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Use of X-Ray Computed Tomography (CT) in UK Sheep Production and Breeding

L. Bünger et al.*
Sustainable Livestock Systems Group,
Scottish Agricultural College, Edinburgh
UK

1. Introduction

The aim of this chapter was to review the use of computed tomography (CT) in UK sheep breeding to improve carcass composition and elements of meat quality, as well as the use of CT scanning as a benchmarking system for faster and cheaper carcass evaluation for use both in practise for the livestock industry and for furthering research aims.

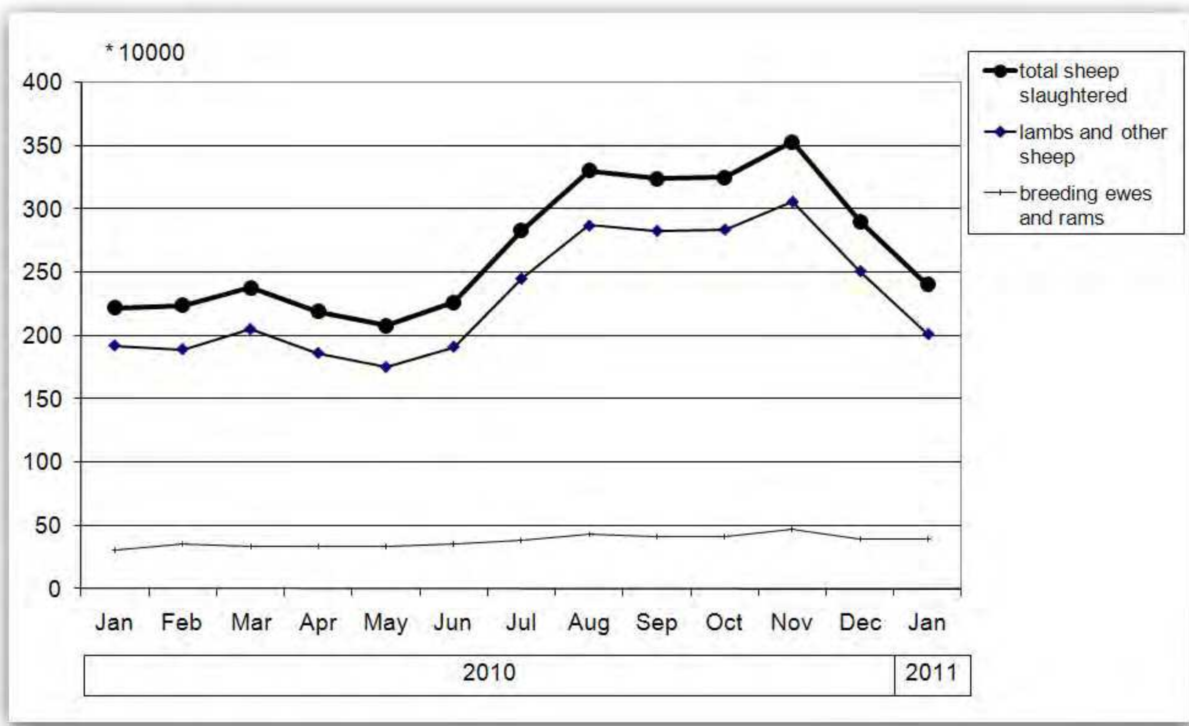
This paper will review some of the work carried out at the Scottish Agricultural College (SAC) in collaboration with Biomathematics & Statistics Scotland (BioSS) in the last 14 years. The work investigated the use of CT scanning alongside ultrasound scanning (US) in a synergistic approach to benefit the UK sheep industry by improving the breeding value of terminal sire (meat) rams. *In vivo* measurements via CT of body composition of the top ranking male selection candidates (pre-selected by their US - measured backfat and muscle depth) are used to enhance the accuracy of selection decisions regarding carcass quality and more recently, also some components of meat quality. CT-derived information provides both directly measured traits for use in the breeding process as well as serving as a bench-marking system for the validation of other techniques such as Video image analysis (VIA) or ultrasound scanning. It also has real potential to replace the "Gold Standard" of carcass evaluation which has always been used in past, which is the dissection of carcass tissues into component parts.

Initially, we will characterise UK sheep breeding and the need to accurately and precisely measure body and carcass composition of breeding animals or their close relatives with the aim of improving the quality of slaughter lambs.

UK sheep industry. There are around 15 million breeding ewes in the UK (www.defra.gov.uk/evidence/statistics/foodfarm/general/auk/latest/excel/index.htm), half of which are purebred and half are crossbred, with hill and lowland areas each containing around 40% of the ewes and upland areas the remaining 20% (Pollott & Stone, 2006). The UK sheep industry is characterised by a stratified structure, which has evolved over many years to best utilise the available land and to match breeds or crosses to different systems. The stratified system has different selection goals within each strata and makes use of specialised sire and dam breeds and crosses and exploits both the complementarities of breeds for crossing e.g. longwool (litter size, milk) x hill (hardiness, intermediate mature

* J.M. Macfarlane, N. R. Lambe, J. Conington, K. A. McLean, K. Moore, C.A. Glasbey[1] and G. Simm
[1]*Biomathematics & Statistics Scotland, King's Buildings, Edinburgh, Scotland*

size) and heterosis for maternal traits, survival, growth and carcass traits. On the hill land, characterised by harsh climatic and nutritional environment, most sheep are purebred hardy breeds which have evolved and been selected to have good maternal and survival characteristics. After about 4 or 5 lamb crops in the hill areas, these hill breed ewes are often drafted down to less harsh upland areas. Here they are crossed with longwool sires (e.g. Bluefaced Leicester) and while the F1 crossbred males are sent to slaughter, the resulting F1 crossbred females (Mules) are used in commercial flocks in upland and lowland environments. These crossbred females are then mated with sires from terminal sire breeds (e.g. Texel, Suffolk, Charollais). Terminal sire breeds are mainly bred for high lean growth. Their matings with Mule sheep produce slaughter progeny. Of the lambs slaughtered in the UK for meat production, 71% are sired by terminal sire breeds (Pollott & Stone, 2006). In the UK there are approximately 13.9 million sheep slaughtered per year (Figure 1) indicating the importance of the genetic quality of the terminal sire breeds as on average, they contribute half of the genes of all lambs slaughtered in the UK. Terminal sire breeds are numerically small but as they sire the majority of slaughter lambs in the UK, they have a large impact on the genetics of the national lamb crop. Genetic selection in these breeds focuses on growth and carcass traits, which is an effective way to improve carcass quality.



Data: http://www.defra.gov.uk/evidence/statistics/foodfarm/food/slaughter/documents/slaughpn.pdf

Fig. 1. UK average weekly sheep/lambs slaughterings (Thousand Head)

Current genetic improvement programs in the main UK terminal sire breeds are based on index selection for improved lean tissue growth including as selection criteria live weight and US-measured fat and muscle depths and, more recently (since 2000), traits measured using CT. The Lean Index was developed and experimentally tested by SAC (Simm & Dingwall, 1989, Simm *et al.*, 2002) and employed by Signet (National genetic evaluation service for cattle and sheep) in response to consumer demand for lean meat. The breeding objective was to increase carcass lean weight whilst minimising any associated rise in fatness. Impressive rates of genetic gain have been achieved in UK terminal sire breeding programs through selection on this Lean Index as shown for example by Macfarlane and Simm (2007).

In the present commercial circumstances, the need for selective breeding decisions is as important as ever. Sheep producers can only maintain their businesses by producing lambs that meet market specifications, in terms of carcass weight and carcass quality (currently assessed mainly via fat class and conformation). Allied to this is the need to monitor production costs to ensure lambs are produced efficiently, and ensure the flock will generate a positive financial return.

A lamb's potential to produce a quality carcass is ultimately limited by its genetic potential. Breeders therefore need to make long-term plans to invest in the right breeding stock for their enterprise, both initially and for its further development, with a focus on production traits such as growth and carcass composition, but also considering traits such as meat quality, disease resistance, easy care (e.g. lambing ease), and lamb survival.

2. *In vivo* measurement of body composition and meat quality

2.1 Body composition assessed by CT

Researchers in animal science have for a long time sought an accurate and reliable method of measuring *in vivo* body composition, mainly with the aim to improve and manage carcass composition. Improving carcass composition can be done by manipulating the environment, primarily through quantity and quality of nutrition (Emmans *et al.*, 2000). However, there are strong reasons why significant emphasis should be put on altering the genetic potential of animals for growth and development of their carcass tissues. Traditional selection, whereby the best animals are kept as parents for the next generation, offers permanent, cumulative gains that fit well within a sustainable livestock production system (Simm, 1998, Hill *et al.*, 2000). Coupled with modern statistical approaches to breeding scheme design and genetic analysis, substantial genetic gains are possible (Simm, 1998). Modern breeding methods also provide the most economic way to select for improvements in a suite of traits (Amer *et al.*, 2007), and methods that are not invasive (unlike physical dissection or slaughter) are highly valuable tools for breeding programs.

There are many technologies available (e.g. reviewed by Speakman, 2001) to measure body composition and they differ in accuracy, reliability and cost. For example, ultrasound scanners, originally used in diagnostic medicine for humans, have been adapted in the last 20-30 years for use on farm animal species with considerable success. Although this technology is still developing and in widespread use, researchers require more accurate methods of evaluating carcass composition. CT is a more sophisticated diagnostic tool, which offers comprehensive and reliable information. It is a non-invasive imaging technology that was also initially developed for use in human diagnostic medicine. CT uses X-rays to generate cross-sectional, two-dimensional images of the body and each image is acquired by rapid rotation of the X-ray tube 360° around the body of the animal. The object being scanned is divided up into spatially consecutive, parallel sections, the data from which are then summed up to produce total estimates of the different tissues in the carcase (Krause, 1999). The amount of radiation transmitted through the body depends on the attenuation rate of the X-rays, which differ between the various tissue types according to their relative densities. With CT, a computer stores a large amount of these attenuation values, which are registered by one or multiple arrays of detectors (single slice and multi slice scanners), from a selected region of the body. This allows the spatial relationship of the radiation-absorbing structures within it to be determined. The image obtained consists of a matrix of attenuation values which are depicted in various shades of grey, thereby creating a spatial image of the scanned object (Wegener, 1993).

Considering that as recently as 1979, Hounsfield and Cormack received the Nobel Prize for their pioneering work in developing this technology for its use in human medicine, the progress in diagnostic developments since then have been impressive. In the early 1980's the potential of CT for use in animal production research was recognized in Norway, pioneered by a team of researchers led by H. Skjervold, and the Agricultural University of Norway who acquired a Siemens Somatom 2 computer tomograph and began development work. Their results indicated that CT had considerable potential for predicting carcass composition in live animals (e.g. Allen & Leymaster, 1985). This increase in accuracy was expected to lead to potentially large increases in rates of genetic improvement (Simm & Dingwall, 1989). However, because of its limited accessibility and relatively high cost, initially it was not widely used in animal breeding and veterinary medicine. Accessibility has since improved and this has increased the need for expertise in the use of this technique in animals (Rivero et al., 2005). CT now has a wide range of applications and is well documented in the literature. CT scanning of live farm animals (mainly sheep and pigs) for breeding purposes has been used commercially in New Zealand, Hungary, Norway and the UK. Some other countries focussed on the use of CT (or MRI) for post mortem scanning of pig carcasses (e.g. Denmark, France, Germany, Norway).

Experimental studies carried out at SAC in the UK from 1997 to 2000 established the best way to incorporate CT scanning for carcass traits into terminal sire breeding programs in the UK (Young *et al.*, 2001; Macfarlane *et al.*, 2009c). CT provides accurate predictions of tissue weights because of a direct relationship between X-ray attenuation and tissue density. Suitable software procedures to extract and quantify the areas of the different tissues in the cross-sectional images were developed using mathematical algorithms for image analysis (Glasbey & Young, 2002). This involves two main steps: 1) segmentation to remove non-carcass portions of the images; and 2) measurement of tissue areas in the segmented images. The complexity of removing the internal organs and to identify tissue boundaries makes the segmentation challenging and time-consuming if done manually. Automatic procedures have recently been developed (Glasbey & Young, 2002; Navajas *et al.*, 2006a). Using software (STAR: **S**heep **T**omogram **A**nalysis **R**outines, Figure 2) developed at SAC and BioSS (Mann *et al.*, 2008), both steps can be performed automatically and therefore more quickly (Figure 3).

Cross-sectional CT scans taken at 3 specific anatomical locations identified from a longitudinal topogram scan (Figure 4, left) provide images from which measurements of lean, fat and bone areas are derived and then used to very accurately predict the weight of lean, fat and bone in the whole carcass. For example, the accuracy of CT based predictions (R^2) for muscle, fat and bone weights in the carcass from a small number of CT scans (3 reference scans, Figure 4) varies between breeds, with the highest R^2 values in meat breeds of 0.99, 0.98 and 0.89 for fat, muscle and bone, respectively, with accuracies in Scottish Blackface sheep just slightly lower (Young *et al.*, 2001). This reference scanning approach was developed with the aim of maximising accuracy of prediction of tissue weights while holding scanning time as short as possible to minimise cost and animal welfare implications. Development of this approach required considerable initial calibration trials in which CT predictions were bench-marked against dissected tissue weights, and where the number of required cross-sectional images and their location were optimised. This provided breed-specific prediction equations, which are still used in CT scanning of commercial ram selection candidates.

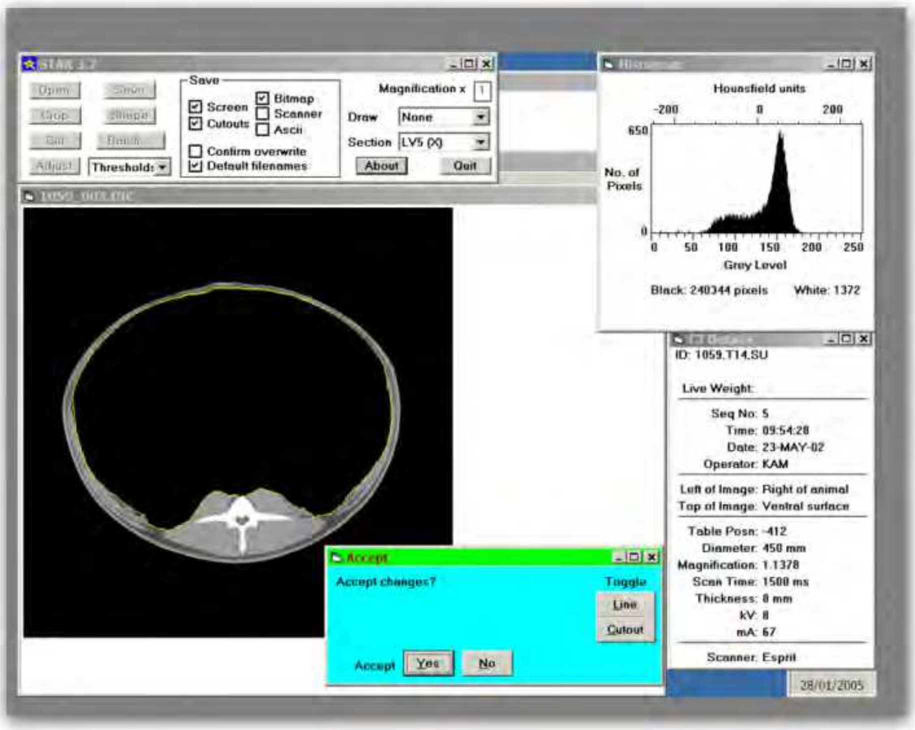


Fig. 2. Screenshot- Software STAR (Sheep tomogram analysis routines) to analyse CT images

Fat is shown as dark grey (less dense), muscle light grey (intermediate density) and bone as white (more dense)

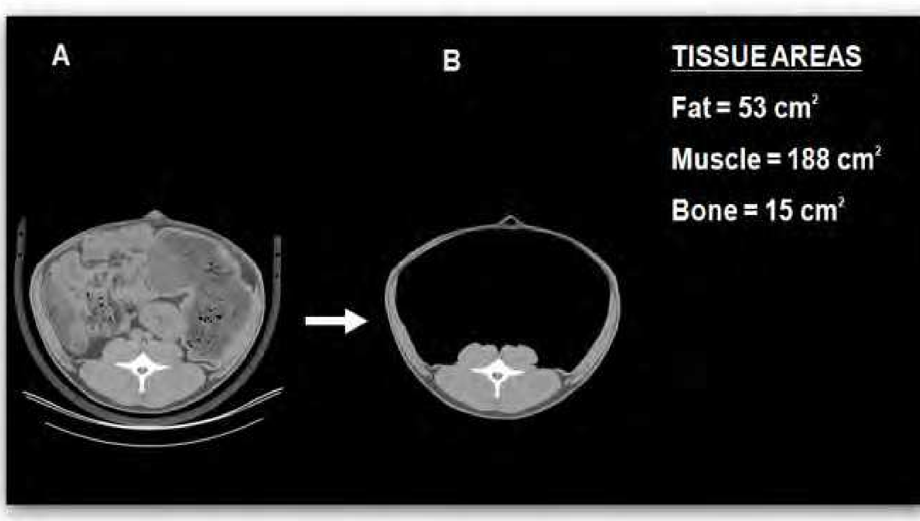


Fig. 3. Cross sectional images at Lumbar vertebra 5 before (A) and after (B) segmentation using STAR software

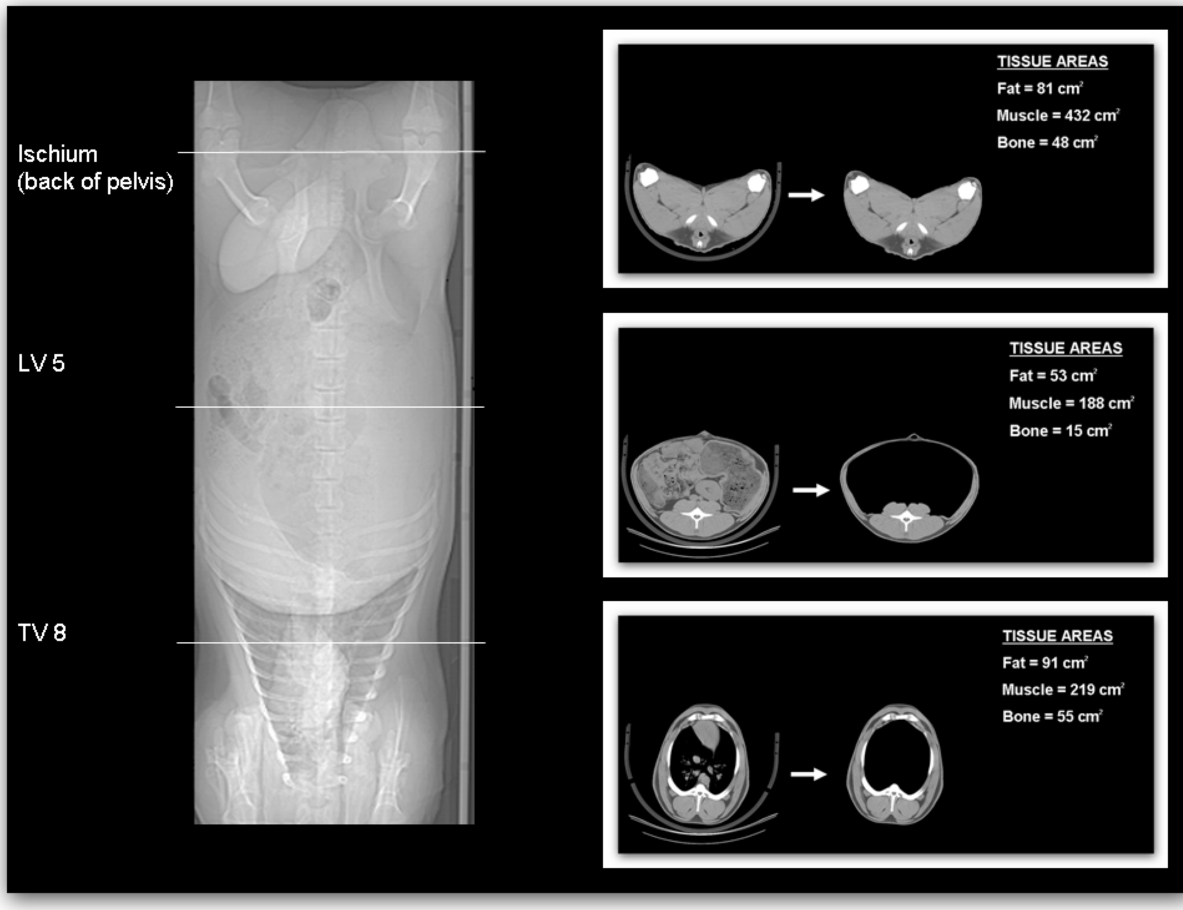


Fig. 4. Reference scanning method showing a longitudinal 2D scan (topogram, left) and cross sectional images at 3 anatomical landmarks and the corresponding tissue areas (right)

2.2 CT based 3D assessment of tissue volumes and weights

An alternative approach to reference scanning (Figure 4) is the *Cavalieri method* in which 15 to 20 cross-sectional, contiguous images are obtained, evenly spaced along the carcass. The volume of each tissue is then calculated from the total area of each tissue from cross-sectional scans multiplied by the inter-scan distance (e.g. Roberts *et al.*, 1993). This provides a direct measure of tissue volumes and weights, which can easily be calculated by multiplying the volume with the specific tissue densities. Both methods (reference scan and *Cavalieri*) show similar accuracies in sheep but require very different time (and therefore economic) inputs for generating the images and interpreting the results. However, if automatic procedures are in place, the *Cavalieri method* is the preferred method as it does not require breed-specific prediction equations or adaptation to allow for changes in a breed over time. Currently, mainly for economic reasons, the reference scan approach is the main method used to provide *in vivo* predictions of carcass composition in sheep breeding programs using CT in the UK.

In addition to carcass composition, CT can also be used to measure *in vivo* muscularity (muscle shape) (Jones *et al.*, 2002). Muscularity is of interest as an objective description of the shape of a carcass, a muscle or a muscle group, which is largely independent of the level of fatness in the carcass. Estimates of muscularity have been undertaken for different muscle regions (loin area and hind leg) and for the whole carcass using the corresponding 2D cross-

sectional images and related measurements of the bone length (Jones *et al.*, 2002). These "semi-3D"-muscularity measures have moderate to high heritabilities (0.30-0.60; Jones *et al.*, 2004) indicating that muscularity traits measured by CT can be effectively used in two-stage selection programs for sheep.
Muscularity of the hind leg (Gigot shape) and the loin region (eye muscle) (Figure 5) are currently incorporated into breeding programs for terminal sire sheep in the UK.

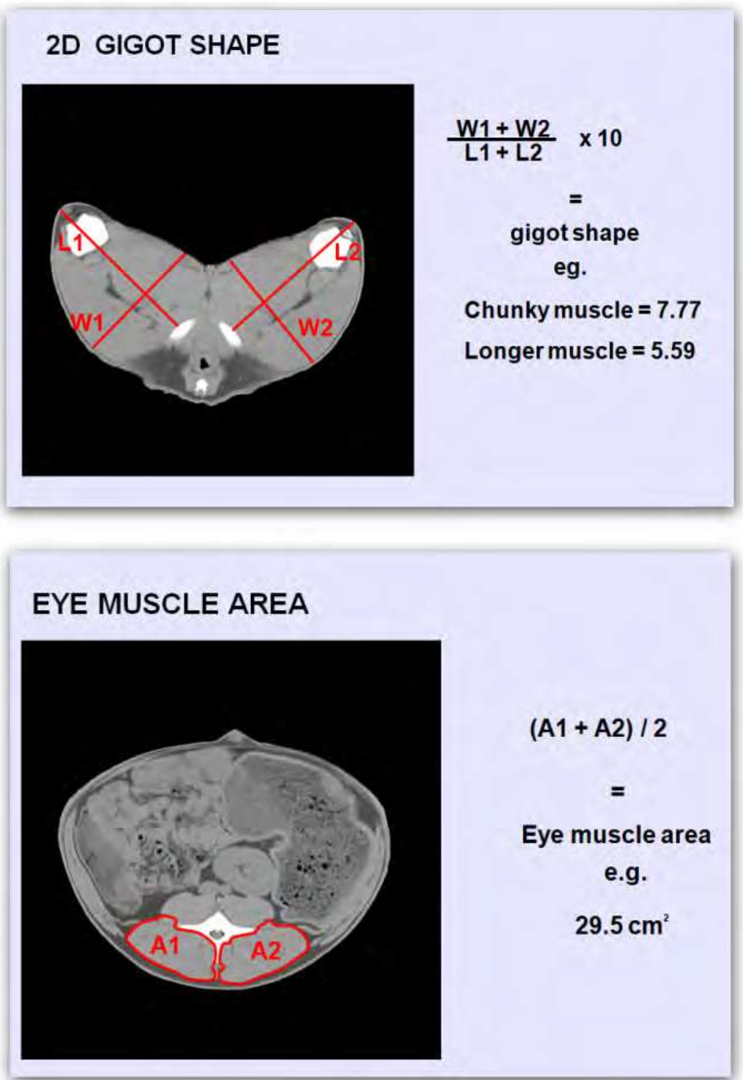


Fig. 5. Description of the shape of the Gigot at the Ischium (above) and measurements of the area of the eye muscle (below, loin or M. longissimus thoracis et lumborum)

Spiral CT scanning (SCTS). In 2002 SAC obtained a new CT scanner (Siemens, SOMATOM Esprit) capable of spiral (or helical) CT scanning. It is a single slice scanner and takes one slice or image as the X-ray beam makes a complete rotation around the animal. Very recent scanners are 64 slice CT scanners, which can take up to 64 slices or images in one rotation. The more detectors a CT Scanner has, the more slices per rotation it is able to acquire and the addition of more detector rows enables the scanner to visualise more anatomy in a shorter amount of time and in greater detail.

SCTS is a rather recent imaging technology which takes a series of images of an object in a similar arrangement to that of a spring or coil. It provides cross-sectional images at intervals of as little as about 1mm (depending on the type of scanner) along the body, which contain a wealth of information. Earlier CT scanners had the X-ray source, which moved in a circular fashion to acquire a single 'slice'. Once the slice had been completed, the scanner table would move to position the animal for the next slice. In the spiral scanner however, the X-ray tube is attached to a freely rotating gantry which rotates continuously in one direction whilst the table on which the animal is lying, is smoothly moved through the gantry.
One major advantage of spiral scanning compared to the traditional 'shoot-and-step approach' is speed, which permits the use of higher resolution acquisitions in the same study time. In addition, the data obtained from SCTS is also well-suited for 3D imaging (Figure 6) allowing volumes and dimensions of the body and of the skeleton to be measured. Recent work has further increased the opportunity to describe muscularity traits. New 3D- muscularity indices for the hind leg and lumbar region in sheep were derived based on the assessment of skeletal dimensions and muscle volumes and mass. Assessments of muscle mass and skeletal dimensions by CT enabled the development of new muscularity measures. Compared to previous CT muscularity indices, the accuracy was much higher with the new index in the hind leg (correlations between CT and dissection indices of 0.89 vs. 0.51). The accurate measurement of femur length by CT used in the new hind leg index made an important contribution to the higher accuracy of this index. The improvement in accuracy was smaller for the loin region (0.55 vs. 0.44). The association of CT muscularity indices and carcass quality in Texel and Scottish Blackface lambs showed that improved muscularity is not phenotypically correlated with detrimental effects on carcass composition (Navajas *et al.*, 2007).

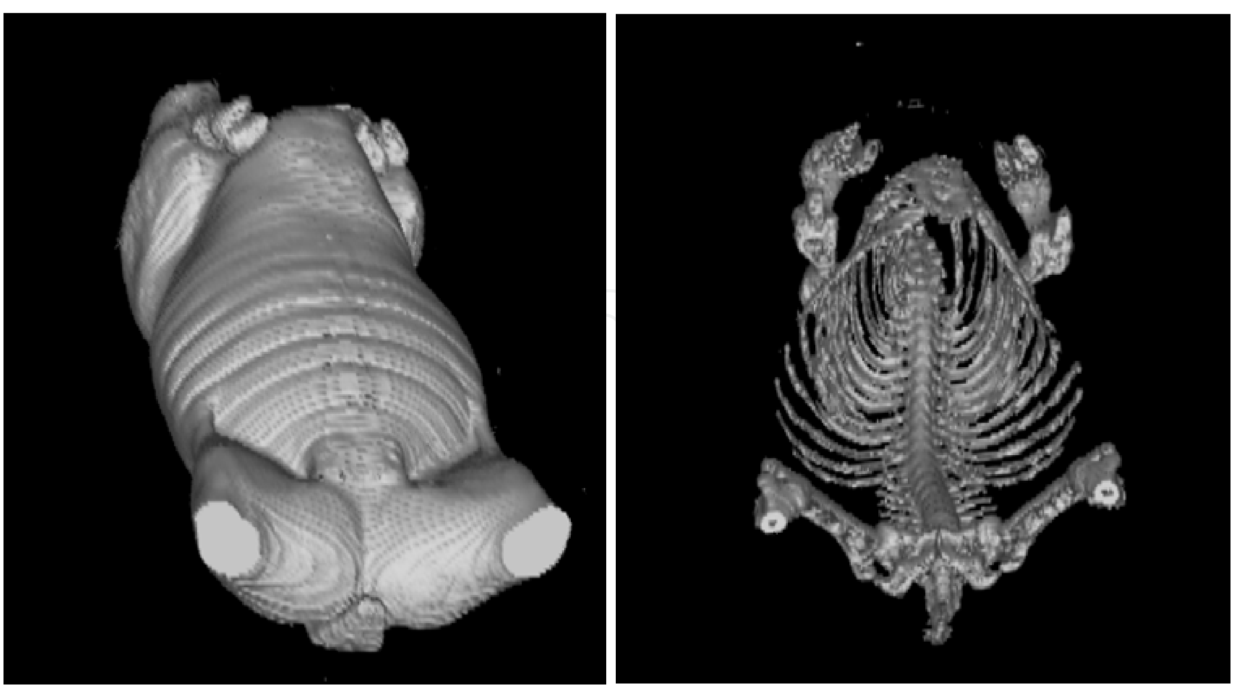


Fig. 6. 3D- reconstruction of the body (left) and skeleton (right) of a live sheep using cross sectional images taken with 8mm distance. A smaller slice distance would make the images smoother and increases the accuracy of dimensional measurements

CT measured muscularity indices provide an alternative method to improve carcass conformation and leanness, using measurements that at a constant weight are independent of fatness (Navajas *et al.*, 2006a; 2007). The heritabilities of the 3D muscularity indices assessed using CT were moderate to high in Texel (h^2= 0.38 to 0.92) and Scottish Blackface (h^2 = 0.42 to 0.78) breeds (Navajas *et al.*, 2006c). This study provided the first estimates of heritabilities for 3D-muscularity indices in Scottish Blackface and Texel sheep. Although the values should be used with caution due to the large standard errors, these estimates show the potential for genetic improvement of muscularity of the whole carcass and of regions with high priced cuts (hind leg and lumbar region). The improvement of muscularity in different regions of the carcass may require the utilisation of different CT indices as selection criteria in an index in these breeds.

SCTS allows rapid, direct estimation of volumes and densities, and therefore weights, of the tissues in the body/carcass and could therefore be used as a "gold standard" for benchmarking other methods of body/carcass quality evaluation. Recently at SAC and BioSS, developments of the STAR software have enabled weights and composition of joints of a carcass to be accurately measured from data captured on a live animal (Macfarlane et al., unpublished). This is done by dividing up the total body spiral scans from a live animal into regions corresponding to carcass joints using anatomical landmarks corresponding to the cuts made by butchers in commercial lamb carcass butchery. This could in future provide sheep breeders with information on direct value of the carcass of the animals being CT scanned.

2.3 Other CT based traits of interest to sheep breeding and production

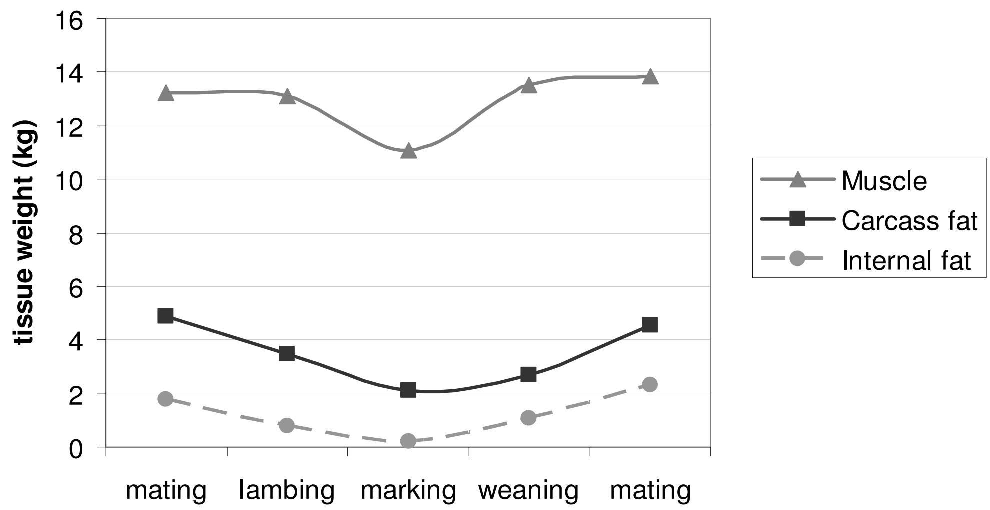
Muscle density and intramuscular fat (IMF). In pigs, efforts have recently been made to increase IMF level because there is some concern that pork from intensely selected, modern lean lines of pigs may have poorer eating quality compared to the fatter genotypes, and this is resulting in reduced consumer satisfaction. At the same time, published data indicate that visible fat content is a major determinant of purchase intent, with consumers preferring leaner pork. These modern very lean pigs have very low levels of intramuscular fat, and thus exhibit very low levels of marbling in their muscles, which is considered a major contributor to the palatability of pork for both domestic and export markets. IMF levels correlate highly with marbling, with greater juiciness, more desirable flavour, greater tenderness and better overall palatability (Murray *et al.*, 2004). A similar study (Fernandez *et al.*, 1999) on the relationship between IMF and pork eating quality showed that this relationship is not linear, as the willingness to eat and purchase the meat were influenced by IMF level and the perception of texture and taste was enhanced with increased IMF levels. This indicates that the acceptability of pork may be improved by increasing IMF level up to a certain threshold. IMF levels higher than 3.5%, were associated with a high risk of meat rejection due to visible fat and the authors pointed out that the positive effect of increased IMF probably holds only true as long as it is not associated with an increase in the level of intermuscular fat, the fat between the muscles. This indicates that IMF should be targeted by selection on optimum values and should be always measured alongside other fat depots.

In sheep there is also increasing concern about low IMF levels especially for terminal sire breeds, and in this context it is of interest that CT scanning can not only provide useful information for carcass composition in terms of tissue volumes and weights and traits describing muscle shape, but the measured muscle densities are valuable in predicting the

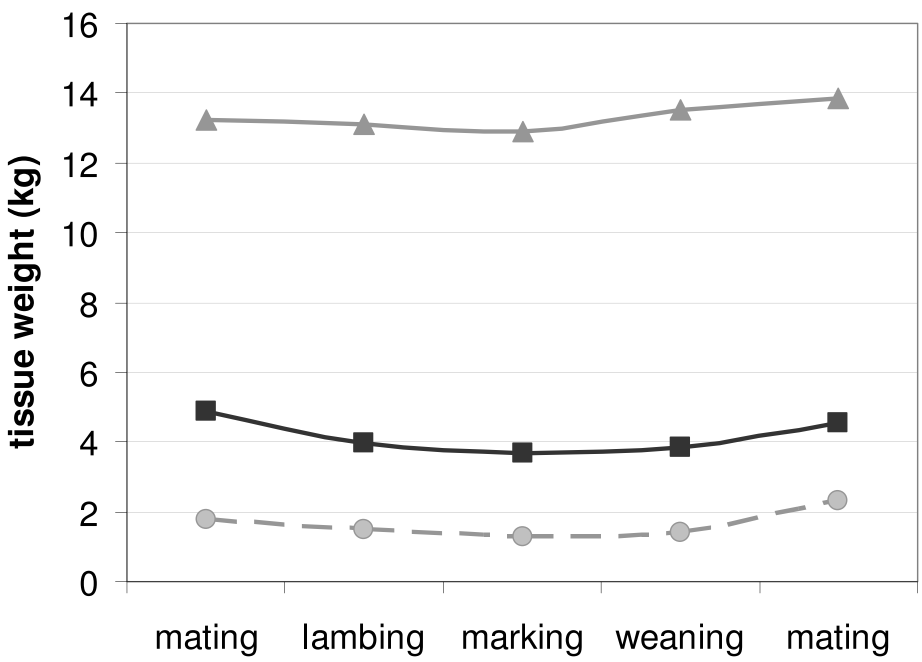
IMF content. This is important, as breeding attempts to reduce carcass fatness may also lead to a correlated reduction in IMF content which is of particular concern as IMF makes an important contribution to meat eating quality, including tenderness, juiciness and flavour. The difficulties of measuring meat quality traits in live breeding animals has meant that they are rarely included in breeding programs. However, recent research has shown a link exists between CT-measured muscle density and IMF content (Young *et al.*, 2001, Macfarlane *et al.*, 2005, 2009b, Karamichou *et al.*, 2006, Navajas *et al.*, 2006b). It is anticipated that this will allow *in-vivo* selection for IMF; however, work is still required on the best way in which to incorporate this trait into breeding programs that also aim to reduce overall carcass fatness.

CT-measured tissue depletion and repletion. Repeated CT scanning of Scottish Blackface ewes of differing reproductive status (pre-mating, pre-lambing, mid-lactation, at weaning [around 18 weeks of age] and at pre-mating the following year) has been used to investigate tissue depletion and repletion. Ewes with higher levels of muscle are more productive than their fatter counterparts (Lambe *et al.*, 2003). The ability to mobilise both muscle and fat depots to fuel lactation for growing lambs leads to heavier lambs and fewer lambs lost before weaning. However, ewes that mobilise larger amounts of their own body tissues are more likely to die, or be culled from the flock, compared to ewes that do not mobilise their body fat and muscle reserves. In other words, ewes that 'look after number one' (themselves) rear poorer and fewer lambs relative to those who 'give it their all', yet they are most likely to be in good condition themselves and survive throughout the year (Figure 7). These results indicate a biological trade-off when it comes to animal performance and produces a bit of a dilemma for the breeders – which type of ewe do they want? Higher-producing, but shorter-living, or lower-producing and longer-living? The answer to that question depends very much on the relative economic returns for ewes that are culled from the flock, compared to the prices obtained for lambs. The results suggest that keeping females in the breeding flock because they maintain their own condition throughout the year, may be have a negative impact on the number and weights of lambs reared to weaning. As long as ewes that have lost condition over summer can regain it before mating in the autumn, they are likely to be the more productive individuals, although they may need to be culled sooner than other ewes in the flock. For the pedigree breeder, the simple answer to this dilemma is to know which animals in their flock have better overall productive performance compared to others, *via* the use of selection indices. The indices used by hill breeds in the UK produce higher scores for animals that carry genes for rearing heavier litters to weaning *and* genes for better ewe longevity. For the commercial producer, buying high index rams to produce female replacements will result in a ewe flock with these preferred combinations of genes and so will minimise the risks associated with the known biological trade-offs. In conclusion, CT can help to identify suitable types of ewes for use in different systems.

CT-measured pelvic dimensions and dystocia. The estimated mean neonatal lamb mortality rate in the UK is approximately 10% (Binns *et al.*, 2002) and the large number of lambs lost early in life has a negative impact on both animal welfare and on the profitably of sheep farming. Lambing difficulty is one of the main causes of lamb losses. It can affect both lamb survival and maternal ability, which are being actively selected for in modern sheep breeding. Many lambing difficulties are due to the disproportionate size of the lamb and ewe. This can be the result of a large lamb, a small pelvic opening, or both. Attempts to measure pelvic dimensions by external measurements have been shown to be impracticable,



The 'giver': Ewes losing and gaining more fat and muscle are likely to wean more and better lambs, but may survive less years in the flock



The 'taker': Ewes losing and gaining less fat and muscle may survive longer, but at the cost of weaning fewer or poorer lambs

Fig. 7. CT-measured tissue weights in a longitudinal study on Scottish Blackface ewes.

although the use of X-ray measured pelvic dimensions showed that an incompatibility in size between the maternal pelvis and the lamb at birth is largely responsible for the need for repeated assistance at birth (Mcsporran & Fielden, 1979). The availability of SCTS has substantially increased the opportunities to measure pelvic dimensions and to derive new selection traits based on CT measured 3D-pelvic dimensions to breed for low dystocia (Bilbe *et al.*, 2005).

CT-measured spine characteristics. The loin muscle is one of the higher priced cuts of meat and commercially one of the most important muscles. The muscle runs the length of the spinal column; hence spine characteristics (lengths of spine, number of vertebrae) should relate to the length of the loin and possibly the number of lamb chop cuts that can be obtained from a lamb carcass. Recently, a project to measure spine characteristics using longitudinal CT scans topograms (Figure 4, left) has been instigated to determine the extent to which number of vertebrae and other spinal characteristics are under genetic control. (Donaldson *et al.*, 2011).

Use of CT to evaluate the phenotypic effects of muscling genes. The advent of genomics provides new opportunities for improving carcass and meat quality through the selection of animals carrying favourable genes and/or quantitative trait loci (QTL; region of DNA that is associated with a particular phenotypic trait). For example, such a QTL had been identified previously in the UK increasing muscle growth in Texel sheep (Texel Muscling QTL, *TM-QTL,* Walling *et al.*, 2004). CT has been used to help comprehensively evaluate the effects of TM-QTL, MyoMAX and LoinMAX on carcass traits in UK sheep breeds and as such has been a valuable tool to provide information on the suitability of these QTL/genes for use in commercial sheep breeding programs (Macfarlane *et al.*, 2009a, Masri *et al.*, 2010)

Use of CT to calibrate video image analysis (VIA) of carcasses online in abattoirs. Internationally there is a move from subjective carcass classification to objective instrumental grading. Any instrumental grading systems must be able to predict carcass conformation and composition with a high level of accuracy and at commercial speed for a value based marketing system (*VBMS)* to be effective (Cross & Whittaker, 1992; Belk *et al.*, 1998). CT could certainly provide the required information from carcasses but would be too expensive and too slow to cope with high slaughter-line speeds, but it can serve as a bench-marking system for other suitable systems. The most promising and suitable technology developed in recent years is *VIA* (e.g. Stanford *et al.*, 1998; Hopkins *et al.*, 2004). This provides a non-invasive system operating at normal chain speeds and enables automatic acquisition of data on carcasses from the side and/or back view. It can be integrated into a slaughter line and can deal with high line speeds. Such *VIA* systems (Figure 8) can provide continuously objective electronic information on conformation and fat class, weight and yield of the most valuable cuts, and can also be used to derive immediate sort criteria. Such systems seem 'future proof' as they can easily be combined or augmented with individual carcass identification systems for traceability and possibly with other suitable systems, for the measurement of crude fat content, colour and textural properties indicative for carcass and meat eating quality. Different *VIA* systems have been studied outside the UK, mostly in beef cattle, to predict on-line carcass value and by the use of additional systems also aspects of meat eating quality (e.g. Cannell *et al.*, 2002; Shackelford *et al.*, 2003; Steiner *et al.*, 2003; Vote *et al.*, 2003, Allen & Finnerty, 2001; Allen, 2005). While there are also a few studies on instrumental grading of lamb carcasses (Hopkins, 1996, Stanford *et al.*, 1998, Brady *et al.*, 2003; Hopkins *et al.*, 2004, Cunha *et al.*, 2004), none of them had been applied to UK conditions for lamb carcasses until very recently. This work in the UK has shown that VIA under abattoir conditions and at a line speed of 800 lambs/h was capable of improving the prediction of primal meat yields compared to the current MLC EUROP carcass classification system. VIA could therefore be used as the basis of a VBMS as it accurately and precisely reflects the value of a sheep carcasses (Rius-Vilarrasa *et al.*, 2009b). Other work from our group allowed also the estimation of heritabilities for VIA-measured traits in sheep.

The VIA System is based on two cameras taking images from the side and back of each carcass and special image processing software.

Fig. 8. Video image analysis of lamb carcasses with an E+V Technology VSS2000 system.

Heritabilities for VIA-predicted primal weights were low to moderate (0.08 to 0.26) and had a high repeatability (>0.9), suggesting that including VIA information in breeding programs would be useful to improve carcass quality. Estimated genetic correlations indicated that it is possible to increase primal meat yield without increasing overall carcass fatness (Rius-Vilarrasa *et al.*, 2009a). This work demonstrated the potential that in the near future estimated primal weights and other measures of saleable meat yield could also be used as a measure of carcass quality in the UK abattoirs. In follow-up studies this dataset was also used to estimate genetic parameters for a number of additional carcass measures (carcass weight, MLC-fat class, MLC-conformation, primal joint weights predicted using MLC-fatclass, and several carcass linear and area measures obtained by VIA). Heritability estimates for subjective carcass traits (MLC-fat class and primal joint weights predicted using MLC-fat class) were low (0.05–0.17), and using them in breeding programs would lead to a lower response to selection for improved carcass quality. However, heritability estimates for objective carcass traits (VIA based linear and area measurements on the carcass) were moderate to high (0.20–0.53), suggesting that the use of these traits in genetic improvement programs could lead to a faster response to selection for improved carcass conformation and to a change of the primal joint tissue distribution within the carcass (Rius-Vilarrasa *et al.*, 2010). VIA, with its automated data capture, if combined with electronic identification of individual animals, could offer a significant opportunity to record very accurate information on carcass characteristics from lambs with the possibility of feeding this information into genetic evaluations, thereby increasing the accuracy of estimated breeding values (EBVs) and rates of response to selection. In the context of CT scanning it is of note that it was possible to refine the VIA prediction for the primal weights by calibrating the VIA system against CT measurements in the loin region. The refined predictions increased the accuracy of predictions of primal joints on average by 16% (Rius-Vilarrasa *et al.*, 2009c.)

3. Use of CT scanning in commercial sheep breeding programs

As shown above, CT scanning is a minimally invasive *in vivo* technique that can provide highly accurate estimates of carcass composition and as such is expected to increase rates of gain over those seen using US information (Jopson *et al.*, 1997, 2004). CT scanning is more expensive than ultrasound and so its incorporation into sheep breeding programs has been as part of a two-stage selection strategy in combination with ultrasound scanning. The theory of such a scheme is that all selection candidates are firstly ultrasound scanned and the best 15-20% of males are then CT scanned. Reference CT scanning is used to provide carcass lean, fat and bone weights and leg and loin muscularity for each animal CT scanned. US and CT scan data collected is then used along with live weights and other information collected on-farm in genetic evaluations to derive estimated breeding values for a range of traits and lean tissue growth index scores. These EBVs and index scores are used to help selecting animals for breeding.

Using ultrasound scan data one can expect prediction accuracies (R^2) in the order of 65% and 50% for fat weight and muscle weight, respectively, with heritabilities for US-measured muscle and fat depth of 0.29 and 0.38, respectively. The accuracies of CT- based predictions of the same tissues from just 3 reference scans are 0.99 and 0.97 in meat sheep, and there are high heritabilities (0.46 and 0.40) for CT-measured lean and fat weight (Young *et al.*, 2001,. The selection response can simply be predicted using following equation:

SR = SD x h^2 , with SR being the selection response, SD, the selection differential (defined as the average difference between the parent generation and the selected parents) and h^2 the heritability. Considering the accuracy of the selection we would need to multiply SR by the accuracy (r_{ua}, which is strictly speaking the accuracy of using the measure u to predict an individual's breeding value), or the correlation between u and an individual's breeding value. To keep it simple we could use above given accuracies and conclude that SR based only on US would be ca. 50-60% of the SR obtained when measurements are fully based on CT. Considering that measuring all selection candidates with CT would be not practical and a two stage selection scheme is applied the advantage of CT based selection is much smaller. However, using data from industry flocks it has recently been shown that response to selection is 7% (CT –measured muscle weight), 10% (CT-measured fat weight) and 20% (CT measured muscularity) higher when CT scanning is used together with ultrasound scanning compared to ultrasound alone (Moore *et al.*, 2011).

In the UK CT scanning has been in use in terminal sire sheep breeding programs since 2000 (Table 1) especially in Texel, Suffolk, Charollais, Hampshire Down, Meatlinc and Beltex sheep. Each year approximately 400-500 lambs in total are CT scanned either using the fixed CT scanner near Edinburgh or more recently a mobile CT scanner (in 2009 and 2010) that can provide a CT scanning service to breeders located at distances from the fixed scanner that previously discouraged them from using CT scanning.

In addition to above considered CT-derived traits describing carcass composition other traits outlined in section 2.3 could also serve as selection traits in sheep breeding programs using existing variation between animals (Figure 9). A pre-requisite for their use are estimations of their genetic parameters.

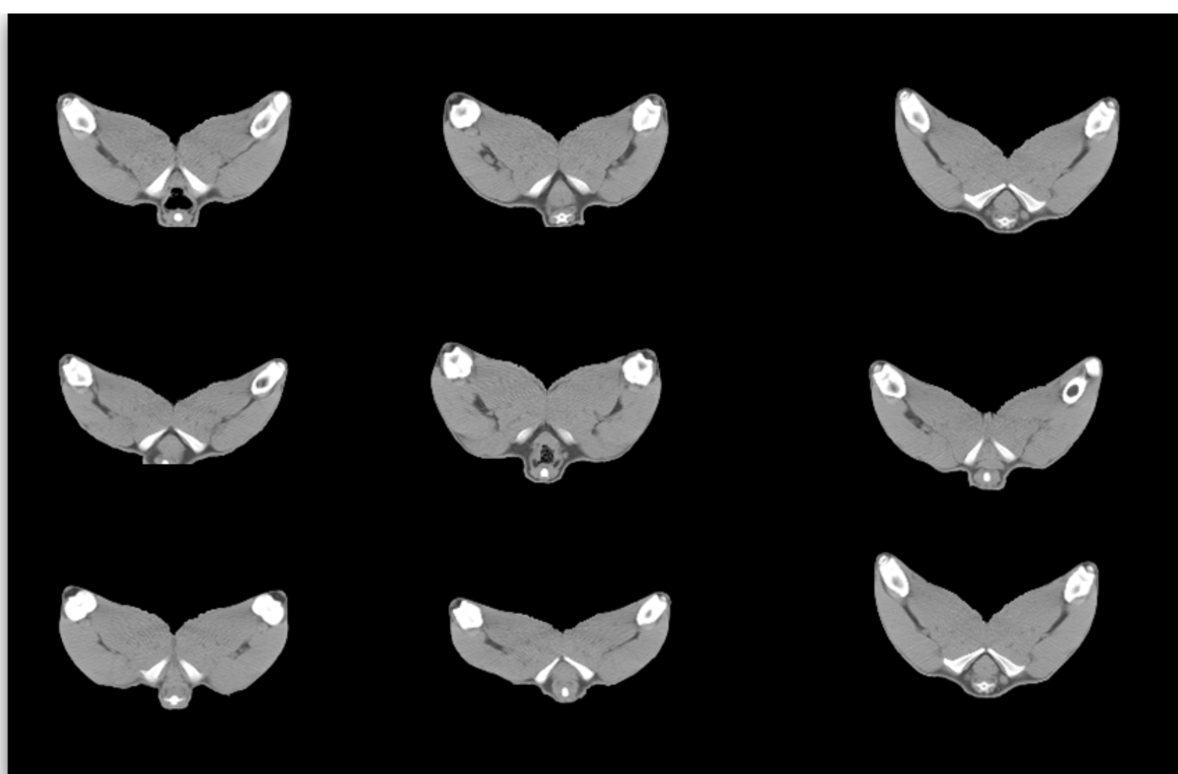


Fig. 9. Examples for Gigot shape variation in sheep

	2000	2001*	2002	2003	2004	2005	2006	2007*	2008*	2009**	2010**	total
Texel	**353**	**0**	**107**	**148**	**204**	**137**	**124**	**83**	**89**	**108**	**198**	**1551**
Suffolk	**353**	**0**	**59**	**100**	**156**	**168**	**107**	**36**	**27**	**128**	**98**	**1232**
Charollais	**129**	**0**	**0**	**58**	**122**	**92**	**134**	**100**	**20**	**107**	**117**	**879**
Hampshire Down	**30**	**0**	**0**	**25**	**25**	**0**	**46**	**21**	**0**	**36**	**27**	**210**
Meatlinc	**57**	**0**	**20**	**25**	**30**	**26**	**0**	**0**	**28**	**24**	**0**	**210**
Beltex									**50**	**34**	**20**	**104**
total per year	**922**	**0**	**186**	**356**	**537**	**423**	**411**	**240**	**214**	**437**	**460**	**4186**

*The outbreak of diseases in the UK and associated movement restrictions lead to low numbers in some of the years
** In 2009 and 2010 a mobile scanning service was offered. About 50% of the sheep were scanned with the mobile scanner. Since 2009 SAC uses also a 16 slice scanner (GE, LightSpeed, rented from Burgess Diagnostics Limited) as a mobile scanner built into a truck to provide CT scanning service to the sheep breeders. This meant that the transport time and costs could be minimised and consequently enable more animals to be CT scanned.

Table 1. The number of commercial sheep scanned at the SAC/BioSS CT Unit in Edinburgh (including mobile CT scanning)

Summary. Because of the capabilities described, CT is a valuable tool for various fields of animal science (health, nutrition, genetics and breeding) and livestock production (management on-farm, abattoirs, supermarkets), and can replace labour-intensive and expensive *post-mortem* dissection in experimental designs, whilst *in vivo* CT also allows longitudinal studies over time. Much of the focus in animal research has been on using CT to improve carcass composition and muscularity in terminal sire sheep although the estimation of changes in different tissues over the reproductive life cycle in accordance with different physiological states has generated new information on the depletion and repletion of body tissues to fuel lactation for lamb growth. As shown above CT scanning is a minimally invasive *in vivo* technique that can provide highly accurate estimates of body or carcass composition, muscle shape and density and provides data on spine and pelvic characteristics all of potential importance in sheep breeding and production. Further work is required to develop a synergistic approach to use CT-scanning together with US and VIA for the genetic improvement of carcass quality, with a two-fold role of CT, as a benchmarking system and as integrated part of the breeding system.

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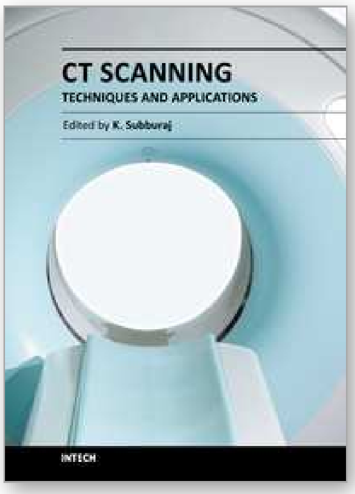

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