1-2013

Index Selection in Terminal Sires Improves Lamb Performance at Finishing

G. C. Márquez
Virginia Polytechnic Institute and State University

W. Haresign
Aberystwyth University

M. H. Davies
ADAS Rosemaund, Preston Wynne

Rainer Roehe
Scottish Agricultural College

L. Bünger
Scottish Agricultural College

See next page for additional authors

Authors
G. C. Márquez, W. Haresign, M. H. Davies, Rainer Roehe, L. Bünger, G. Simm, and Ronald M. Lewis

Index selection in terminal sires improves lamb performance at finishing[1]

G. C. Márquez,* W. Haresign,† M. H. Davies,‡ R. Roehe,§ L. Bünger,§ G. Simm,§ and R. M. Lewis*§[2]

*Department of Animal and Poultry Science, Virginia Polytechnic Institute and State University, Blacksburg 24060; †Institute of Biological, Environmental, and Rural Sciences, Aberystwyth University, Aberystwyth SY23 3FG, UK; ‡ADAS Rosemaund, Preston Wynne, HR1 3PG, UK; and §Sustainable Livestock Systems Group, Scottish Agricultural College, Edinburgh EH9 3JG, UK

ABSTRACT: Lamb meat is often perceived by consumers as fatty, and consumption has decreased in recent decades. A lean growth index was developed in the UK for terminal sire breeds to increase carcass lean content and constrain fat content at a constant age end point. The purposes of this study were 1) to evaluate the effects of index selection of terminal sires on their crossbred offspring at finishing and 2) to evaluate its effectiveness within terminal sire breeds. Approximately 70% of lambs marketed in the UK have been sired by rams of breeds typically thought of as specialized terminal sires. The most widely used are Charollais, Suffolk, and Texel. These breeds participated in sire referencing schemes from the early 1990s by sharing rams among flocks selected on the lean growth index. From 1999 to 2002 approximately 15 "high" and 15 "low" lean growth index score rams were selected from within their sire referencing schemes and mated to Welsh and Scottish Mule ewes. Their crossbred offspring were commercially reared on 3 farms in the UK. Lambs were finished to an estimated 11% subcutaneous fat by visual evaluation. At finishing, lambs were weighed, ultrasonically scanned, and assessed for condition score and conformation. Records were obtained for 6356 lambs on finishing BW (FWT), ultrasonic muscle depth (UMD), ultrasonic fat depth, overall condition score (OCS), and conformation of gigot, loin, and shoulder. Ultrasonic fat depth was log transformed (logUFD) to approach normality. High-index-sired lambs were heavier at finishing (1.2 ± 0.2 kg) with thicker UMD (0.7 ± 0.2 mm) and less logUFD (0.08 ± 0.01 mm; $P < 0.05$). There were no differences in OCS or conformation based on the sire index or breed ($P > 0.08$). Suffolk-sired lambs were heavier than Charollais (1.0 ± 0.3 kg), which were heavier than Texel (0.9 ± 0.3 kg; $P < 0.001$). Texel-sired lambs had thicker UMD than Charollais (0.7 ± 0.2 mm; $P < 0.001$) but were not different than Suffolk. Charollais-sired lambs had greater logUFD than both Texel (0.098 ± 0.016 mm) and Suffolk (0.061 ± 0.017 mm) sired lambs ($P < 0.001$). Within a breed, high- and low-index-sired lambs differed in performance with the exceptions of FWT and UMD in Suffolks. Index selection produced heavier and leaner lambs at finishing. Producers have flexibility in choosing the terminal sire that best fits their production system.

Key words: crossbred lambs, index selection, lamb performance, terminal sire

J. Anim. Sci. 2013.91:38–43
doi:10.2527/jas2012-5383

INTRODUCTION

There has been growing preference among consumers for leaner meats (Woodward and Wheelock, 1990; Webb and O'Neill, 2008). This has particularly impacted the competitiveness of lamb, which has been considered overly fatty. As a consequence, selection programs in terminal sire sheep have focused on reducing excess fatness (Simm et al., 2002).

Lambs from breeds that have historically generated terminal sires account for 70% of the lamb crop in

[1]We acknowledge the Meat and Livestock Commission [now EBLEX (Kenilworth, UK), Quality Meats Scotland (QMS), and Hybu Cig Cymru– Meat Promotion Wales (HCC; Ty Rheidol, Pave Merlin, Aberystwyth, UK)], the Department of Environment, Food and Rural Affairs (London, UK), the British Charollais Sheep Society (Norfolk, UK), the Suffolk Sheep Society (Ballymena, UK), and the British Texel Sheep Society (Kenilworth, UK) for funding this study. We also thank the technical staff at Aberystwyth University, ADAS Rosemaund, and the Scottish Agricultural College for their support of the experimental program and E. Stephens for technical editing.

[2]Corresponding author: rmlewis@vt.edu

Received April 17, 2012.
Accepted September 24, 2012.

the UK (Pollott and Stone, 2004). The most widely used breeds are Charollais, Suffolk, and Texel. Therefore, genetic improvement in these breeds should substantially impact market animals. A lean growth index was adopted by the UK terminal sire sheep industry to improve the lean content of the carcass (Simm and Dingwall, 1989). Although there have been clear benefits within experimental populations (Lewis et al., 1996; Simm and Murphy, 1996; Simm et al., 2002), evidence from commercial settings is more limited (Márquez et al., 2012).

In the UK many terminal sire flocks are managed intensively. This benefits the efficacy of selection by avoiding constraints on growth within that environment. More intensively managed young rams also can be marketed earlier, which reduces production costs and decreases their generation interval. Commercial lambs, however, are reared at grass, which can be growth limiting. Thus, it is necessary to test if genetic improvement in one environment translates to gains in the other.

The objectives of this study were to test 1) whether index selection within the terminal sire industry has improved the quality of crossbred lambs at finished condition and 2) whether any benefits of that selection are consistent within breeds.

MATERIALS AND METHODS

Animal Care and Use

The Animal Experiment Committees at the Institute of Biological Environmental and Rural Sciences, the Scottish Agricultural College, and ADAS UK Ltd. approved all procedures and protocols used in the experiment.

Animal Resources

In each year from 1998 to 2000, Scottish and Welsh Mule ewes were developed from the matings of Bluefaced Leicester rams with Scottish Blackface and (Welsh) Hardy Speckled Face ewes (van Heelsum et al., 2003, 2006; Mekkawy et al., 2009). After weaning in each of those years, the ewes were distributed among 3 research farms in the UK: Rosemaund, England; Edinburgh, Scotland; and Aberystwyth, Wales. The ewes were first bred to terminal sire rams to lamb at approximately 2 yr of age.

From 1999 to 2002 the ewes were mated to rams from the Charollais, Suffolk, and Texel breeds. The rams originated from the sire referencing schemes of their breeds and were selected according to a lean growth index designed to increase carcass lean growth and constrain fat growth at a constant age end point (Simm and Dingwall, 1989). The rams used were chosen from the top and bottom 5% of available rams with index scores and were categorized as "high" and "low" lean growth index categories. The index score of high-index rams was 198 ± 8 points greater than that of low-index rams, and their EBV for index traits differed. Body weight EBV was 6.6 ± 0.5 kg greater, ultrasonic muscle depth (**UMD)** EBV was 2.3 ± 0.2 mm larger, and ultrasonic fat depth (**UFD**) EBV was 0.49 ± 0.12 mm smaller in high- vs. low-index rams (Márquez et al., 2012).

Sires were used for 2 breeding seasons and were moved between the 3 farms to create genetic links among farms and years. After their first breeding season, one third of rams stayed at their current farm and two thirds were moved to another farm. This ensured that performance from crossbred lambs born in different locations and to different dam breeds could be fairly compared. Both ewe breeds were represented in each farm and year, thus avoiding confounding. Details of the mating design and husbandry were provided by Márquez et al. (2012).

Production and Finishing of Crossbred Lambs

At birth, each lamb had its ancestry, sex, and BW recorded. If a ewe had more than 2 lambs, any surplus lambs were fostered. Ewes and their lambs were turned out to pasture within 48 h after birth.

Early life growth traits in these lambs were considered previously (Márquez et al., 2012). In this study, from approximately 10 wk, lambs were scored for fat cover every 2 wk. They were harvested on reaching a target finished condition of 3L fat score, which was assessed subjectively by feel (as for condition scoring) and corresponds to approximately 11% subcutaneous fat (Kempster et al., 1986). This approach was adopted to harvest lambs at comparable levels of physiological maturity. Because lambs of different breed types were being compared, comparisons at fixed maturity levels were deemed more appropriate to evaluate potential differences in body composition.

Once finished, lambs were weighed, scored for condition and conformation, and ultrasonically scanned. Overall condition (**OCS**) was scored on a scale from 1 to 5 in 0.5 point intervals, where a greater score indicated better condition (fatness). Shoulder (**CONS**), loin (**CONL**), and gigot (**CONG**) conformation were scored on a scale of 1 (poor) to 6 (superior) in 0.5 point intervals. Muscle depth was ultrasonically measured at the deepest point of the eye muscle (musculus longissimus lumborum) at the third lumbar vertebra, and UFD was measured at the same position and at 1 and 2 cm lateral to it and then averaged. Once finished, lambs were processed at a commercial abattoir. Data were available on 6356 lambs over the 4 yr of the experiment.

Statistical Analysis

Body Weight and Ultrasound Scanning. The distribution of the data for finished BW (**FWT**), UMD, and UFD was investigated. Skewness, kurtosis, and normality were evaluated. Significant nonnormality was detected only for UFD, and the Box-Cox procedure (Box and Cox, 1964) was applied to define a parsimonious transformation. The log likelihood was maximum with a log transformation, which was applied. A log transformation also was used previously for this trait (van Heelsum et al., 2001; Husain et al., 2007).

The FWT, UMD, and log-transformed UFD (**logUFD**) data were analyzed (SAS Inst. Inc., Cary, NC) fitting a linear mixed model. Fixed effects were sire index category (high or low), sire breed (Charollais, Suffolk, or Texel), sex (castrate or ewe lamb), dam breed (Scottish or Welsh Mule), age of dam (2 to 5 yr), farm and birth year. Interactions between sire index category and sire breed, and between farm and year, also were fitted. A combined birth-rearing rank effect was fitted with 4 categories: single born/single reared, twin or more born/single reared, single or twin born/twin reared, and triplet or quadruplet born/twin reared. No interaction between sire and dam breed was detected in preliminary analyses, and therefore, it was omitted from the final model fitted. Random effects were rearing dam, sire nested within breed and index category, and the residual. Variance components were estimated simultaneously in the analysis. The covariates included in the model depended on the trait. For FWT and UMD, the estimated subcutaneous fat percentage of the carcass was fitted; it was centered to the target finishing condition of 11% subcutaneous fat cover (Kempster et al., 1986). For logUFD, lamb age at measurement was the covariate.

Least squares means were estimated and mean comparisons were conducted with a Tukey-Kramer adjustment for multiple comparisons. The statistical significance of fixed effects was tested using partial sums of squares. Differences between index categories were tested within breeds.

Condition Scores. Condition scores and CONS, CONL, and CONG were subjectively measured ordered categorical variables, and their distributions did not approach normality. Therefore, they were analyzed using a generalized linear mixed model. A multinomial distribution was fitted with a logit link function using ASReml (Gilmour et al., 2009). The fixed effects in these models were sire index category and sire breed, along with their interaction, sex, dam breed, age of dam, farm, birth year, and age at measurement as a covariate. The interaction between farm and birth year was not fitted because some scores did not occur in all farm–birth year combinations. Sire nested within index category and breed was fitted as a random effect. Rearing dam was not included as a random effect in this model because a likelihood ratio test indicated it did not define significant variation in any of these scores.

RESULTS

Performance at Finished Condition

Sire index and breed were significant sources of variation for FWT, UMD, and logUFD ($P < 0.001$). Their interaction was significant for logUFD ($P = 0.02$) and FWT ($P = 0.007$). This interaction in logUFD was due to the difference between lambs sired by high- and low-index Charollais rams being greater (0.14 ± 0.02) than that in the other 2 breeds (on average, 0.03 ± 0.01; Fig. 1). For FWT, the differences between breeds were greater within low-index compared with high-index sired lambs. Still, there were no rerankings among index categories from any breed for any trait.

High- and low-index-sired lambs differed ($P < 0.001$) for FWT, UMD, and logUFD, as reported in Table 1. High-index-sired lambs were 1.2 ± 0.2 kg heavier at finishing, with 0.7 ± 0.2 mm greater UMD and 0.08 ± 0.01 mm lower logUFD (1.21 mm less UFD). Suffolk rams sired heavier lambs than Charollais (0.96 ± 026 kg), which sired heavier lambs than Texel (0.85 ± 0.26 kg; $P < 0.01$). Suffolk- and Texel-sired lambs did not differ in either UMD or logUFD. However, Charollais sired lambs had less UMD than Texels (0.66 ± 0.17 mm; $P < 0.001$) and more logUFD than both Texel (0.098 ± 0.016 mm; $P < 0.001$) and Suffolk (0.061 ± 0.017 mm; $P < 0.001$) sired lambs.

Although lambs sired by high-index Suffolk rams were numerically heavier with thicker UFD than their low-index contemporaries, these differences were not significant ($P > 0.2$). Only for logUFD were significant differences observed ($P = 0.02$), with lambs sired by high-index compared with low-index Suffolk rams being leaner (–0.056 ± 0.024 mm logUFD). Significant differences between high- and low-index Suffolk-sired lambs were not found in the

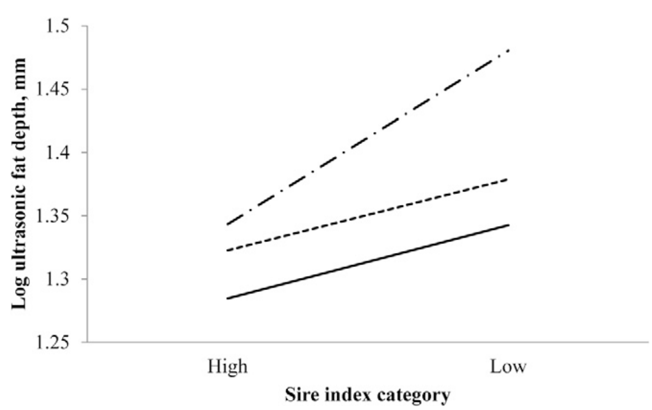

Figure 1. Adjusted means for logarithmic ultrasonic fat depth of lambs sired by either high- or low-index sires of the Charollais (dot-dashed line), Suffolk (dashed line), and Texel (solid line) breeds.

Table 1. Adjusted least squares means for finishing traits in crossbred lambs by sire index and breed and dam breed[1]

Item	No.[2]	FWT ± SE, kg	UMD ± SE, mm	logUFD ± SE, mm
Sire breed				
Charollais	2282	41.3 ± 0.2[b]	24.3 ± 0.1[b]	1.41 ± 0.01[a]
Suffolk	1968	42.2 ± 0.2[a]	24.6 ± 0.1[ab]	1.35 ± 0.01[b]
Texel	2106	40.4 ± 0.2[c]	24.9 ± 0.1[a]	1.31 ± 0.01[b]
Sire index				
High	3170	41.93 ± 0.2[a]	25.0 ± 0.1[a]	1.32 ± 0.01[b]
Low	3186	40.73 ± 0.2[b]	24.3 ± 0.1[b]	1.40 ± 0.01[a]
Dam breed				
Scottish Mule	3020	42.1 ± 0.2[a]	24.9 ± 0.1[b]	1.35 ± 0.01[b]
Welsh Mule	3336	40.5 ± 0.2[b]	25.5 ± 0.1[a]	1.37 ± 0.01[a]

[a–c]Within a column, means without a common superscript differ ($P < 0.05$).

[1]FWT = finishing BW; UMD = ultrasonic muscle depth; logUFD = log ultrasonic fat depth.

[2]No. of lambs within each category.

earlier growth of these lambs either (Márquez et al., 2012). However, in the other 2 breeds, high-and low-index-sired lambs differed, with high-index-sired lambs being heavier, with thicker UMD and thinner UFD ($P < 0.01$).

Breed of the dam affected all traits ($P < 0.001$). Lambs from Scottish Mules were heavier at finish but had less UMD and logUFD than lambs from Welsh Mules (Table 1). The age of the dam defined variation in FWT ($P < 0.001$) but not in UMD ($P = 0.7$) or logUFD ($P = 0.6$). The birth-rearing category explained variation in FWT and logUFD ($P < 0.001$) but not in UMD ($P = 0.9$; results not shown).

An interaction between year and location was observed in all traits ($P < 0.001$). There was no clear pattern to this interaction, although in the first year of the experiment all ewes were primiparous 2-yr-olds with the finishing weights of lambs lower than in later years ($P < 0.01$). In general, lambs born in Scotland were heavier at FWT than those born in the other locations.

Finished Condition Score and Conformation

Most lambs (47%) had an OCS of 3. The OCS scores did not differ with respect to sire index category ($P = 0.8$), sire breed ($P = 0.08$), or their interaction ($P = 0.9$). However, OCS was affected by farm and birth year of the lamb ($P < 0.001$).

The most common score for all 3 conformation measures was 4 (CONS: 52%; CONL: 48%; CONG: 44%). Sire breed, index category, and their interaction did not define variation in any of the conformation scores ($P > 0.2$), although the age of the dam and birth year of the lamb did ($P < 0.001$); farm explained variation in both CONS and CONG ($P < 0.001$).

DISCUSSION

Performance at Finished Condition

Sire Index and Breed. High-index-sired lambs performed better than low-index-sired lambs for FWT, UMD, and logUFD, in agreement with previous results. After 9 yr of selection with this index, sheep weighed 4.9 kg more and had 1.1 mm less UFD and 2.8 mm thicker UMD at 150 d of age than an unselected line (Simm et al., 2002). Furthermore, these changes in index score have resulted in economically desirable changes in composition: carcasses have proportionally more lean and less fat contents (Lewis and Emmans, 2007).

High- and low-index Suffolk-sired lambs did not differ in FWT or UMD, which was consistent with their earlier growth (Márquez et al., 2012). This was not the case for the other 2 breeds. We have hypothesized that seasonal or nutritional constraints did not allow these lambs to reach their full genetic potential. Husbandry also may have been more intensive on purebred farms, the source of the rams used in this study, than at the commercial farms on which the crossbred lambs were reared. This may have been more pronounced in the Suffolk breed, with the consequence that their offspring were not able to perform as well as anticipated (Márquez et al., 2012). These results were not expected because persistent differences between a Suffolk line selected on the same index, relative to its control, have been reported (Simm et al., 2001, 2002; Lewis and Emmans, 2007).

Lambs in this study were finished to a constant fatness to compare them at similar degrees of physiological maturity. Because the lambs differed in genetic background, reflecting crosses of several sire and dam breed types, this approach avoided inferring differences in body composition among them simply as an artifact of differences in mature size. Furthermore, although other end points are also used commercially (e.g., age, BW), a target fat level is by far the most common within UK systems.

Although the differences between high- and low-index-sired lambs were relatively small in an absolute scale, they were observed and would translate to increased profits for producers. Forming predictions of the performance of crossbred offspring of purebred rams is difficult. The purebred rams used in this experiment were selected on criteria measured at a fixed age, with high-index rams allowed to reach heavier (mature) BW. Their crossbred offspring were finished to a constant fatness, with progeny of high-index rams being heavier. Even if it were possible to account for nutritional and other environmental differences between purebred and crossbred farms, it is not clear what the exact translation between purebred selection and their crossbred progeny performance should be.

No interaction between sire and dam breed was identified for any measure, which suggests that our results may apply to other terminal sire breed crosses. This lack of an interaction agrees with most previous literature (Cameron and Drury, 1985; Freking and Leymaster, 2004; Hopkins et al., 2007). However, Kempster et al. (1987) did identify such an interaction, although they considered more diverse sire and dam breeds in their study. The absence of sire-dam interaction may not be surprising for traits measured in lambs after weaning, as maternal effects wane. Maternal heritabilities for UMD and UFD have been generally found to be low and in some cases not different from 0 (Larsgard and Olesen, 1998; Husain et al., 2007).

Environment. Environmental contributions to finishing characteristics are important, but their explicit cause often is difficult to identify. However, there are exceptions. Often, primiparous ewes will rear smaller offspring, which was the case in the growth of these lambs from birth to 10 wk (Márquez et al., 2012) and at finishing. Conington et al. (1998) suggested that differences between locations may be greater than those between years but that both significantly affect finishing traits.

Ultrasonic Measurements. Ultrasound provides a way to predict carcass characteristics before slaughter, which then can be used to delineate genetic differences in carcass merit among animals (Wilson, 1992). This tool has been successfully used in sheep at relatively low cost (e.g., Kvame and Vangen, 2007; Emenheiser et al., 2010). Kvame and Vangen (2007) obtained genetic correlations of 0.70 ± 0.13 between UMD and carcass lean muscle content and of 0.82 ± 0.10 between UFD and carcass fat content. In our case, index selection resulted in lambs with thicker UMD and thinner UFD, which, according to these correlations, would translate into increased lean and reduced fat contents of the carcass. This was the goal of the index and provides economic benefit to producers.

Finished Condition Score and Conformation

Conformation at marketing is evaluated subjectively but is important in determining the value of lamb. The lack of differences in the conformation of high- and low-index-sired lambs indicates that selection for lean growth will, at least, not adversely affect conformation avoiding potential discounts at harvest. Live conformation score depends on both muscling and fat (Lewis et al., 1996; Jones et al., 1999; Navajas et al., 2008). Positive genetic correlations have been found between logUFD, UMD, and OCS, indicating that selection for UMD may improve conformation, but selection against logUFD could lead to a decrease in conformation score (van Heelsum et al., 2001). These antagonisms were not apparent from the index selection characterized in this experiment, nor were breed differences observed.

Conformation should be predictive of carcass composition, but this correlation was found to be low (Jones et al., 1999). Van Heelsum et al. (2003) reported that live conformation of sires was uncorrelated to the lean and fat contents of the carcasses of their crossbred offspring. Similarly, Mekkawy et al. (2009) estimated a heritability of 0.11 (95% confidence region of 0.02 to 0.19) for the conformation scores in the dams of lambs in this study. Although conformation is one of the measures used for determining the price of lambs in the UK, it is likely not a good indicator of carcass composition.

Overall condition score at finishing also is measured subjectively and is intended to reflect differences in fatness alone. It has been found to be correlated with subcutaneous and intermuscular fat in the lumbar region (phenotypic correlation of 0.76; Frutos et al., 1997) but is an inaccurate predictor of body composition generally (Frutos et al., 1997; Lambe et al., 2008). Mekkawy et al. (2009) estimated a moderate heritability (0.24; 95% confidence region of 0.12 to 0.37) for condition score premating for the dams of lambs in this study. Selection on the lean growth index did not change the OCS of lambs, which may be due to the constant fatness end point used in this experiment. Other studies have found that ultrasonic measures and FWT are better indicators of carcass quality than condition or conformation scores (e.g., Lambe et al., 2008), and ultrasonic measures alone may be even better. Although conformation and condition scores are primary measures on which lambs are selected to be slaughtered, other objective measures may be more reflective of actual carcass quality.

In conclusion, the results of this study indicate that selection in terminal sire breeds for lean growth rate improves finishing characteristics in their crossbred progeny. Differences in the performance of crossbred lambs sired by purebred high- and low-index rams were less than anticipated on the basis of differences in the EBV of their sires. This justifies reevaluating whether current breeding programs are optimal for improving crossbred progeny performance at grass. However, forming clear expectations is challenging: beyond inheriting only one half of the genes of their sires, crossbred lambs are reared under different conditions and are evaluated (harvested) at different end points. Still, differences among sire breeds in BW and ultrasound measures exist, indicating that producers have flexibility in choosing the terminal sire breed that best suits their production system. No differences were found among sire breeds or index category in conformation or condition score; relative to BW and ultrasound, their value in characterizing differences in carcass composition seems equivocal. Therefore, selection decisions based on objective evaluation of lean growth, as captured in the lean growth index, provide a more reliable approach for improving carcass quality in lamb.

LITERATURE CITED

Box, G. E. P., and D. R. Cox. 1964. An analysis of transformations. J. R. Stat. Soc. Ser. B Stat. Methodol. 2:211–252.

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

Conington, J., S. C. Bishop, G. A. Waterhouse, and G. Simm. 1998. A comparison of growth and carcass traits in Scottish Blackface lambs sired by genetically lean or fat rams. Anim. Sci. 67:299–309.

Emenheiser, J. C., S. P. Greiner, R. M. Lewis, and D. R. Notter. 2010. Validation of live animal ultrasonic measurements of body composition in market lambs. J. Anim. Sci. 88:2932–2939.

Freking, B. A., and K. A. Leymaster. 2004. Evaluation of Dorset, Finnsheep, Romanov, Texel, and Montadale breeds of sheep: IV. Survival, growth, and carcass traits of F1 lambs. J. Anim. Sci. 82:3144–3153.

Frutos, P., A. R. Mantecón, and F. J. Giráldez. 1997. Relationship of body condition score and live weight with body composition in mature Churra ewes. Anim. Sci. 64:447–452.

Gilmour, A. R., B. J. Gogel, B. R. Cullis, and R. Thompson. 2009. ASReml user guide release 3.0. VSN Int. Ltd, Hemel Hempstead, UK.

Hopkins, D. L., D. F. Stanley, L. C. Martin, and A. R. Gilmour. 2007. Genotype and age effects on sheep meat production 1. Production and growth. Aust. J. Exp. Agric. 47:1119–1127.

Husain, S. S., B. T. Wolf, and W. Haresign. 2007. Genetic parameters of lamb weights and ultrasonic muscle and fat depths in Beulah Specklefaced sheep. Small Rumin. Res. 70:116–123.

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

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

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

Kvame, T., and O. Vangen. 2007. Selection for lean weight based on ultrasound and CT in a meat line of sheep. Livest. Sci. 106:232–242.

Lambe, N. R., E. A. Navajas, C. P. Schofield, A. V. Fisher, G. Simm, R. Roehe, and L. Bünger. 2008. The use of various live animal measurements to predict carcass and meat quality in two divergent lamb breeds. Meat Sci. 80:1138–1149.

Larsgard, A. G., and I. Olesen. 1998. Genetic parameters for direct and maternal effects on weights and ultrasonic muscle and fat depth of lambs. Livest. Prod. Sci. 55:273–278.

Lewis, R. M., and G. C. Emmans. 2007. Genetic selection, sex and feeding treatment affect the whole-body chemical composition of sheep. Animal 1:1427–1434.

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

Márquez, G. C., W. Haresign, M. H. Davies, G. C. Emmans, R. Roehe, L. Bunger, G. Simm, and R. M. Lewis. 2012. Index selection in terminal sires improves early lamb growth. J. Anim. Sci. 90:142–151.

Mekkawy, W., R. Roehe, R. M. Lewis, M. H. Davies, L. Bunger, G. Simm, and W. Haresign. 2009. Genetic relationship between longevity and objectively or subjectively assessed performance traits in sheep using linear censored models. J. Anim. Sci. 87:3482–3489.

Navajas, E. A., N. R. Lambe, A. V. Fisher, G. R. Nute, L. Bünger, and G. Simm. 2008. Muscularity and eating quality of lambs: Effects of breed, sex and selection of sires using muscularity measurements by computed tomography. Meat Sci. 79:105–112.

Pollott, G. E., and D. G. Stone. 2004. The breeding structure of the British sheep industry 2003. Dep. Environ. Food Rural Affairs, London.

Simm, G., and W. S. Dingwall. 1989. Selection indices for lean meat production in sheep. Livest. Prod. Sci. 21:223–233.

Simm, G., R. M. Lewis, J. E. Collins, and G. J. Nieuwhof. 2001. Use of sire referencing schemes to select for improved carcass composition in sheep. J. Anim. Sci. 79:255–259.

Simm, G., R. M. Lewis, B. Grundy, and W. S. Dingwall. 2002. Responses to selection for lean growth in sheep. Anim. Sci. 74:39–50.

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

van Heelsum, A. M., R. M. Lewis, M. H. Davies, and W. Haresign. 2003. Growth and carcass characteristics in wether lambs of a crossbred dam line. Anim. Sci. 76:45–53.

van Heelsum, A. M., R. M. Lewis, M. H. Davies, and W. Haresign. 2006. Genetic relationships among objectively and subjectively assessed traits measured on crossbred (Mule) lambs. Anim. Sci. 82:141–149.

van Heelsum, A. M., R. M. Lewis, W. Haresign, S. P. Williams, and M. H. Davies. 2001. Non-normality in carcass quality measurements and effects on the genetic evaluation of sheep. Livest. Prod. Sci. 69:113–127.

Webb, E. C., and H. A. O’Neill. 2008. The animal fat paradox and meat quality. Meat Sci. 80:28–36.

Wilson, D. E. 1992. Application of ultrasound for genetic improvement. J. Anim. Sci. 70:973–983.

Woodward, J., and V. Wheelock. 1990. Consumer attitudes to fat in meat. In: J. D. Wood and A. V. Fisher, editors. Reducing fat in meat animals. Elsevier, London. p. 66–100.