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Development of a NUCTECH prototype DEXA scanner for determination of lamb carcase composition

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Executive summary

This pilot study evaluated the ability of a prototype NUCTECH DEXA system to differentiate fat, lean muscle and bone tissue using tissue calibration blocks of known composition. Additionally, this study assessed the ability of this DEXA prototype to predict the CT fat, lean muscle and bone % of lamb carcases.

The NUCTECH engineering team successfully developed a prototype DEXA system following a series of iterative hardware and software refinements. The prototype DEXA scanner was developed around a conveyor to facilitate the scanning of tissue calibration blocks, while a steel frame was custom built to allow entire lamb carcases to be scanned through the prototype DEXA device. A medical-grade CT scanner was sourced at a Beijing hospital to scan lamb carcases and assess the ability of the prototype DEXA to predict carcase composition (Milestones 1 & 2).

In Experiment 1, tissue calibration blocks were constructed from dissected lamb fat, lean and bone tissue, in defined mixtures and thicknesses. The calibration blocks were transported to Beijing for scanning with the prototype DEXA scanner. The prototype DEXA system was able to identify the thickness, chemical fat %, and bone % of the scanned tissue blocks, showing good capacity to differentiate between carcase tissue types. From these scans, a series of tables were constructed enabling the matching of DEXA pixel R values to tissue types and thicknesses. The NUCTECH engineering team reviewed the development of these tables and the subsequent equations used to predict lamb carcase composition from DEXA images with researchers at Murdoch University (Milestone 3).

In Experiment 2, seven lamb carcases locally sourced in Beijing were scanned using both the NUCTECH prototype DEXA system, and the medical CT scanner. A thresholding method was applied to images separating soft-tissue pixels from bone-containing pixels, before the equations derived in Experiment 1 were applied to the images. The NUCTECH DEXA system was able to determine CT lean% and bone% with good precision, however the prediction of CT fat % was imprecise, suggesting that further development is needed in this area.

The next phase of work will be to install a commercial prototype DEXA that can operate at chain speed in an Australian abattoir. This will enable calibration against a larger population of lambs slaughtered under standard Australian conditions that reflect industry genotypes (Milestone 4).

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1 Background

Developing technologies for the objective measurement of carcase traits is a high priority for the Australian lamb industry. Lean meat yield (LMY) is an important carcase trait as consumers demand lean meat and thus carcases with higher proportions of lean muscle are more valuable. Carcase LMY can be accurately and precisely measured using medical computed tomography (CT), which provides a complete virtual dissection of a carcase into muscle, fat and bone components. However, the slow speed of medical CT technology currently prevents its application in commercial abattoirs. An alternative approach taken in Australia in recent years has been to measure carcase composition using dual energy X-ray absorptiometry (DEXA). These systems have demonstrated excellent accuracy and precision for determining carcase CT fat, lean muscle and bone percentage at line-speed in lamb abattoirs, and also have the advantage of being adapted to automated robotic boning systems to guide de-boning of carcases.

Aside from automation, DEXA presents multiple opportunities for the lamb meat industry. A reliable measure of carcase composition will enable trading on LMY rather than just carcase weight. It will also underpin reliable feedback to producers enabling them to improve stock management for LMY; to geneticists to improve selection for LMY; and for processors to predict carcase cut weights and optimise the cutting specifications for different lamb carcases. Given the potential value of DEXA for the Australian lamb meat industry, substantial incentive exists to develop alternative DEXA systems that are cheaper, easier to deploy, and small in size thus minimising the abattoir footprint. In response to this demand, NUCTECH are developing a prototype DEXA for the prediction of lamb carcase LMY. NUCTECH are one of the world leaders in airport baggage scanning, with DEXA prototypes that offer good potential for adaptation to the meat industry given their robust design and rapid image acquisition.

2 Project objectives

This study evaluates the ability of a NUCTECH prototype DEXA system to differentiate fat, lean muscle and bone tissue using calibration blocks of known tissue composition. Additionally, this pilot study assesses the ability of the DEXA prototype to predict the CT fat, lean and bone % of lamb carcases.

3 Methodology

This study involved two main experimental phases, first to establish the basic relationships between DEXA and chemical fat, lean and bone composition for tissues of varying thickness, and second to apply these relationships to the determination of carcase composition as measured by computed tomography (CT). This series of experiments were conducted at the NUCTECH research facilities in Beijing.

3.1 Experiment 1. Tissue calibration block scanning

3.1.1 Tissue calibration block construction

To establish the base relationship between DEXA values and lean, fat and bone composition, samples of bone, fat and lean tissue were dissected from lamb carcases and homogenised separately. The fat and lean tissues were then weighed and combined to create tissue mixtures composed of fat:lean ratios of 0:100, 20:80, 40:60, 60:40, 80:20 and 100:0. Each tissue mixture was homogenised and sampled to determine chemical fat percentage (Table 1).

Each fat:lean mixture was applied to custom-built moulds to create calibration blocks of 4 different uniform thicknesses; 12mm 40mm, 80mm and 200mm. The height and width of each block were approximately 110mm x 110mm. Duplicates were created for each 12mm tissue block.

Table 1. Chemical fat percentage of dissected fat and lean mixtures.

Fat:Lean mixture	Chemical fat %
0:100	3.82
20:80	20.6
40:60	36.9
60:40	50.7
80:20	68.6
100:0	85.9

Bone tissue blocks were created separately using ground and homogenised long bones dissected from lamb carcases. The bones were trimmed of attached fat and muscle and were cut along their long axis before grinding and homogenisation. Custom built moulds were again used to transform the ground bone into standard square calibration blocks of 12mm and 40mm thickness. The height and width of these blocks were again approximately 110mm x 110mm. Five replicates of the 12mm thickness block and three replicates of the 40mm block were created.

3.1.2 DEXA scanning hardware

X-Ray images were then generated using a single emission from a X-ray tube, with a set of 2 images captured using 2 photodiodes. These photodiodes were selected for low and high energy photons respectively.

3.1.3 Tissue calibration block scanning protocol

The tissue blocks were scanned using the NUCTECH prototype DEXA scanner in Beijing. Each of the soft tissue calibration blocks were DEXA scanned in various combinations to produce a data array of varying tissue compositions of fat:lean at various thicknesses.

Bone calibration blocks were also scanned in combination with the soft tissue calibration blocks . The weight of each calibration block scanned was also recorded.

Prior to commencing the image analysis, the images acquired from the two detectors were normalized according to the following formula ($I_{low\text{-}normed}$ and $I_{high\text{-}normed}$ is provided by NUCTECH scanning software):

$I_{low\text{-}normed} = (I_{low} - I_{lowbackground}) / (I_{lowair} - I_{lowbackground})$;
$I_{high\text{-}normed} = (I_{high} - I_{highbackground}) / (I_{highair} - I_{highbackground})$;

Where: I_{low} represents the pixel value in the low energy image
I_{high} represents the pixel value in the high energy image
I_{lowair}, $I_{highair}$ represents the pixel value corresponding to the un-attenuated photons within each image that have passed through air only.
$I_{lowbackground}$, $I_{highbackgound}$ represents the pixel value of the background radiation.

Regions of interest were then selected within each tissue phantom image. R values were calculated within this region of interest according to the following formula:

$$R\ value = (-\ln(I_{low\text{-}normed})) / (-\ln(I_{high\text{-}normed}));$$

The R values for the pixels of each calibration block scanned were then averaged to give a single R value representing that tissue-mixture/thickness combination. The $-\ln(I_{low\text{-}normed})$ for the pixels of each tissue mixture were also averaged to give a single $-\ln(I_{low\text{-}normed})$. For each tissue mixture, the soft-tissue weight and bone weight were also recorded.

3.1.4 Algorithm description/training process

For soft-tissue calibration blocks, $Table_{soft}$ was constructed to represent the relationship among $-\ln(I_{low\text{-}normed})$, R value, and tissue weight. And for bone-containing calibration blocks, $Table_{bone}$ was constructed to represent the relationship among $-\ln(I_{low\text{-}normed})$, R value, soft tissue weight and bone weight.

Lastly, for comparative purposes, the carcase composition calculation was also undertaken using the method previously developed by Murdoch University (Gardner et al., 2018).

3.2 Experiment 2. Calibration of lamb carcase DEXA scans against CT scans

3.2.1 Carcase Description

Seven local lamb carcases were purchased for DEXA and CT scanning in Beijing, China. The lambs were slaughtered the day prior to DEXA scanning and stored at 2 degrees celcius throughout the experiment. The carcases were DEXA scanned entire and then were cut into fore, rack, loin and hind sections. The cold weight of the carcases, the weight of each section, and the carcase fatness measured at the GR site are shown in Table 3.

Table 3. The cold carcase weight (CCW, in kg), fore, rack, loin and hind section weight (Wt, in kg) and the GR fat depth (mm) of each carcase measured at the time of CT scanning.

Carcase	CCW	Fore Wt	Rack Wt	Loin Wt	Hind Wt	GR
1	26.7	8.58	5.15	3.52	9.45	9
2	26.66	9.05	4.56	3.76	9.29	10
3	22.97	8.35	3.92	2.62	8.08	5
4	15.78	5.22	2.45	2.15	5.96	6
5	16.02	5.12	3	2.35	5.55	13
6	14.41	5.02	2.5	1.83	5.06	5
7	13.75	4.65	2.45	1.6	5.05	8

3.2.2 Carcase DEXA scanning protocol

Carcase DEXA images were generated using the same hardware described in Experiment 1. To capture the DEXA images carcases were hung from a custom-made metal frame using steel hooks, with the brisket facing the X-ray source, as shown in Figure 10.

3.2.3 Carcase image analysis

The R value and $-\ln(I_{Low\text{-}normed})$ of each pixel were used along with $Table_{soft}$ and $Table_{bone}$ defined in Experiment 1, to calculate the fat%, lean% and bone% according to the following process.

Step 1. The carcase image was segmented into two parts – soft tissue containing pixels and bone containing pixels. This segmentation was based on thresholding using the atomic number associated with each pixel (Fig. 10).

Step 2. For the soft tissue containing pixels, the fat% and tissue weight were calculated according to $Table_{soft}$ using the $-\ln(I_{low\text{-}normed})$ and R value for each pixel.

Step 3. We then calculated the mean fat% using the results of the soft tissue part of the image excluding bone-containing pixels, which is equivalent to fat weight divided by total soft-tissue weight.

Step 4. For soft-tissue scanned with bone, the soft tissue weight, bone weight and mean fat % were determined according to $Table_{bone}$, based upon the $-\ln(I_{low\text{-}normed})$ and R value of each pixel.

Step 5. The carcase fat% was computed by the total fat weight divided by the total soft tissue weight and bone weight. The carcase lean% is computed by the total lean weight divided by the total soft tissue weight and bone weight. The carcase bone% is computed by the total bone weight divided by the total soft tissue weight and bone weight.

3.2.4 Carcase CT scanning protocol

The chilled lamb carcasses were transported to a hospital for CT scanning using a Picker PQ 5000 spiral CT scanner. Scanning was completed within 24 hours of DEXA scanning to determine the proportions of carcase fat, lean and bone. Prior to scanning the carcasses were split into four primal components to enable more rapid post scanning processing of the CT images for analysis of fore-section, rack, loin and hind section composition. The fore section was separated from the saddle by a cut between the fourth and fifth ribs. The rack was separated from the loin between the 12^{th} and 13^{th} rib. The hind section was separated from the saddle by a cut through the mid-length of the sixth lumbar vertebrae.

The pilot CT scan length was 512 mm, field of view set at 480mm, Index 20, kV 110, mA 150, revs 40, pitch 1.5 and standard algorithm selected. The carcasses were scanned in 10 mm slice widths, with each slice taken 10 mm apart.

The images produced from the CT scan were edited to remove non-carcass image artefacts and were partitioned into bone, muscle and fat components (Image J version 1.37v, National Institutes of

Health, Bethesda, MD, USA, used in conjunction with Microsoft Excel). The discrimination point to identify the Hounsfield barriers for associating pixels with fat, muscle and bone were –235 to 2.3 for fat, 2.4 to 164.3 for lean and >164.3 for bone. An estimate of volume using Cavalieri's method (Gundersen & Jensen, 1987; Gundersen et al., 1988) was calculated as follows:

$$\text{Volume}_{\text{Cav}} = d \times \sum_{g=1}^{m} \text{area}_g - t \times \text{area}_{max}$$

in which m is the number of CT scans taken and d is the distance between cross-sectional CT scans, in this case 10 mm. The value of t is the thickness of each slice (g), in this example 10 mm, and area max is the maximum area of any of the m scans.

The average of the Hounsfield units of the pixels of each component was then determined and converted into density (kg/L) using a linear transformation (Mull, 1984). This was then used along with the volume of each component to determine the weight of fat, lean and bone, which was then expressed as a percentage of total carcass weight at the time of scanning.

3.2.5 Description of simple comparative analysis of DEXA versus CT

To convert the DEXA estimated mass of fat, lean and bone into the equivalent CT measured proportion of fat, lean and bone, general linear models were fitted. CT component (bone, lean, or fat) was fitted as the dependent variable, and DEXA estimate of bone, lean, or fat was the independent variable.

4 Results

4.1 Tissue calibration block scanning experiment

There was a linear association between soft tissue thickness and the $-\ln(I_{low\text{-}normed})$ in the low energy DEXA image, and between soft tissue thickness and $-\ln(I_{high\text{-}normed})$ for the high energy image (Figure 1). Both these associations varied at different levels of chemical fat %, though the relationship between the -ln of high energy image pixels and tissue thickness was influenced less by changes in tissue fat % (Fig. 1).

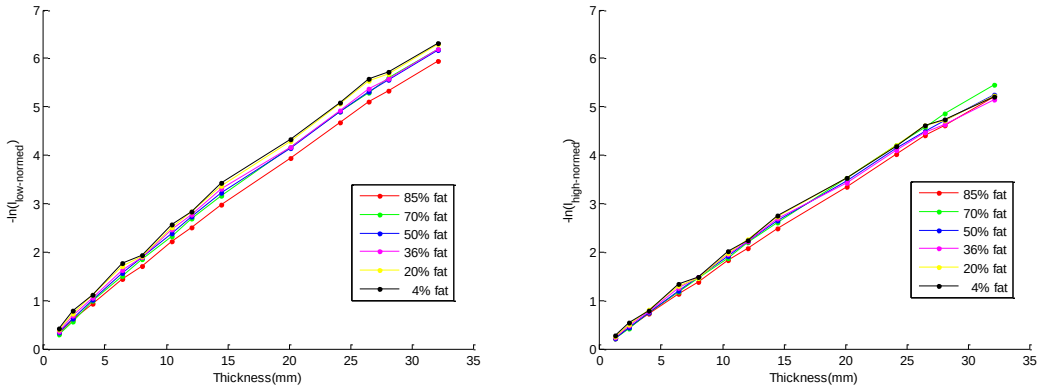


Figure 1 Relationship between tissue thickness and the $-\ln(I_{low\text{-}normed})$, tissue thickness and $-\ln(I_{high\text{-}normed})$ for the low and high energy image at varying levels of chemical fat %.

There was a spline function between soft tissue weight and the $-\ln(I_{low\text{-}normed})$ in the low energy DEXA image, and between soft tissue weight and $-\ln(I_{high\text{-}normed})$ for the high energy image (Fig. 2).

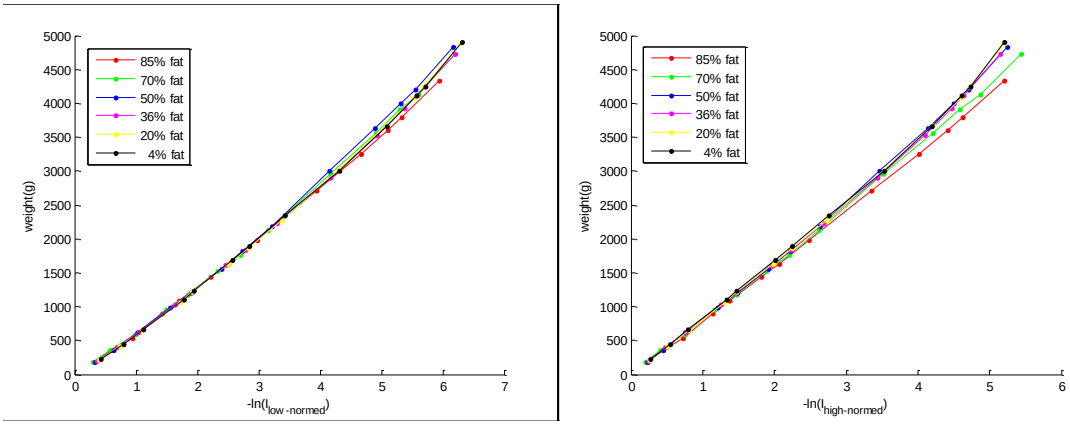


Figure 2. Relationship between tissue weight and the $-\ln(I_{low\text{-}normed})$, tissue weight and $-\ln(I_{high\text{-}normed})$ for the low and high energy image at varying levels of chemical fat %.

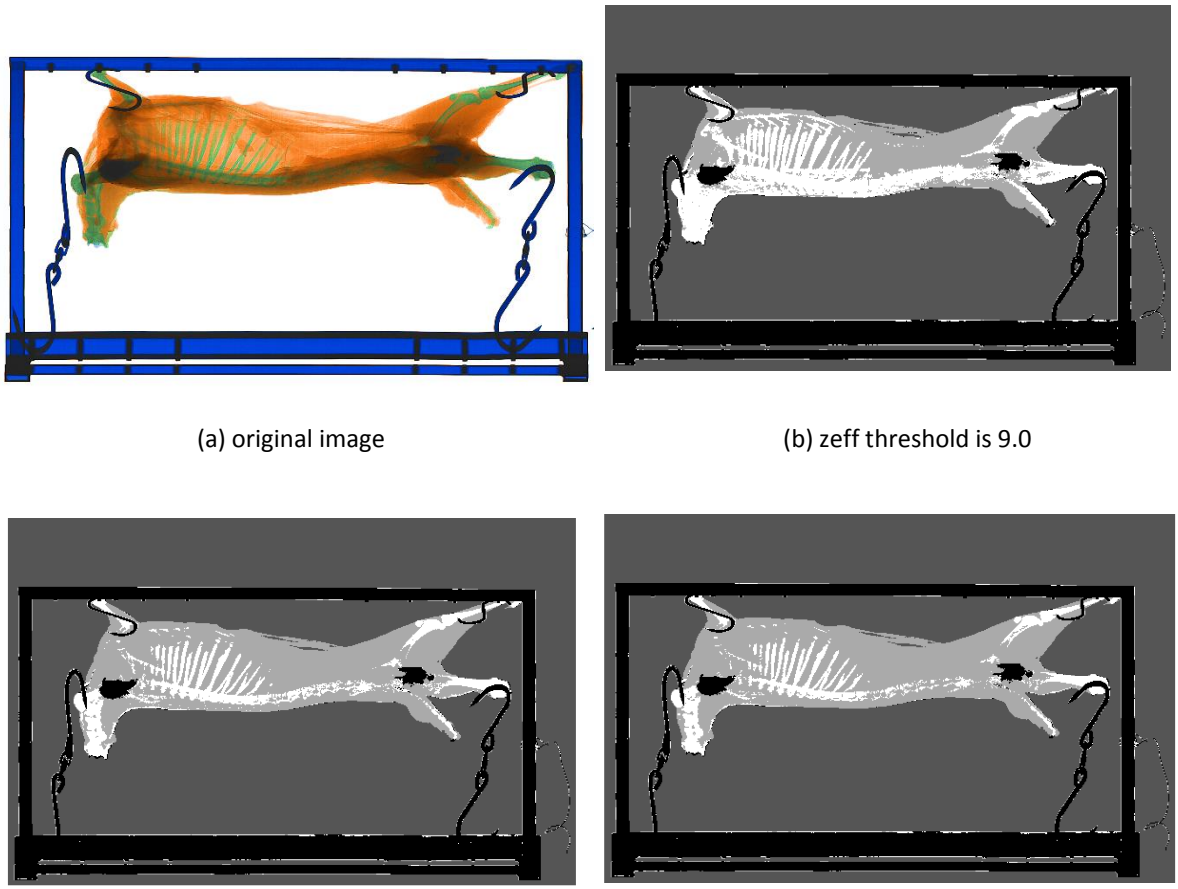
4.2 Carcase scanning experiment

Descriptive statistics of CT and DEXA values for the 7 carcases (mean, STDEV, min, max) are shown in Table 3.

Table 2. Descriptive carcase statistics for the 7 lambs selected for dual energy x-ray absorptiometry (DEXA) and computed tomography (CT) scanning in Beijing, 2018.

	Mean	Standard Deviation	Minimum	Maximum
Cold Carcase Weight (kg)	20.4	5.4	13.8	26.7
GR Tissue Depth (mm)	8.4	3.7	5	16
CT lean %	53.8	6.23	40.1	65.3
CT fat %	27.6	6.74	12.0	39.1
CT bone %	18.5	2.19	15.0	22.7

Differentiating bone-containing tissue from soft tissue is shown for one lamb carcase in Figure 3. Differentiation was achieved using a specified atomic number (zeff) as a threshold. From Figure 3, the effect of varying the zeff threshold on differentiation is evident. The lower the zeff threshold, the more bone regions were included, but this also results in some misclassification. In this report, we have used 9.0 as the zeff threshold for differentiation.



(a) original image (b) zeff threshold is 9.0

(c) zeff threshold is 9.5 (d) zeff threshold is 10.0

Figure 3. Segment results of one lamb (4th). The white region represents the bone, the light grey represents the meat, the charcoal grey represents the air, the black region represents thick or dense tissues including the iron hook and frame where X-rays have not penetrated to the detector.

Table 4. The composition (fat, lean and bone%) of each carcase as determined by CT scanning and DEXA scanning, using the NUCTECH method and previously published Murdoch University method for calibration and analysis of DEXA images.

Lamb index	CT scanning			NUCTECH DEXA method			Murdoch University DEXA method	
	Fat%	Lean%	Bone%	Fat%	Lean%	Bone%	Fat%	Lean%
1	27.83	53.14	19.02	21.36	61.15	17.49	34.87	65.13
2	27.28	52.81	19.91	19.22	63.58	17.20	31.75	68.25
2^	27.28	52.81	19.91	22.63	58.51	18.86	33.91	66.09
2^	27.28	52.81	19.91	19.99	59.62	20.39	31.78	68.22
3	12.00	65.29	22.71	21.83	56.38	21.79	35.79	64.21
3^	12.00	65.29	22.71	22.39	55.36	22.25	35.57	64.43
3^	12.00	65.29	22.71	22.35	55.05	22.6	35.71	64.29
4	25.20	56.73	18.07	36.71	48.64	14.65	49.24	50.76
4^	25.20	56.73	18.07	36.67	48.6	14.73	49.16	50.84
4^	25.20	56.73	18.07	36.48	48.31	15.21	48.97	51.03
5	30.51	54.51	14.99	32.39	56.06	11.55	44.66	55.34
5^	30.51	54.51	14.99	31.77	56.65	11.58	44.27	55.73
5^	30.51	54.51	14.99	31.67	56.4	11.93	44.27	55.73

6	26.13	56.71	17.16	33.87	51.47	14.66	45.91	54.09
6^	26.13	56.71	17.16	33.92	51.17	14.91	45.85	54.15
6^	26.13	56.71	17.16	33.78	51.05	15.17	45.67	54.33
7	27.74	55.22	17.04	30.34	54.29	15.37	43.96	56.04
7^	27.74	55.22	17.04	30.39	53.97	15.64	44.19	55.81
7^	27.74	55.22	17.04	30.19	53.81	16.00	43.91	56.09

^ Represents lambs that were DEXA scanned multiple times for determination of fat, lean and bone%.

The linear association between DEXA values and the corresponding CT fat%, lean%, and bone% are shown in Figures 4-6.

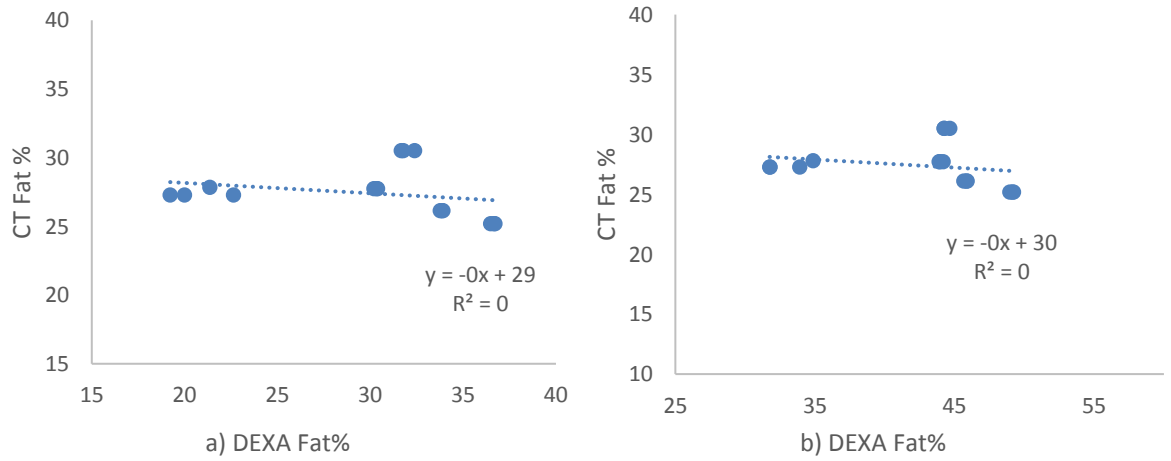


Figure 4. The association between DEXA predictions and CT predictions of carcase fat % using a) the NUCTECH method for fat determination and b) using Murdoch University method for fat determination.

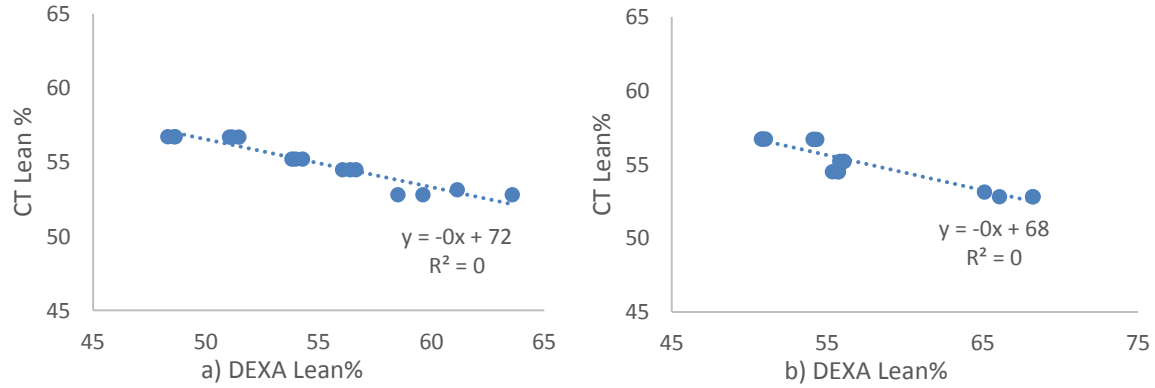


Figure 5. The association between DEXA predictions and CT predictions of carcase lean % using a) the NUCTECH method for lean determination and b) using Murdoch University method for lean determination.

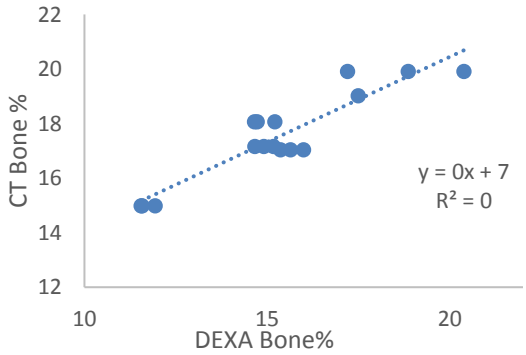


Figure 6. The association between DEXA predictions and CT predictions of carcase bone% using the NUCTECH method.

5 Discussion

5.1 Tissue calibration block experiment

The scanning of soft tissue and bone calibration blocks has demonstrated the ability of the NUCTECH DEXA scanner to successfully identify thickness, chemical fat %, and bone % of scanned tissues. The relationships between the negative log of high and low energy pixel DEXA images shown in Figure 1 demonstrates that the thickness of the tissue can be determined with little influence of the chemical fat %, particularly for the high energy DEXA image. Using the calculated R value of each pixel and the thickness represented by that pixel, we can determine the proportions of fat, lean and bone within each pixel in an image. This indicates that the prototype NUCTECH DEXA system has the capacity to differentiate the tissue components within a carcase. The precision with which this system can predict the composition of lamb carcases needs to be assessed by training and validating the device against the gold standard measurement of carcase composition, computed tomography (CT).

5.2 Carcase scanning experiment

This experiment demonstrates that the NUCTECH DEXA scanner can predict CT composition in lamb carcases, albeit in a very small data set currently. Using the relationships between DEXA R value, tissue thickness and Chemical fat % established in experiment 1, the NUCTECH DEXA device was able to predict CT lean% and bone% with good precision. The prediction of CT fat % was imprecise, demonstrating that further development is needed in this area. The positioning of carcases for DEXA scanning in this trial is a limitation, as lamb carcases could not be hung for DEXA scanning as they are in Australian abattoirs. The carcases were therefore scanned in a more lateral aspect in this experiment, with the legs not stretched and well separated as they would be when scanned on the chain in an Australian abattoir. This change in positioning may have a small impact on estimates of carcase composition, as previous work has shown that scanning lamb carcases dorsal to ventral (back to brisket) instead of ventral to dorsal influences DEXA prediction of CT composition (Gardner et al 2018). In addition the differences in positioning may account for the regions of the carcase that were too dense for X-ray penetration of the NUCTECH DEXA device (Fig. 3), as the density of the carcases will reduce, particularly in the hind region, when the carcases are scanned on a ventral-dorsal plane rather than on a slightly lateral plane.

6 Conclusions/recommendations

6.1 Future work

There are several items to address in future experimental work. This includes:

a) Calibrating the NUCTECH DEXA device against CT measures of composition in Australian lambs that have been processed under standard conditions of dressing, chilling and hanging. Substantially larger data sets are required to properly assess the transportability of this measurement.

b) Testing of algorithms predicting carcase composition across multiple DEXA scanners.

c) Testing of alternative algorithms to differentiate bone from soft-tissue.

d) Further work to optimise voltage and current settings in order to improve image acquisition and minimise those regions where complete attenuation of x-rays have occurred.

e) Testing of a prototype design that can operate at chain speed in a commercial abattoir

6.2 Conclusions

Overall this pilot study has produced promising results, demonstrated that the NUCTECH DEXA device is capable of predicting CT composition of lamb carcases, though larger studies of the NUCTECH device in a commercial setting is needed to fully establish its ability to predict lamb carcase composition.

7 Key messages

- NUCTECH have developed a DEXA device capable of differentiating between carcase tissue types (bone, lean muscle and fat) of varying thicknesses.

- The prototype NUCTECH DEXA device is capable of predicting the CT composition of lamb carcases, though more carcases need to be scanned in a commericial setting to fully demonstrate this capacity.

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