb carcass specification to change?
Yes ☐ No ☐

If yes, what changes do you expect?____________________

Would you be willing to discuss some of these answers further if required? Yes ☐ No ☐

Would you be willing to attend a possible discussion forum to discuss 'breeding sheep for current and future lamb markets – what is required ?'
Yes ☐ No ☐

Any other comments ?

Thank you for your co-operation

Appendix 3

Retailer questionnaire

All answers given to any part of this questionnaire will be treated as confidential.

Please answer each questions in the space provided (underlined), or tick the appropriate box (shaded) where required.
Please give any additional comments that you feel would be useful/important in the space provided at the end of the questionnaire.

Name of company: ______________________ Telephone: ______________

Name of respondent: ______________________

Position in the company: ______________________

1(a) Buying in lamb

Who are your main suppliers of lamb? ______________________

In what form do you buy in lamb?

Whole carcasses ☐ Primals ☐ Retail packs ☐

When buying in lambs what specifications are given to your supplier?

Carcass weight: ______________________

Carcass conformation: ______________________

Carcass fat class: ______________________

Weight of primals: ______________________

Fat depth over primals, min: ______________________

max: ______________________

Does this differ for different joints and if yes, what are the differences and why? ______________________

Other specifications? ______________________

Why have these specifications been chosen? ______________________

Have you undertaken any research (consumer research or other) to decide on the specifications most suitable for you and if yes please give details?

If specifications could be outlined as a single carcass weight and conformation and fatness classification, what would be the ideal carcass?

Carcass weight:______

Why? ______

Conformation:______

Why?______

Fat class:______

Why?______

Are carcasses of higher conformation (E vs U, U vs R) preferred? Yes ☐ No ☐

if yes, why?______

If no why not?______

Could conformation be adequately measured by focusing on one or two joints? Yes ☐ No ☐

If yes, which joints?______

If no, why not?______

1(b) Muscle thickness/depth

Are there any joints were a higher muscle depth would be preferred and if yes, which joints?

Would you be willing to pay premiums for carcasses with higher muscle depths in these joints? Yes ☐ No ☐

Why ? ______

2(a) Selling Lamb

Do you sell lamb on a fixed weight/price basis? Yes ☐ No ☐

What % of your total sales (by volume) is sold as: %

Bone-in roasting joints ______

Bone-in cuts (i.e. chops) ______

Bone-less roasting joints ______

Other bone–less products (please specify):

______________________________ ______

______________________________ ______

______________________________ ______

______________________________ ______

______________________________ ______

Do you have any speciality lamb lines? Yes ☐ No ☐

If yes, how does this line differ from your standard lamb line?______________________________

____

____

____

____

2(b) Bone-less products

Do you expect the proportion of lamb sold as boned products to increase in the future?

Yes ☐ No ☐

If yes, what % do you expect in future (bone-less joints and other)?________________%

Do you outline a different carcass weight range from which to produce boned products and if yes what?

____

It has been suggested that in future larger carcass weights could be used for producing bone-less products. Do you see a limit to the carcass weight that could be used and if yes, what weight and why this limit?

____

____

____

____

____

3. Future marketing of lamb

Over the next 10-15 years would you expect the carcass specifications you give to your lamb suppliers to change ?

Yes ☐ No ☐

If yes, what changes do you expect?

Carcass weight:______________________________

Conformation:______________________________

Fatness:______________________________

Other changes:______________________________

What do you see as the main priorities to be addressed, when looking at 'breeding lambs to meet current and future market requirements'?______________________________

Would you be willing to discuss some of these answers further if required?

Yes ☐ No ☐

Would you be willing to attend a possible discussion forum to discuss 'breeding sheep for current and future lamb markets – what is required ?'

Yes ☐ No ☐

Any other comments?

Thank you for your co-operation

Appendix 4 Percentage of carcasses within the range of 16-22 kg classified in each fatness and conformation class (1998-1999)

	1	2	3L	3H	4L	4H	5	Total
E		0.2	0.5	0.2	0.1			1.0
U		2.0	8.3	4.5	1.1	0.4	0.1	16.4
R	0.3	10.6	34.4	14.8	2.8	0.8	0.2	63.9
O	0.6	5.7	8.8	3.0	0.6	0.2		18.9
P								0.0
Total	0.9	18.5	52.0	22.5	4.6	1.4	0.3	

Source: MLC