NUCTECH COMPANY LIMITED

Final report

Nuctech DEXA CT system validation for beef chining automation

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Abstract

The Nuctech DEXA CT system has the potential to rapidly scan beef sides or product to predict the composition of the beef (lean%, fat% and bone%) and provide 3-dimensional imagery to inform automated boning at abattoir line speed. Nuctech initially upgraded the hardware and software componentry of the existing XT2100 series CT system to enhance its ability to differentiate bone and soft tissues in beef enabling it to drive automated chining. The adapted CT system was then shipped to JBS Brooklyn, VIC, for testing. 24 bone-in beef primals (12 rib sets and 12 short loins) and 3 beef sides were selected from JBS Brooklyn abattoir to represent a wide phenotypic range in weight and fatness. The primals were scanned individually by the Nuctech CT and then boxed for scanning in several configurations, before the boxed beef primals were frozen and transported to Murdoch University for medical CT scanning – the gold standard measure of beef composition. The 3 beef sides were cut into 5 sections for scanning through the Nuctech CT system. To assess image resolution, dimension estimation and the ability of the Nuctech CT to differentiate tissue of differing density an XTE-CT test piece was also scanned. The stability of system's scanning field was also tested by scanning the test piece in 10 positions within the CT aperture, while the repeatability of the system was tested by repeatedly scanning the test piece in 3 of those locations.

XTE-CT test piece scans demonstrated that the Nuctech CT system has good image resolution and ability to measure dimensions in a scaled and highly repeatable fashion. The Nuctech CT was able to successfully differentiate materials of differing density within the XTE-CT test piece, where Nuctech CT pixel values demonstrated a strong linear relationship with density, similar to medical CT. The Nuctech CT pixel values produced in XTE-CT density tests were highly repeatable and positioning of the test piece within the Nuctech CT field of view did not impact on density values ($P > 0.05$). A range of thresholds were applied to pixel values to differentiate fat, lean and bone in Nuctech CT primal scans. These were analysed to determine the optimal thresholding values. Analysis of all primals using these thresholds demonstrated the excellent capacity of the Nuctech CT scanner to differentiate fat, lean and bone in rib sets and bone-in short loins, and thus its ability to predict medical CT fat, lean and bone % with excellent precision. CT fat % was predicted with an R^2 of 0.95 and root mean square error (RMSE) of 1.37 fat % units in short loins, and with an R^2 of 0.99 and RMSE of only 0.65 fat % units in rib sets. CT lean % was predicted with similarly high precision; with an R^2 of 0.95 and RMSE of 1.37 lean % units in short loins and with an R^2 of 0.98 and RMSE of only 0.63 in rib sets. CT bone % was predicted with higher precision still, with an R^2 of 0.99 in both primals and a similar RMSE of only 0.14 in short loins and 0.17 bone % units in rib sets. Furthermore, qualitative assessment of beef carcase scans and of boxed beef primal scans demonstrated that the

quality of the Nuctech images. Their ability to differentiate tissue types based on pixel value thresholds were not influenced by the cut of meat or by continuous scanning over 5 minutes. One limitation of this system was where the thickness of beef product scanned was increased by stacking boxes of primals (up to 720 mm in thickness). This produced image shadowing and substantially limited the ability of the system to differentiate fat from lean tissue. Despite this limitation, the ability to differentiate bone from soft tissue was well maintained.

Executive summary

This report details the image resolution, dimension estimation, pixel value consistency across the field of view and repeatability of the Nuctech CT system using the XTE-CT test piece. It also tests the ability of Nuctech CT scans to differentiate bone, lean and fat tissue within bone-in beef primals (short loins and rib sets) of variable weight and fatness and thereby predict medical CT composition. This study also looked at the impact of continuous scanning, increasing scan thickness and of diverse beef side sections on the quality of Nuctech CT images. Key initial outcomes are:

1. Good image resolution and the ability to measure dimensions in a scaled and highly repeatable fashion, as demonstrated through scans of the XTE-CT test piece, demonstrates the capacity of the Nuctech CT system to provide imagery suitable for automation.
2. Provision of raw unscaled Nuctech CT scans of the XTE-CT test piece demonstrated that positioning of this test piece within the Nuctech CT field of view did not impact density values. This contrasted with the earlier interim report submitted in December 2023 which suggested a large impact, but was the result of image scaling that biased these early results.
3. Fat, lean and bone tissues were well differentiated using pixel value thresholds in Nuctech CT scans of bone-in short loin and rib set primals. The Nuctech CT scanner was thus able to predict the medical CT composition (fat, lean and bone %) of these beef primals with excellent precision.
4. The ability to differentiate tissues in Nuctech CT images of beef rib sets scanned continuously over a 5 minute period was maintained, while differentiation of fat and lean tissue was slightly reduced in the largest sections when entire beef sides were scanned in 5 sections.
5. Increasing the thickness of beef product scanned by scanning boxes of primals 2 wide (720mm) and 3 boxes high (540mm) produced shadowing in Nuctech CT images that also limited the ability of the system to differentiate fat from lean tissue. Differentiation of bone from soft tissue remained good in these images despite the increased tissue thickness. The limits of the Nuctech CT capacity in terms of tissue thickness thus warrants further investigation.

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1. Background

The development of novel X-ray technologies provides many opportunities to improve the efficiency of beef production and processing in Australia. Medical computed tomography (CT) is now considered the gold standard imaging method for assessing and quantifying different tissue types in beef, providing a complete 3-D virtual dissection of carcasses or carcass components. While the slow speed and expense of medical CT scanning prevents its commercial use, this device is used as the gold standard in the training and testing of novel technologies aiming to predict beef composition.

In addition to the potential to improve measurement of carcass composition or lean meat yield; X-ray technologies also offer the opportunity to improve the automated beef deboning. While currently 2-D X-ray images are adequate to provide the precise skeletal coordinates to direct the automated cutting of lamb carcasses, in the beef industry commercial cutting lines predominantly involve the identification of seams between muscles and fat depots and therefore 3-D imaging of beef carcasses or primals is needed to advance automation.

Nuctech's industrial CT systems may have the capacity to produce rapid 3-D scans of beef sides or portions of beef to inform automated boning at line speed. Nuctech have taken their existing XT2100 series CT system used for airline inspection and made several changes to the mechanical structure, image acquisition system and software to improve its suitability for rapid differentiation of tissue in beef. However, the ability of this system to differentiate tissue types and thereby determine the composition, bone landmarks and muscle seams in beef primals when compared to medical CT needs to be determined.

2. Objectives

The objective of this report was to assess the image quality of the Nuctech CT system installed in an Australian abattoir using the test devices available within the XTE-CT test piece, including the image resolution, dimension estimation, stability across the scan field and repeatability. This test piece has been adopted as the calibrating device for CT scanners used to provide reference data for technologies seeking commercial accreditation for predicting carcase lean and fat% in Australia. The ability to differentiate fat, lean and bone tissue and thereby to determine CT composition %, bone landmarks and muscle seams in Nuctech CT scans of beef primals was also assessed, in addition to the quality of imaging beef sides scanned in 5 sections.

3. Methodology

The resources and consumables used in delivering the project include but are not limited to hardware in modifying XT2100HS, MAX1000, data generated from XT2100HS, data generated from MAX1000, consulting service from Murdoch University, 24 boxed beef primals, 3 beef carcass and leasing of XTE-CT test piece from Murdoch University.

3.1 Installation of the Nuctech at JBS Brooklyn

Following upgrades made to the existing XT2100 Nuctech CT system to improve beef meat or carcase imaging (detailed in the S1 report) in China, the Nuctech beef CT system was shipped to Australia. A suitable area for its install was found at the JBS Brooklyn site (Vic), within reasonably close proximity to the beef boning area, however some site works were required before the Nuctech system could be installed, in particular widening of the doors into the room to allow for its entry. This allowed the installation of the Nuctech CT system into this room. The Nuctech system was transported in crates, that were craned from the trucks into JBS Mechanical storage, before the three components of the system were then moved to the install site using a 16 T forklift and into position within the assigned room using a 2. 5T electric forklift, jacks and skates (Figure 1a-c). The three components were then adjusted to the right level before they were adjoined to complete the system install (Figure 1d) and start commissioning.

Following power connection with assistance from JBS, the system was commissioned with the cable connection and hardware checked before the system status as checked via the control panels. The system was then calibrated and the radiation dose rate monitored. Multiple scanning checks were then conducted before the system was ready for beef scanning. The radiation output of the device was continually monitored using a GH-1021 Geiger counter (Figure 1e) to ensure radiation levels around the device were within safe and regulated levels. JBS received the radiation license for the device while a Nuctech team member has a radiation use license to operate the system.

Figure 1. Nuctech CT system installation into JBS Brooklyn (a to c), the installed system (1d) and the Geiger counter measuring the radiation output of the Nuctech CT system (1e).

3.2 Beef primal selection

Bone-in beef rib set (AUSMEAT item 2220) and bone-in short loin (AUSMEAT item 1552, without the tenderloin) primals were selected at JBS Brooklyn abattoir from the carcases available over one day. The below optimal grid (Table 1) was used to drive selection of maximal phenotypic range in primal weight (kg) and fatness (mm). However, the actual selection achieved (Table 2) was restricted by the carcases available on the day of selection. The carcase side weight, P8 fat depth, primal weights and the number of vertebrae within each short loin are shown in Table 3. The bone-in rib sets and short loins were obtained from the same side in 10 of the carcases, with the additional 2 rib sets obtained from different carcases to the remaining 2 short loins (Table 3). Carcase sides ranged in weight by 100 kg (119.5 to 229 kg) and by 20 mm in P8 fatness (5 to 35 mm). The number of vertebrae in the short loin ranged from 6.5 to 7.5, while there were consistently 6 ribs included in each rib set primal.

Table 1. Optimal bone-in rib set and short loin selection to maximise the phenotypic range in weight and fatness.

Primal Weight (kg)	Fatness (P8 fat)			
Rib sets	1 – 10mm	11 - 15mm	16 – 20mm	>20mm
< 7 -9 kg	1	1	1	1
9 - 11 kg	1	1	1	1
11 - > 13 kg	1	1	1	1
Short loins				
< 5 – 7 kg	1	1	1	1
7 – 9 kg	1	1	1	1
9 - > 11 kg	1	1	1	1

Table 2. Actual selection of bone-in rib sets and short loins achieved.

Primal Weight (kg)	Fatness (P8 fat)			
Rib sets	1 – 10mm	11 - 15mm	16 – 20mm	>20mm
< 7 -9 kg	1	3	2	0
9 - 11 kg	2	2	0	0
11 - > 13 kg	0	0	0	2
Short loins				
< 5 – 7 kg	0	0	0	0
7 – 9 kg	1	2	2	1
9 - > 11 kg	1	3	0	2

Table 3. The hot standard carcass weight, P8 fat depth, rib set and short loin primal weight for the beef primals scanned in this experiment.

Carcass side weight (kg)	P8 fat depth (mm)	Rib set weight (kg)	Short loin weight (kg)	Number vertebrae in short loin
168.5	11	7.82	9.7	7.5
144	7	9.12	9.9	7.5
189	15		9.38	7
145.5	16	7.66	8.34	7.5
179.5	24		8.48	7
229	25	11.32	10.6	6.5
121.5	5	6.46	7.08	7
125	15	7.48	8	7
160	12	9.42	8.64	7
119.5	15	10.88	9.7	6.5
201.5	35	12.32	9.98	6.5
129.5	19	7.5	7.86	7
137	10	9.78		
176.5	13	8.48		

3.3 XTE-CT test piece scanning

3.3.1 Nuctech CT scanning

The XTE-CT test piece was scanned by the Nuctech CT system within a plastic tub. This avoided the test piece being moved out of position by the lead curtains on entry to the tunnel.

Given the large field of view of the Nuctech CT system, the XTE-CT test piece was scanned in 10 positions within this field of view to assess the stability of the image across these regions (Figure 2). The XTE-CT test piece was scanned in 5 positions across the width of the field (positions 1-5, where 1 is far left, 3 in central and 5 is far right), and at 2 heights – low (on the belt) and high (elevated 220 mm on a plastic tub), as shown in Figure 2.

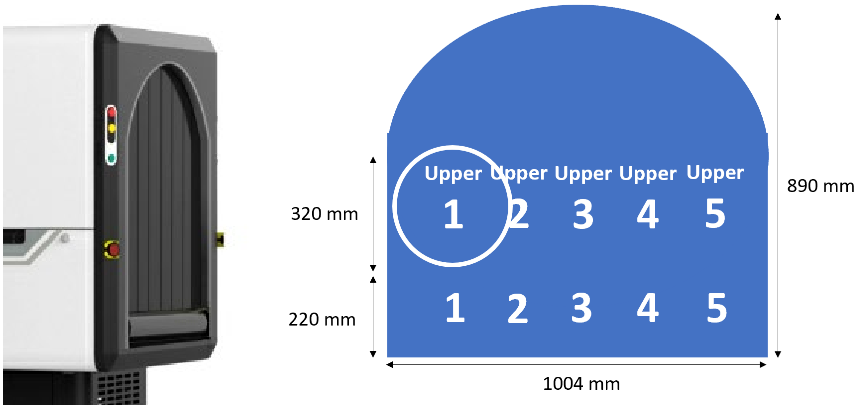


Figure 2. The 10 positions that the XTE-CT test piece was scanned through the Nuctech CT system field of view. The XTE-CT test piece (320 mm in diameter) is represented by the white circle in scanning position 'upper 1', where the XTE-CT was elevated by 220mm (for upper positions 1 - 5).

The XTE-CT test piece was then scanned repeatedly (5 times) in positions 1, 3 and 5 to test the repeatability of the system. For each scan the XTE-CT test piece within a tub was attempted to be in the exact same position.

Figure 3. Scanning the XTE-CT test piece through the Nuctech CT system (in a tub, in position 3).

3.3.2 Medical CT scanning

The XTE-CT test piece was then scanned repeatedly (5x) in the same position through the medical CT scanner at Murdoch University (a Siemens Somatom Scope 16 slice CT scanner).

3.4 Beef scanning

All the bone-in beef primals were vacuum packaged, weighed and labelled before Nuctech CT scanning at a speed of 0.25m/sec over the course of one day.

3.4.1 Nuctech CT scanning of beef primals

The primals were initially scanned individually, positioned with the chine or spine on the belt in the centre of the field of view (Position 3 in Figure 2) and consistently oriented with the cranial aspect of each primal entering the scanning tunnel first.

The Nuctech beef primal images have been provided to Murdoch University in DICOM format for analysis.

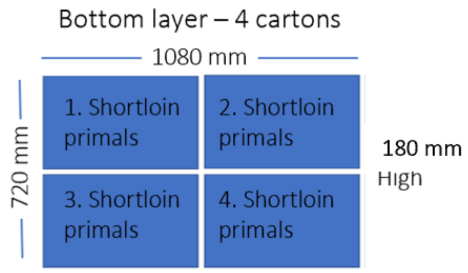
Figure 4. Scanning vacuum packaged bone-in primals individually through the Nuctech CT system.

3.4.2 Nuctech CT scanning of boxed primals

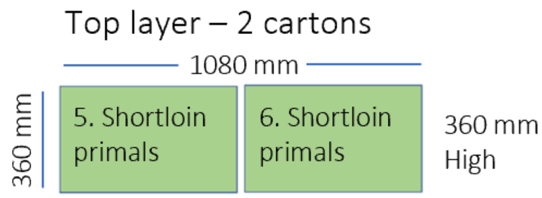
After individual scanning the 24 primals were then packaged into boxes, with approximate dimensions of 360 mm wide, 540mm long and 180 mm high. While it was intended to pack 2 x Rib sets and 2 x short loins into each box, creating a total of 12 boxes, the rib sets were too large to fit 2 primals into 1 box therefore needed to be boxed individually, creating 12 boxes of rib sets (1 – 12) and 6 boxes of short loins (1-6).

The boxed primals were then scanned in 3 configurations through the Nuctech CT scanner.

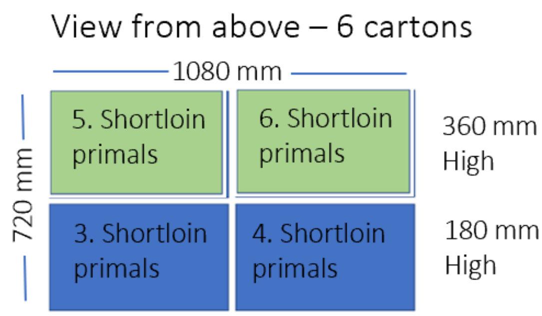
- **Configuration 1 - 2 boxes high, 2 wide.**
    - Cartons will be stacked in 2 layers creating an object with approximate dimensions of 720 mm wide, 1080 mm in length and 340 mm height.
    - 4 boxes of primals form the bottom layer (4 short loin boxes in below example)



    - 2 boxes of primals form the Upper layer (2 short loin boxes) as shown:



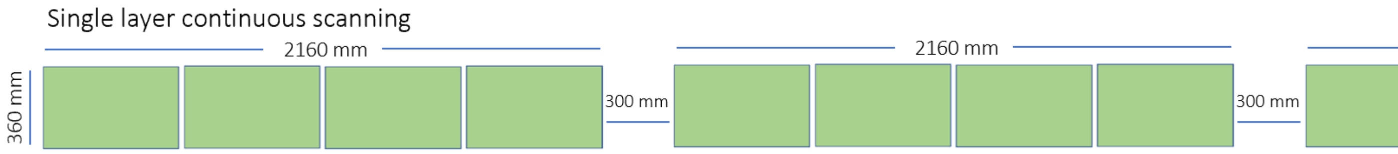
    - The top layer will be positioned over one side of the bottom layer as shown by the bird's eye or view from above shown below:



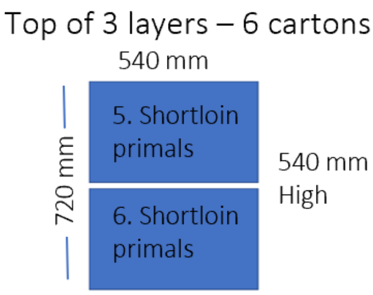
This configuration was then repeated for the boxes of individual rib sets, with the same order and configuration applied to rib set boxes 1-6 and then boxes 7-12.

- **Configuration 2. – Continuous scanning**
    - Scanning a single line of boxed primals repeatedly to test the Nuctech CT's ability to scan and output data continuously.

- The 12 boxes of rib sets were scanned in groups of 4 on a continuous basis over a 5-minute time period.
- A space of approximately 300mm will be left between each group of 4 boxes scanned.



- **Configuration 3. – 3 boxes high, 2 wide**
  - Stacking 3 layers of 2 boxes, creating an object approximately 540 long, 720mm wide and 540mm high or deep.



This configuration was then repeated for the boxes of individual rib sets, with the same order and configuration applied to rib set boxes 1-6 and then boxes 7-12.

Figure 5. Scanning boxes of beef primals in configuration 3 through the Nuctech CT scanner.

3.4.3 Nuctech CT scanning of beef sides in 5 sections

Three beef carcases were selected from JBS Brooklyn abattoir for scanning through the Nuctech CT scanner- 1 light-weight beef side (146 kg), 1 medium-weight (186.5 kg) and 1 heavy-weight (208.5 kg). Each beef side was cut into 5 sections to facilitate moving the beef sides from the chillers to the Nuctech CT system for scanning. The beef sections were scanned through the Nuctech CT scanner located in the centre of the scanning field (lower position 3, Figure 2).

3.4.4 Medical CT scanning of beef primals

Following Nuctech CT scanning the boxes of bone-in rib set and shortloin primals were frozen for transport to Murdoch University for CT scanning. The primals were defrosted and weighed prior to medical CT scanning. Following standard calibration of the CT scanner (a Siemens Somatom Scope 16 slice CT scanner) using air, water and the XTE-CT calibration test piece, all rib sets and short loins were CT scanned at settings of 120 mA, and at 5mm slice thickness. The CT scanner has a field of view of 480mm, a pitch of 1, rotation time of 0.8 seconds and was set to an Abdomen soft tissue algorithm.

The primals were scanned individually and two boxes of short loins were scanned on top of one another, replicating Nuctech boxed primal scanning Configuration 1. However, unlike configuration 1 Nuctech scans, only 1 box wide could be medical CT scanned given the limited diameter (480mm) of the aperture or scan window, which also precluded scanning 3 boxes high (Nuctech scan Configuration 3).

3.5 Analysis of XTE-CT test piece images

The Nuctech CT and Murdoch University medical CT XTE-CT test piece images were analysed in DICOM format using ImageJ software. A number of quantitative tests were undertaken using the XTE-CT test piece scans to assess the comparative image quality of these two devices. In all cases the performance of each of these tests was assessed across each of the 5 repeat scans, enabling quantification of repeatability of these performance indicators.

3.5.1 Spatial resolution test

The spatial resolution test uses a “crows-foot” design in which tapered Perspex elements are a maximum of 10mm apart at their outer edge, tapering centrally to a point at the centre of a circle where they converge (Figure 6a). The spatial resolution test determines the point at which the individual elements can no longer be differentiated or resolved, corresponding to the resolution limit for the system (Figure 6b). The resolution of the system can be calculated as:

Resolution limit (mm) = 10[L1/(L1+L2)]*

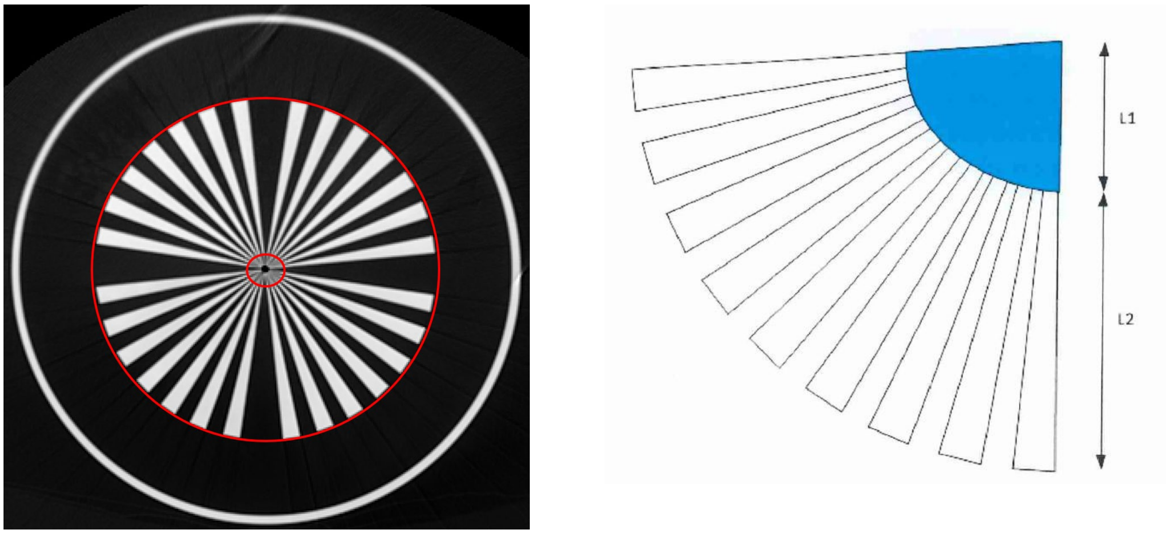


Figure 6. The spatial resolution test uses Perspex elements separated by 10mm at their outer edge, and tapering to a point where they meet in the centre of the circle shown (a). The blue region represented in (b) represents the area where the bars can no longer be observed. This length is represented by the formula L1 = 100mm-L2

3.5.2 Grid resolution test

The grid resolution test (Figure 7) is similar to the spatial resolution test, although more qualitative in its interpretation. Slots of 1mm to 6mm thickness are visualised in the CT image, and the smallest size that can be differentiated or resolved determines the resolution of the image.

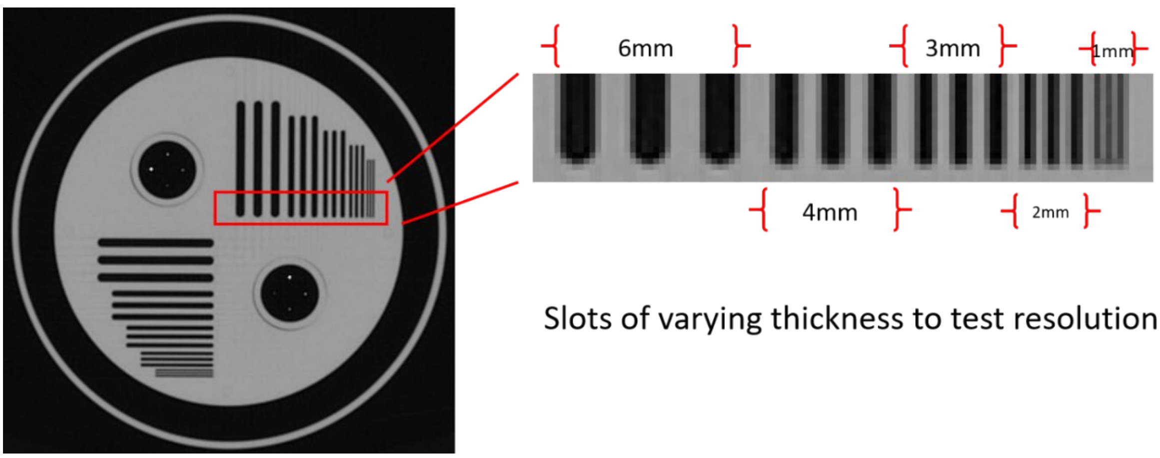


Figure 7. The grid resolution test showing slots cut into Perspex that are separated by between 1mm to 6mm.

3.5.3 Simple image dimensions

Measuring simple XTE-CT test piece image dimensions assesses the capacity of the CT scanner to accurately and repeatably determine the size and thickness of objects scanned. To measure size the diameter of a uniform 200mm section of the XTE-CT test piece was measured (Figure 8). To measure thickness a 40mm plastic section was detected through a series of cross-sectional scans (Figure 9).

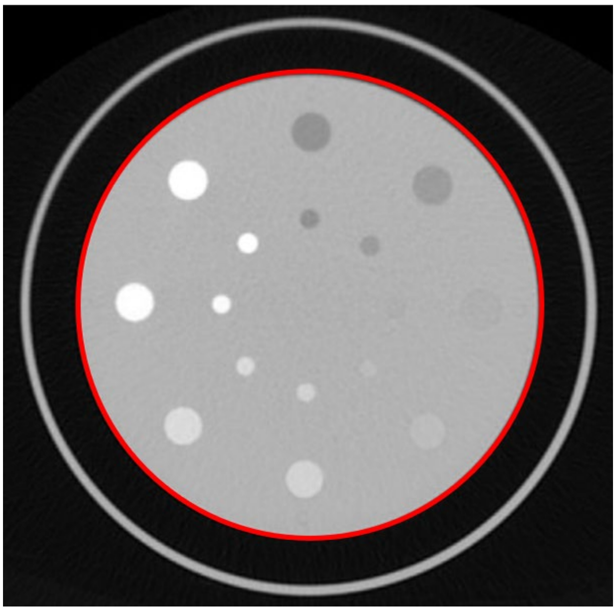


Figure 8. A **simple dimension measurement was taken using the diameter of the region encompassed by the red circle shown within the figure. Within the XTE-CT test piece the diameter of this reference material was a uniform 200mm.**

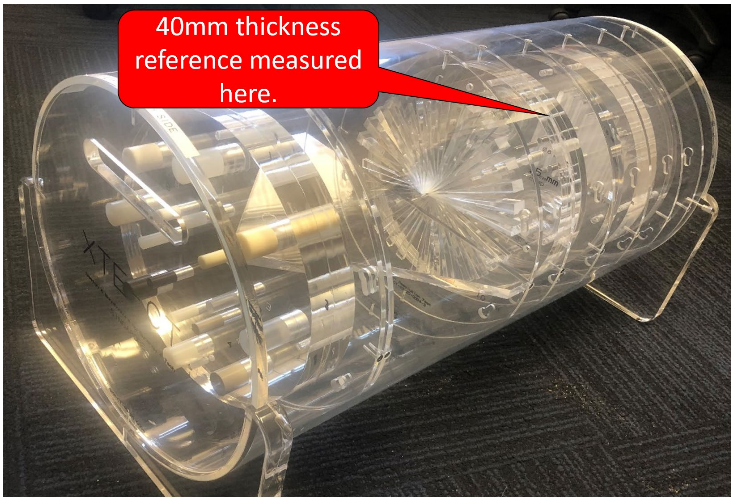


Figure 9. A simple thickness measurement was taken within the XTE-CT test piece using the section shown which was designed to be a uniform 40mm thickness.

3.5.4 Density test

The density test uses a series of rods inserted into Perspex within the XTE-CT test piece. The rods are selected to provide a variety of densities in the organic material range, with cross-sectional scans captured both within the Perspex where the rods are completely surrounded by Perspex (right side image in Figure 10), and also where they extrude from the Perspex and are therefore surrounded by air (left side image in Figure 10). The average Hu value of the pixels within each of the rods was determined. The rods and their corresponding densities included polypropylene (0.91 g/cm^3), acrylonitrile butadiene styrene (1.0 g/cm^3), polycarbonate (1.1 g/cm^3), peek (1.3 g/cm^3), Delrin (1.4 g/cm^3), Delrin AF (1.5 g/cm^3), chlorinated PVC (1.5 g/cm^3), polyvinylidene fluoride (1.75 g/cm^3), Teflon (2.2 g/cm^3), and the scattering plate consisted of Perspex (1.2 g/cm^3).

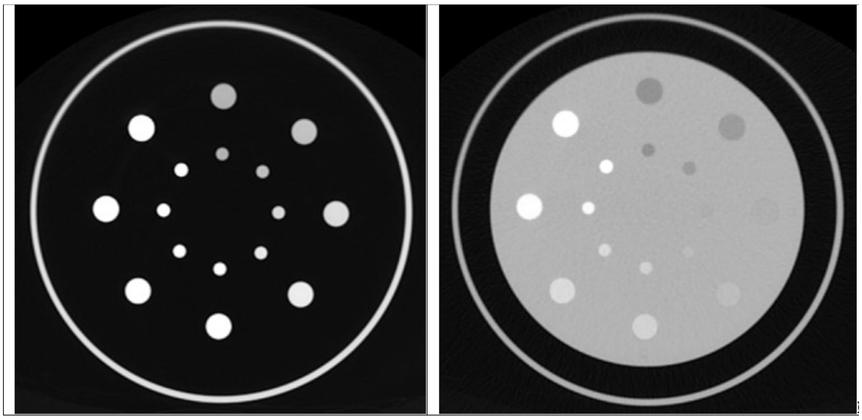


Figure 10. The rods of varying density embedded in Perspex (right) and extending out of Perspex and surrounded by air (left) used in the density test.

3.6 Analysis of beef primal and carcase images

Nuctech and medical CT images of the beef primals, boxed primals and carcase components were analysed in DICOM format using ImageJ software. Medical CT images were analysed using established protocols for the differentiation of carcass lean, fat and bone tissue %. Pixels lower than -500 were determined to be air and deleted from the image sets. The pixel Hounsfield unit thresholds used to associate pixels with fat, muscle and bone were −235 to 2.3 for fat, 2.4 to 164.3 for lean and 164.3 or greater for bone. Cavalieri's method (Gundersen et al., 1988, Gundersen and Jensen, 1987) was used to estimate volume according to the calculation:

$Volume_{Cav}$ = ¼ d Σareag−t areamax g ¼ 1 where m is the number of CT scans taken; d is the distance between cross-sectional CT scans (5mm); 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 Hounsfield units of the pixels of each tissue was then determined and converted into density (kg/L) using a linear transformation (Mull, 1984), and combined with the volume of each tissue to determine the weight of fat, lean and bone. These weights were then expressed as a percentage of the weight of each beef primal at the time of scanning (CT fat, lean and bone %).

Nuctech CT images were qualitatively assessed using Image J software for their ability to differentiate tissue types; to differentiate bone 3-D structural geometry, and to differentiate the seams between muscles within the beef primals, with medical CT images providing a higher resolution point of comparison for tissue differentiation. Pixel value thresholds to differentiate fat, lean and bone tissues in Nuctech images were then assessed, initially by qualitative assessment of all beef primal scans. Pixel values of around 6400 appeared to give the best differentiation of fat tissue and surrounding air, though this varied from 6000 to 7000 between primals and slices within primals. Bone and lean tissue differentiation was estimated to be optimal at a pixel value of 29500, though varied between 29000 and 30000. Differentiation between fat and lean tissue appeared to be optimal at a pixel value of 26200, but again ranged from 25800 to 2670. All Nuctech CT beef primal scans were therefore analysed using fat: air thresholds of 6000, 6200, 6400, 6500, 6600 and 6800; fat: lean thresholds 25800, 26000,26100, 26200, 26300, 26500 and 26700, and lean: bone thresholds of 29000, 29200, 29400, 29500, 29600, 29800 and 30000. When testing each tissue thresholds the other two tissue thresholds were set at the estimates optimal threshold (6400, 26200 and/or 29500). After differentiating tissues in the beef primals according to these different thresholds, Cavalieri's method was used to estimate each tissue's volume (Gundersen et al., 1988, Gundersen and Jensen, 1987) and the medical CT linear density transformation (Mull, 1984) was used to determine the weight of each tissue and calculate the percentage of each tissue type in the primal (Nuctech fat, lean and bone %).

After the optimal tissue thresholds were identified by analysing the ability of the Nuctech fat, lean and bone % to predict CT fat, lean and bone %, these thresholds were applied to the boxed beef and beef carcase images qualitatively assessed the impact of scan thickness, scan duration and alternative cut of meat on the ability to differentiate tissue types via pixel thresholding.

3.7 Statistical analysis

3.7.1 XTE-CT test piece scans

For assessment of the XTE-CT test piece, where quantitative values were available, these were pooled across the 5 Nuctech CT scans captured in 3 positions. The mean, standard deviation, minimum, and maximum values across these 5 scans was then reported. This process was repeated for the 5 medical CT scans of this test piece.

3.7.2 Beef primal scans

Nuctech determined lean, fat and bone % values determined using the different tissue thresholding values were then analysed using general linear models (SAS) for their ability to predict medical CT lean, fat and bone % of each beef primal. Assessing the precision (R-squared or coefficient of variation and root mean square error or RMSE) of Nuctech CT prediction of medical CT composition allowed the optimal tissue thresholds to be defined for Nuctech images and thus the precision with which Nuctech CT scans can predict medical CT lean, fat, and bone% to be determined.

4. Results

Analysis of the XTE-CT test piece scanned by the Nuctech CT scanner and by the medical CT scanner demonstrates the resolution of the devices as well as their ability to measure and differentiate materials of differing density. Repeat scanning of the XTE-CT test piece then demonstrates the consistency of density measures and the impact of XTE-CT test piece positioning within the Nuctech CT scanner on density measures. Results section 4.1 details the results of the analysis of XTE-CT test piece images that were initially output from the Nuctech CT in December 2023. However, in February 2024 it was discovered that the Nuctech CT images had undergone an automated software scaling procedure that changed the density values of these images, particularly the consistency of density values between repeated scans and in different positions within the Nuctech field of view. Results section 4.2 of this report thus details the revised XTE-CT test piece image analysis results using raw unscaled Nuctech CT images. The scaling procedure automatically applied to the original Nuctech XTE-CT test piece images impacted on density values but did not impact the resolution, dimension and thickness tests (Section 4.1.1). As such, this section has not been revised.

4.1 XTE-CT test piece – Initial results

4.1.1 Resolution, dimension and thickness tests

The Nuctech CT demonstrated resolution that approached that of the medical CT scanner used in this study. This was demonstrated by the grid resolution test (Figure 11) which showed differentiation of the 2mm sections although not the 1mm sections, and the spatial resolution test in which the resolution was calculated to be 2.51mm (Table 4). In comparison, the medical CT scanner showed differentiation of 1mm sections within the grid resolution test (Figure 11), and a calculated resolution of 1.0mm in the spatial resolution test (Table 4). For both CT scanners these values varied little across the 5 slices where resolution was repeatedly measured, although when resolution measures were repeated in different scans the Nuctech CT scanner demonstrated greater variation in resolution (standard deviation of 0.34mm), likely due to the effect of position on the Nuctech CT scans.

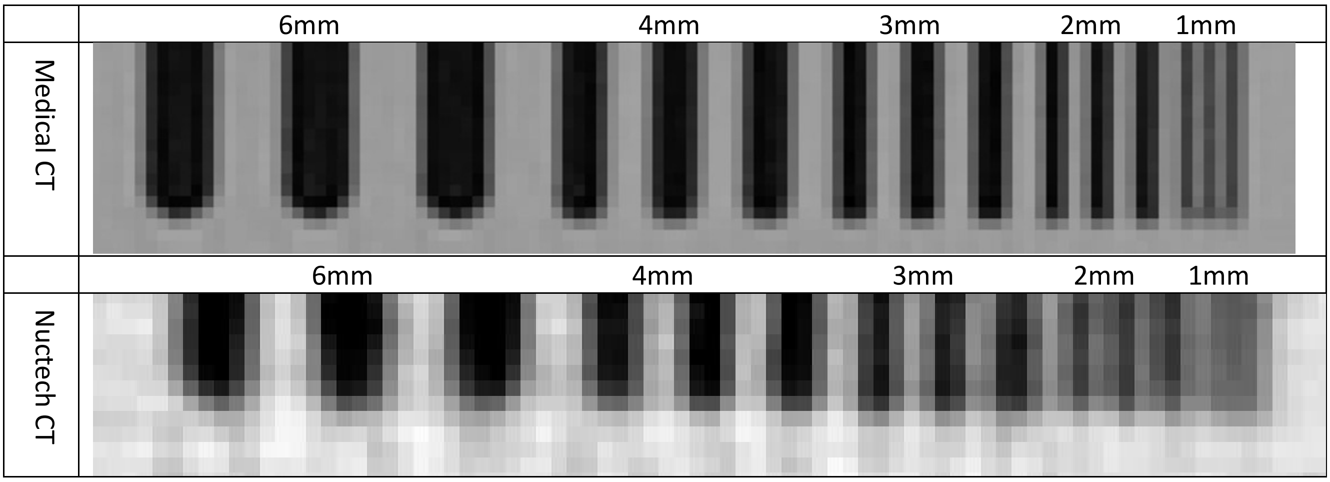


Figure 11. Grid resolution test for the medical CT and the RTT110 CT scanner, enabling qualitative comparison of resolution.

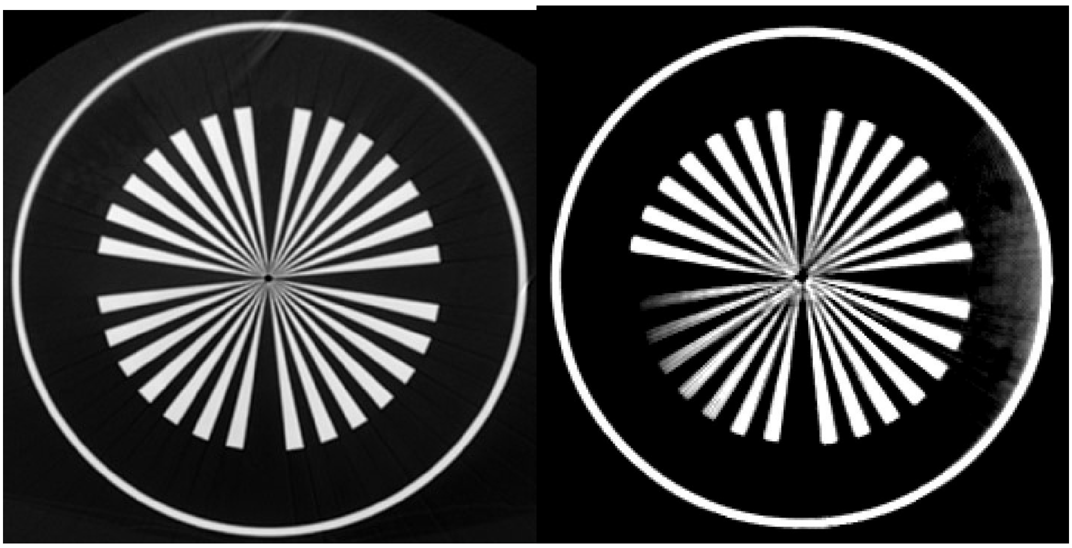


Figure 12. Images of the XTE-CT spatial resolution tests from the Medical CT scanner (left) and the Nuctech CT scanner (right).

Simple dimension measurements for both scanners were highly precise, although the Nuctech CT demonstrated some inaccuracy likely reflecting the need for scale calibration. This was demonstrated by the diameter measurement of the 200mm section which was measured with excellent repeatability across both scanners, although measured inaccurately on the Nuctech CT, with average values of only 179mm compared with measures of 201mm using the medical CT scanner (Table 4). Alternatively, the thickness measurement of a 40mm reference standard in the XTE-CT test piece, based upon the count of 1mm slice widths, was accurate and repeatable across both scanners (Table 4).

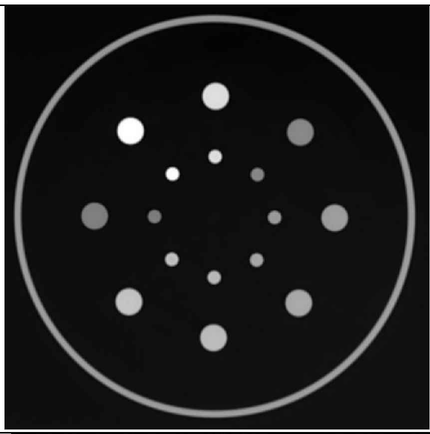
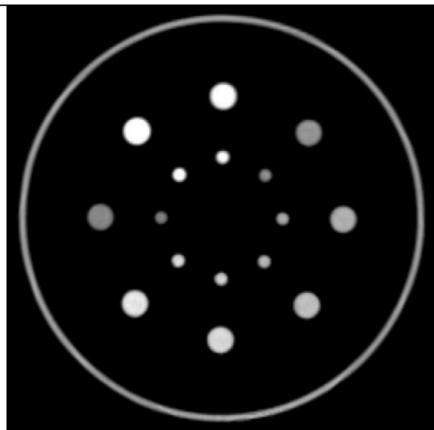
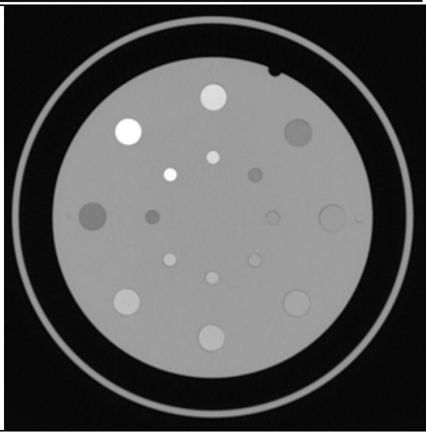
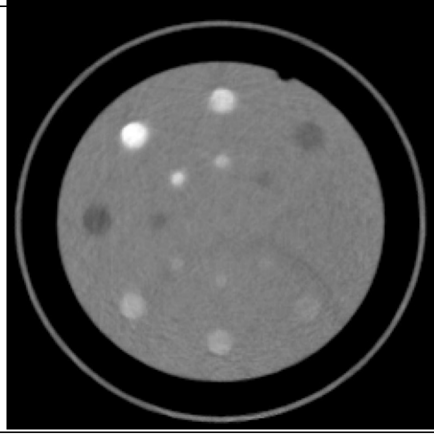
Table 4. Comparison of Medical CT and the Nuctech CT values in the spatial resolution, 200mm dimension, and 40mm thickness XTE-CT tests. Values shown are the mean, minimum, maximum, and standard deviation of test values captured across 5 separate scans of the XTE-CT test piece**. Given the difficulty replicating position in repeated Nuctech CT scans of the XTE-CT** test piece **the spatial resolution values are also shown for 5 cross-sectional slices within 1 scan of the XTE-CT test piece.**

	Mean	Minimum	Maximum	Standard deviation
	Spatial resolution test (mm)			
Medical CT	1.00	0.92	1.11	0.07
Nuctech				
In 5 slices of 1 scan	1.92	1.60	2.06	0.22
In 5 scans in Position 3	2.51	2.12	3.07	0.34
	Simple 200mm dimension test (pixels)			
Medical CT	201	200	202	0.64
Nuctech	179	178	180	0.68
	Thickness test (resolution limited to count of 1mm or 1.33 mm slice widths)			
Medical CT	41.00	41.00	41.00	0.00
Nuctech	40.17	39.90	41.23	0.56

4.1.2 Density tests

The analysis of materials with varying densities within the XTE-CT test piece demonstrated marked differences in reported HU values for these materials, but also marked differences between the Nuctech CT and the medical CT scanners (Table 5). This reflects that the Nuctech CT is calibrated across a different Hu value range compared to the medical CT. None-the-less, the Nuctech CT scan values demonstrated a strongly linear association with increasing density of the plastic materials when surrounded by air (Figure 13) in the XTE-CT test piece, that was maintained when these materials were embedded within Perspex (Figure 14), with this association closely matching medical CT values of the same materials (Figures 13 and 14).

Table 5. Images of the density tests from the XTE CT test piece taken using a Medical CT scanner and the Nuctech CT scanner. Images on the left show plastics of different densities surrounded by air, while images on the right show the same plastic rods surrounded by Perspex.

	Medical CT	Nuctech CT
Density in air test		
Density in Perspex test		

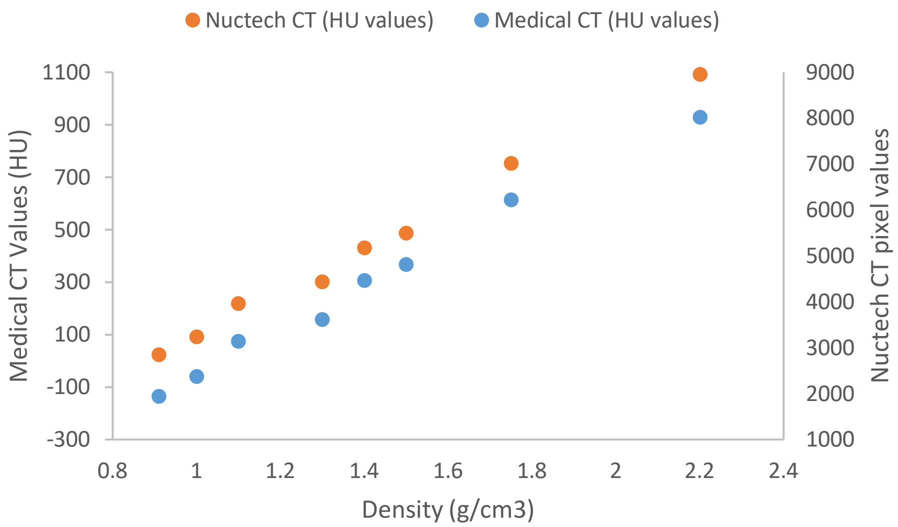


Figure 13. Hounsfield unit (HU) values for the medical CT scanner (left vertical axis, blue points) and pixel values for the Nuctech CT scanner (right vertical axis, orange points) across the density of materials surrounded by air in the XTE-CT test piece.

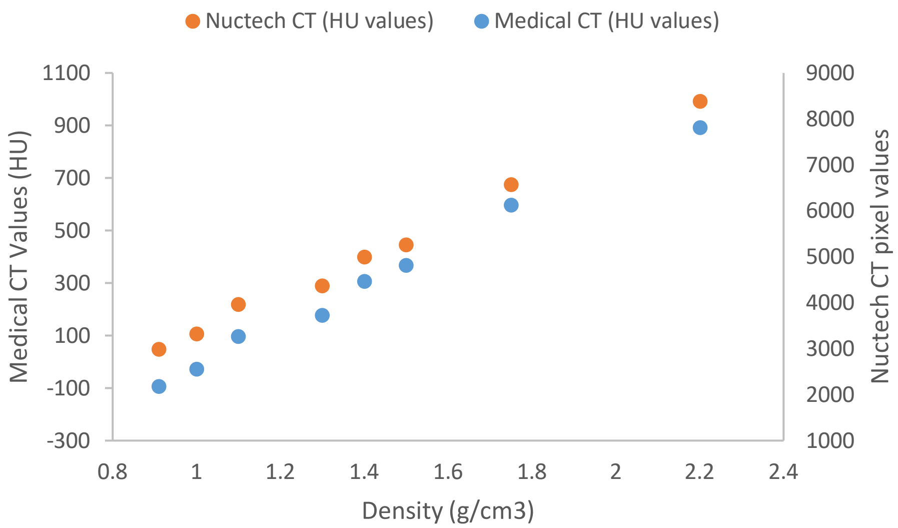


Figure 1. Hounsfield unit (HU) values for the medical CT scanner (left vertical axis, blue points) and pixel values for the Nuctech CT scanner (right vertical axis, orange points) across the density of materials embedded in Perspex in the XTE-CT test piece.

4.1.3 Repeatability of the density tests

The variability in the Hu value of each of the plastic rods in the XTE-CT density test measured by the Medical CT and Nuctech CT are shown in Table 6. This table captures the variability in the Hu values (minimum, maximum and standard deviation) between repeated XTE-CT test piece scans in the same position of the medical CT and Nuctech CT scanners, as well as the variability in Hu values between repeated CT slice measures of a single Nuctech XTE-CT test piece scan. This is a more accurate reflection of Hu variation in the Nuctech CT images, given that repeat Nuctech CT scanning of the XTE-CT test piece involves repositioning of the test piece for each scan. Therefore the exact position of the test piece is very difficult to exactly replicate and thus the Hu value variability of 5 different Nuctech CT scans will capture some positioning effects. In contrast, during medical CT scanning the test piece is fixed in 1 position on a bed or table that moves back and forth into the aperture for repeat scanning. This means that unlike Nuctech CT scans, repeat Medical CT scans can maintain the exact same positioning which improves the repeatability of results. The positioning of the XTE-CT test piece for repeated scans through the Nuctech CT scanner in positions 2, 3 and 4 is shown in Figure 15. The variation in pixel values within the area selected (156 or 52 pixels) in a single CT slice measurement is also shown in Table 6.

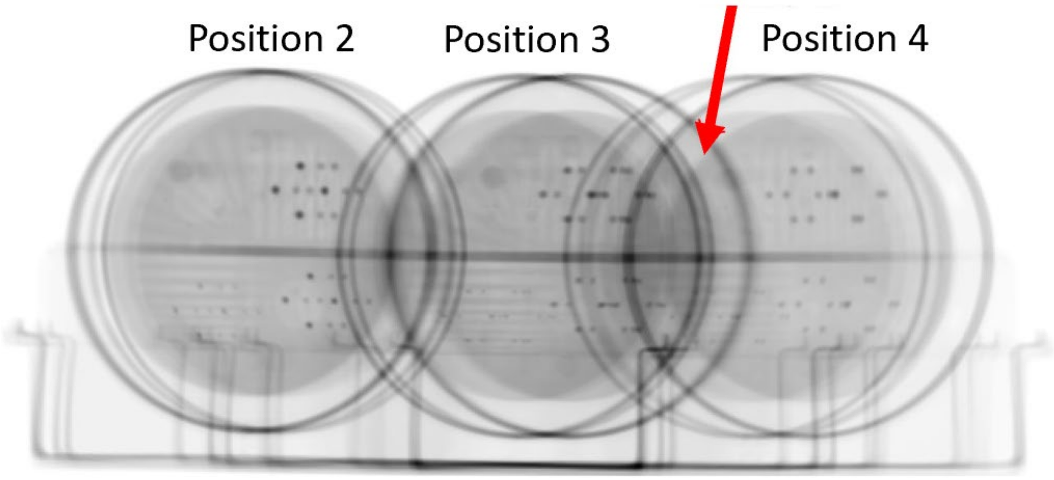


Figure 2. Nuctech CT Z projection demonstrating the positioning of the XTE-CT test piece (circle shape) in the 5 repeated scans of the test piece in positions 2, 3 and 4. The circles should perfectly overlay one another if the positioning was exactly the same in each repeat scan. The test piece scan identified by the red arrow was supposed to be in position 4, therefore was excluded from the repeatability analysis.

Table 6. A comparison of the Hounsfield units and pixel values of materials of differing density in the XTE-CT test piece scanned by the medical CT and Nuctech scanner (scaled images). The average Hu values are shown between 5 slices of 5 repeated XTE-CT test piece scans, in addition to within 5 slices of 1 Nuctech XTE-CT test piece scan given the difficulty replicating scan position precisely in this system. A 156 pixels region of interest was used for each medical CT image measure, while only 52 pixels could be clearly identified to measure in Nuctech CT images. Values are the mean, minimum, maximum and standard deviation (SD) of those 5 measurements. The "SD of pixels" is the standard deviation of the 156 or 52 pixels, with the value representing the mean of these 5 standard deviation values.

	Medical CT HU (5 slices x 5 scans, same position)					Nuctech CT pixel values (5 slices x 5 scans, ~ same position)					Nuctech CT pixel values (5 slices, 1 scan)				
Material in air	Mean	Min	Max	SD	SD of pixels	Mean	Min	Max	SD	SD of pixels	Mean	Min	Max	SD	SD of pixels
Polypropylene	-135	-142	-120	8.71	7.42	2838	2488	3279	279.2	110.6	2741	2733	2751	8.51	91.25
ABS	-60	-70	-53	7.00	6.66	3237	2852	3647	280.55	114.8	3102	3096	3112	6.67	111.00
Polycarbonate	75	63	87	10.41	6.30	3956	3543	4470	335.1	121.7	3807	3801	3813	5.35	99.02
Peek	156	144	166	7.94	5.95	4427	3959	4972	370.3	139.6	4272	4259	4282	8.75	96.62
Delrin	305	297	316	7.58	6.34	5171	4615	5795	417.1	127.4	4976	4964	4995	12.54	98.69
Delrin AF	366	354	375	10.68	7.04	5495	4911	6105	430.5	177.5	5305	5258	5327	27.65	134.77
PVDF	613	587	643	26.43	12.36	7018	6287	7793	516.5	251.6	6777	6764	6787	10.28	156.05
Teflon	928	891	977	44.36	20.66	8949	8120	9834	648.5	272.1	8725	8699	8753	19.71	164.83
Material in Perspex															
Polypropylene	-94	-100	-81	7.94	12.95	2988	2589	3464	300.5	104.18	2804	2793	2810	7.51	120.30
ABS	-28	-39	-15	8.40	11.44	3327	2932	3710	288.4	108.84	3183	3162	3212	18.62	108.46
Polycarbonate	97	83	110	9.76	10.82	3959	3510	4511	337.7	110.08	3779	3739	3800	24.26	111.71
Peek	176	161	184	9.76	9.86	4365	3844	5171	394.6	113.61	4106	4083	4132	20.80	89.83
Delrin	307	300	313	5.13	11.53	4990	4383	5670	436.4	123.95	4738	4693	4797	48.27	108.99
Delrin AF	367	360	374	4.84	11.82	5253	4596	5984	439.8	145.84	5043	5009	5070	25.30	162.70
PVDF	597	573	619	17.98	14.33	6563	5858	7339	507.1	204.67	6580	6550	6597	19.82	205.97
Teflon	891	848	947	37.15	16.05	8383	7357	9372	717.25	237.65	8172	8125	8237	53.29	256.09

4.1.4 The impact of Nuctech scan position on the density tests

When the effect of scanning position within the Nuctech CT aperture was tested there were marked differences identified. Moving from scanning position 1, through to scanning position 5 there was initially a general downward trend in HU values from position 1 – 3, which then rebounded from 3 – 5 (Figure 16). There was relatively little difference between the lower and upper regions of the field of view. This trend was evident across all materials in the test piece (Table 7).

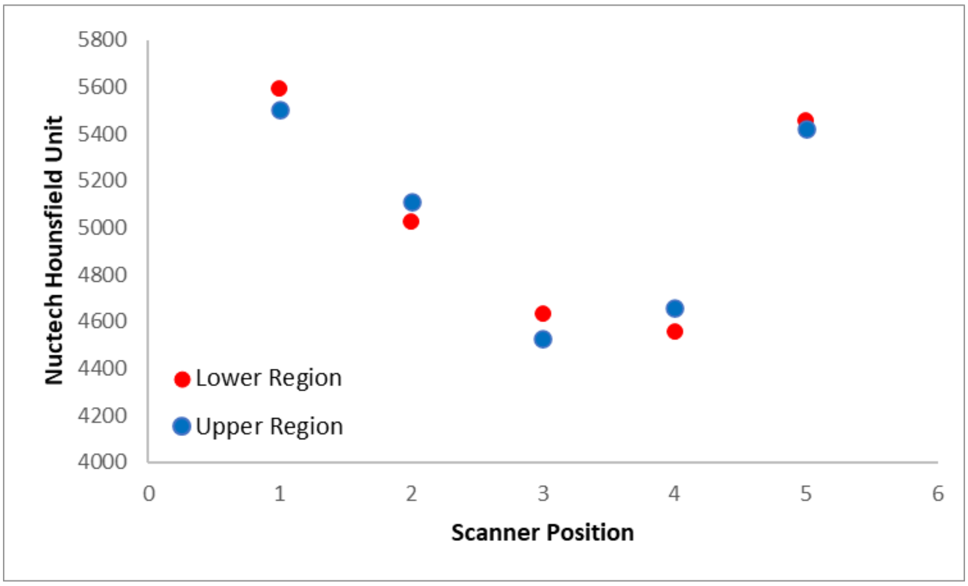


Figure 3. Pixel values for the Nuctech CT, captured within the upper and lower regions of the scanning field of view, and across 5 horizontal positions. Values represented are the mean value of all materials tested with the XTE-CT test piece.

Nuctech XTE-CT test piece density measures were most repeatable in the centre of the field of view, as demonstrated by the lower standard deviation in Hu values in position 3, while position 4 demonstrated higher variability in Hu values and thereby lower repeatability (Table 7). This is likely related to the exact positioning of the repeat XTE-CT test piece scans, which were difficult to exactly replicate when the XTE needed to be manually repositioned for each repeat scan. The positioning of the repeat XTE-CT test piece scans measured in Table 7 is shown in Figure 15. Despite the scan identified by the red arrow in Figure 15 being excluded from the analysis due to mispositioning (was supposed to be in position 4), there remains more variability in the test piece location in position 4, which likely underpins the increased hu value variability in this position (Table 7).

Table 7. Mean, min, max and standard deviation of Nuctech CT pixel values taken from 5 cross-sectional slices from 5 separate scans (total 25 values) for the 8 plastics of differing densities in the XTE-CT test piece. In addition, there were 4 resolution measurements taken from 5 separate scans (totalling 20 values). These scans were all acquired at 3 separate scanning positions –positions 2, 3, and 4 (lower).

		Nuctech CT scan Position 2 pixel values				Nuctech CT scan Position 3 pixel values				Nuctech CT scan Position 4 pixel values			
Material		Mean	Min	Max	Standard deviation	Mean	Min	Max	Standard deviation	Mean	Min	Max	Standard deviation
Polypropylene	In Air	2820	2751	2898	68.19	2694	2666	2741	29.89	2983	2648	3220	233.42
ABS	In Air	3287	3181	3377	79.17	3083	3051	3120	30.54	3381	3039	3580	243.29
Polycarbonate	In Air	4004	3890	4085	79.24	3786	3737	3811	31.41	4124	3751	4373	298.46
Peek	In Air	4456	4346	4542	83.42	4196	4137	4272	48.71	4588	4163	4836	306.62
Delrin	In Air	5170	5002	5285	104.48	4897	4792	4976	66.88	5350	4834	5685	371.92
Delrin AF	In Air	5465	5358	5579	82.73	5217	5108	5305	70.70	5680	5185	5972	344.94
PVDF	In Air	7119	6952	7268	119.97	6712	6596	6777	69.44	7287	6660	7632	441.49
Teflon	In Air	8995	8797	9235	194.39	8593	8475	8725	106.09	9350	8509	9756	554.53
Polypropylene	In Perspex	2925	2825	3071	107.17	2787	2752	2832	31.27	3125	2809	3350	235.26
ABS	In Perspex	3355	3253	3403	60.48	3128	2961	3218	107.15	3465	3132	3688	251.20
Polycarbonate	In Perspex	3990	3898	4073	68.92	3763	3647	3811	66.59	4126	3709	4375	296.76
Peek	In Perspex	4390	4231	4492	102.18	4119	4091	4154	29.78	4498	3939	4851	384.33
Delrin	In Perspex	4900	4822	5002	82.32	4698	4611	4740	57.19	5119	4553	5439	370.46
Delrin AF	In Perspex	5144	5038	5366	133.90	4980	4925	5043	48.23	5488	4904	5795	381.26
PVDF	In Perspex	6693	6575	6737	69.78	6366	6258	6580	129.56	6892	6274	7261	419.28
Teflon	In Perspex	8386	8062	8646	222.44	7980	7873	8172	117.78	8755	7922	9294	554.28
Spatial resolution test (mm)		2.28	1.95	2.56	0.22	2.02	1.92	2.13	0.09	2.41	2.27	2.59	0.14

4.2 XTE-CT test piece – Revised results

4.2.1 Density tests – Revised results

The revised analysis of the XTE-CT test piece scans showed that materials with varying densities within the XTE-CT test piece again demonstrated marked differences in reported HU values, but also marked differences between the Nuctech CT and the medical CT scanners (Table 5). This reflects that the Nuctech CT is calibrated across a different Hu value range compared to the medical CT. None-the-less, the Nuctech CT scan values continued to demonstrate a strong linear association with increasing density of the plastic materials when surrounded by air (Figure 17) in the XTE-CT test piece, and when materials were embedded within Perspex (Figure 18), with this association closely matching medical CT values of the same materials (Figures 17 and 18).

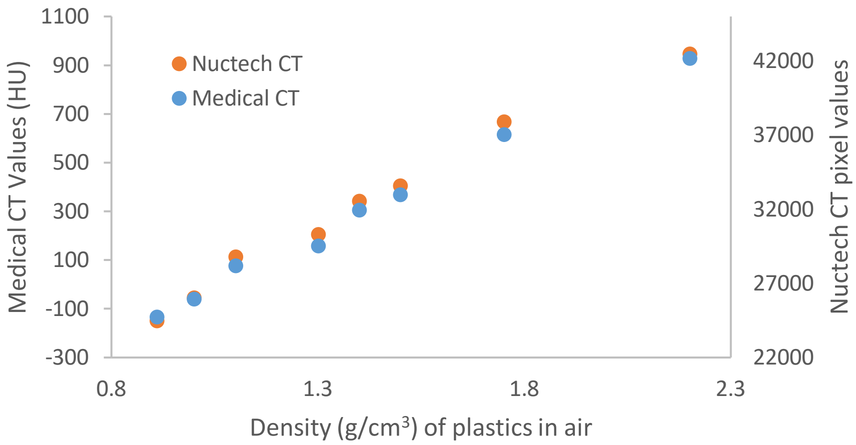


Figure 17. Medical CT Hounsfield units (HU) (left vertical axis, blue points), and Nuctech CT pixel values from raw unscaled images (right vertical axis, orange points) versus the density of materials surrounded by air in the XTE-CT test piece.

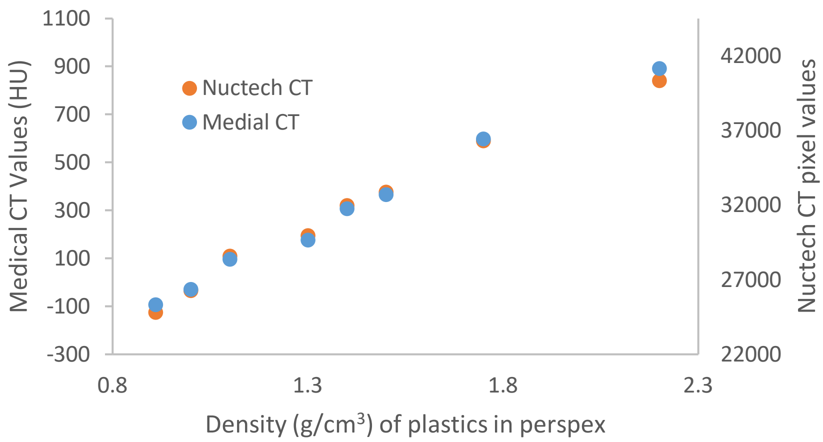


Figure 4. Medical CT Hounsfield units (HU) (left vertical axis, blue points), and Nuctech CT pixel values from raw unscaled images (right vertical axis, orange points) versus the density of materials embedded within Perspex in the XTE-CT test piece.

4.2.2 Repeatability of the density tests – Revised results

The variability in the Hu or pixel value of each plastic rod in the XTE-CT density test measured by the Medical CT and raw images from the Nuctech CT are shown in Table 8. This table captures the variability in the Hu or pixel values (minimum, maximum and standard deviation) between repeated XTE-CT test piece scans in the same position in the medical CT and Nuctech CT scanners, as well as the variability in pixel values between repeated CT slice measures of a single Nuctech XTE-CT test piece scan. This single Nuctech CT scan was additionally assessed for repeatability given the lack of consistent positioning between repeated scans of the XTE-CT test piece through the Nuctech CT scanned. In the medical CT system the XTE-CT test piece is placed on a table that moves in and out of the aperture for each scan, allowing entirely consistent positioning of the XTE-CT test piece for repeated scans. In contrast, the XTE-CT is placed on a belt for scanning through the Nuctech CT, emerging out the other side, thus the XTE-CT needs to be physically moved back onto the belt for each repeated scan. The exact position of the XTE-CT test piece in the aperture is thus very difficult to exactly replicate compared to the medical CT, and the pixel value variability of 5 different Nuctech CT scans will capture some positioning effects. In contrast, during medical CT scanning the test piece is fixed in the exact same position on a bed or table that moves back and forth into the aperture for repeat scanning. This means that unlike Nuctech CT scans, repeat Medical CT scans can maintain the exact same positioning which improves the repeatability of results. The positioning of the XTE-CT test piece for repeated scans through the Nuctech CT scanner in positions 2, 3 and 4 is shown in Figure 15. The variation in pixel values within the area selected (156 or 52 pixels) in a single CT slice measurement is also shown in Table 8.

This analysis of the raw Nuctech CT images greatly improved the repeatability of Nuctech XTE-CT density values, though the variability values in Table 8 appear higher than previous results (Table 6) due simply to the removal of the scaling factor. Additionally, there was no longer a position effect on raw unscaled Nuctech CT images, therefore there is minimal difference between the repeatability of the XTE-CT in 5 repeat scans in the same position or in 5 slices of a single scan (Table 8). The lack of positioning effect greatly reduced the variability (standard deviation) in mean pixel values for each material, which are thereby now smaller than the “SD of pixels” or the variability in pixel values between pixels of the same material within the 52 pixel measurement area in a single image slice (Table 8). The coefficient of variation (CV) has been included in this table which allows the direct comparison of variation in the medical CT against the Nuctech CT despite the differing scale of each system’s pixel value outputs. The CV values show that the Nuctech CT device is producing less variability in the pixel values of each material within the XTE-CT test piece across repeated scans. In this test piece each material is very homogenous in its composition and density and thus should have produced consistent pixel values of minimal variability. This contrasts with animal tissue where each pixel represents a differing mixture of tissue types of differing density and thus variability in pixel values is inherent and expected.

Table 8. A comparison of medical CT pixel Hounsfield units and Nuctech CT pixel values of materials of differing density in the XTE-CT test piece. The mean pixel values are from 5 slices of 5 repeated XTE-CT scans, in addition to within 5 slices of a single Nuctech CT XTE-CT scan given the difficulty replicating scan position precisely in this system. A 156 pixel region of each material was used for each medical CT image measure, while only 52 pixels could be clearly identified to measure in Nuctech CT images. Values are the mean, minimum, maximum, standard deviation (SD) and coefficient of variation (CV) of those 5 measurements. The "SD of pixels" is the standard deviation of the 156 or 52 pixel area measured within a single image slice, with the value representing the mean of SD values from 5 slices. These are revised results using raw unscaled Nuctech CT images.

	Medical CT HU (5 slices x 5 scans, same position)						Nuctech CT pixel (5 slices, 1 scan, approx. same position)						Nuctech CT pixel (5 slices, 1 scan)				
Material in air	Mean	Min	Max	SD	CV	SD of pixels	Mean	Min	Max	SD	CV	SD of pixels	Mean	Min	Max	SD	SD of pixels
Polypropylene	-135	-142	-120	8.71	6.45	7.42	24466	24180	24597	93.44	0.38	348.21	24552	24507	24597	42.57	356.64
ABS	-60	-70	-53	7.00	11.67	6.66	26030	25903	26133	56.63	0.22	390.11	26083	26031	26128	46.58	336.92
Polycarbonate	75	63	87	10.41	13.88	6.30	28754	28617	28854	64.73	0.23	281.21	28764	28745	28795	19.37	274.52
Peek	156	144	166	7.94	5.09	5.95	30264	30199	30310	35.81	0.12	259.66	30241	30199	30279	32.51	275.64
Delrin	305	297	316	7.58	2.49	6.34	32550	32447	32649	60.22	0.19	256.70	32598	32582	32625	16.92	245.91
Delrin AF	366	354	375	10.68	2.92	7.04	33556	33216	33679	113.09	0.34	378.00	33663	33649	33679	13.25	443.58
PVDF	613	587	643	26.43	4.31	12.36	37861	37731	38020	76.69	0.20	363.82	37835	37774	37884	51.55	413.21
Teflon	928	891	977	44.36	4.78	20.66	42464	42055	42689	146.13	0.34	371.47	42628	42565	42689	59.16	376.04
Material in Perspex																	
Polypropylene	-94	-100	-81	7.94	8.45	12.95	24823	24543	25040	122.03	0.49	493.90	24797	24707	24891	85.17	447.19
ABS	-28	-39	-15	8.40	30.00	11.44	26273	25971	26658	142.70	0.54	530.49	26245	26191	26293	41.31	475.66
Polycarbonate	97	83	110	9.76	10.06	10.82	28603	28267	29021	194.62	0.68	394.24	28484	28409	28571	58.16	437.78
Peek	176	161	184	9.76	5.55	9.86	29953	29657	30237	144.89	0.48	346.18	29766	29657	29911	106.67	366.17
Delrin	307	300	313	5.13	1.67	11.53	31982	31673	32283	175.98	0.55	374.92	32097	31905	32283	147.57	363.86
Delrin AF	367	360	374	4.84	1.32	11.82	32874	32420	33153	163.71	0.50	423.78	32903	32863	32967	42.51	447.41
PVDF	597	573	619	17.98	3.01	14.33	36303	35577	36783	360.75	0.99	819.08	36725	36659	36783	52.29	779.38
Teflon	891	848	947	37.15	4.17	16.05	40343	39700	41120	377.86	0.94	978.27	40896	40673	41120	170.19	875.07

4.2.3 The impact of Nuctech scan position on the density tests – Revised results

When raw Nuctech CT images of the XTE-CT test piece were analysed the effect of scanning position within the Nuctech CT aperture had no impact on density pixel values ($P > 0.05$). The contrasts with the previous report, where a position effect was identified, but the images had been processed through an automatic scaling procedure. The lack of position effect in the 10 positions tested is shown in Figure 19, where the scale of Nuctech pixel values in the raw images on the y-axis is equivalent to the scale of the initial results (Figure 16) where the Nuctech pixel values had undergone the automated scaling procedure.

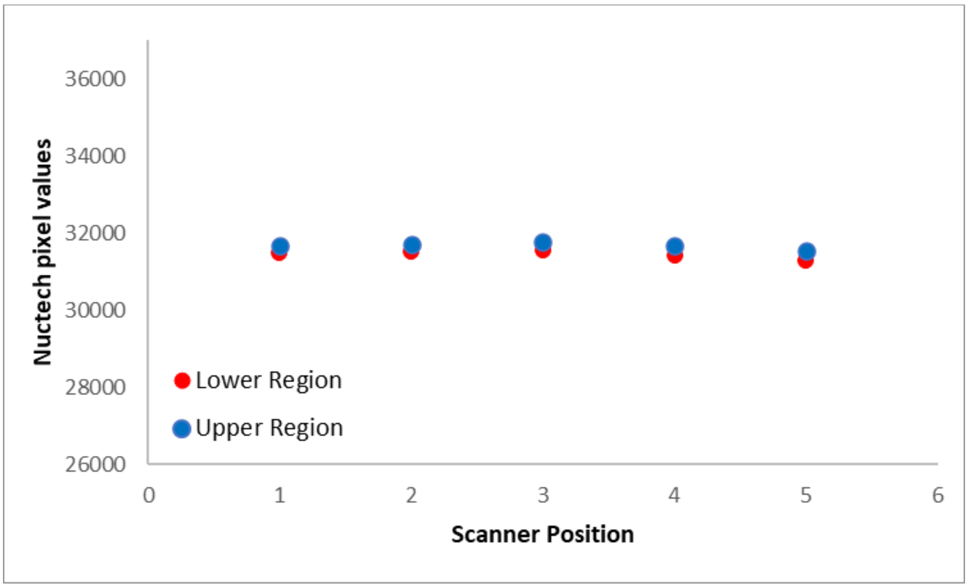


Figure 5. Pixel values of raw unscaled Nuctech CT scans of the XTE-CT test piece, captured within the upper and lower regions of the scanning field of view, across 5 horizontal positions. Points represent the mean value of all density tests with the XTE-CT test piece. Revised results using raw Nuctech CT images.

Nuctech XTE-CT density measures were highly repeatable in each position given the lack of positioning effect on pixel values (Table 9). While the mean, min, max and standard deviation of pixel values between repeated scans in each position appear higher than initially reported results (Table 7), this is due to the different scales of pixel values in these raw Nuctech CT images.

Table 9. Mean, min, max and standard deviation of pixel values taken from 5 cross-sectional slices from 5 separate scans (total 25 values) for the 8 different plastics in raw Nuctech CT scans of the XTE-CT test piece. In addition, there were 4 resolution measurements taken from 5 separate scans (totalling 20 values). These scans were all acquired at 3 separate scanning positions –positions 2, 3, and 4 (lower).

	Scan Position 2 – Pixel values				Scan Position 3 – Pixel values				Scan Position 4 – Pixel values			
Material in air	Mean	Min	Max	SD	Mean	Min	Max	SD	Mean	Min	Max	SD
Polypropylene	24333	24287	24372	32.7	24466	24396	24552	57.5	24536	24437	24627	91.5
ABS	25931	25529	26124	231.2	26030	25973	26083	38.9	25992	25923	26092	69.6
Polycarbonate	28653	28503	28750	96.1	28754	28663	28813	62.0	28606	28467	28838	142.2
Peek	30217	30160	30261	44.9	30264	30224	30296	31.7	30122	30038	30274	99.1
Delrin	32366	32247	32478	103.2	32550	32476	32624	60.3	32498	32431	32653	91.2
Delrin AF	33348	33285	33390	41.3	33556	33386	33663	107.2	33505	33433	33596	75.7
PVDF	37836	37679	38012	148.3	37861	37818	37934	44.7	37921	37812	38009	80.4
Teflon	42317	42023	42461	176.8	42464	42261	42628	134.9	42482	42333	42587	107.4
			Mean SD	109.3			Mean SD	67.1			Mean SD	94.6
Material in Perspex												
Polypropylene	24816	24586	24955	147.2	24823	24741	24877	54.8	24844	24789	24918	61.7
ABS	26476	26294	26643	147.5	26273	26083	26407	123.9	26226	25943	26339	189.6
Polycarbonate	28646	28544	28719	80.7	28603	28374	28850	183.6	28509	28399	28679	123.7
Peek	30007	29894	30103	82.4	29953	29766	30114	130.9	29843	29707	30013	126.6
Delrin	31808	31499	31926	175.8	31982	31709	32097	159.4	31837	31711	31963	102.8
Delrin AF	32411	32299	32570	111.7	32874	32739	32997	100.8	32783	32751	32821	29.3
PVDF	36125	35553	36453	350.0	36303	35738	36725	361.8	36414	35896	36722	358.6
Teflon	39491	38265	40549	853.8	40343	39835	40896	391.7	40291	40016	40628	253.3
			Mean SD	243.7			Mean SD	188.4			Mean SD	155.7
Spatial resolution test (mm)	2.28	1.95	2.56	0.22	2.02	1.92	2.13	0.09	2.41	2.27	2.59	0.14

4.3 Beef scanning

4.3.1 Beef primal composition

Bone, fat and lean tissues were well differentiated on qualitative assessment of Nuctech CT images of bone-in rib set and shortloin primals. This can be seen in the example image slices shown in Tables 12 and 13, where the equivalent medical CT image slice of the same primal is shown alongside as a direct comparison. The primals shown in these tables were selected to demonstrate the heaviest and fattest primals (Rib set 9 , shortloin 11), the lightest and leanest (Rib set 1 , shortloin 7), the lightest and fattest (Rib set 10, shortloin 12), and primals with mid-weight and fatness (Rib set 11, shortloin 1). Some muscle seams can also be visually identified in Nuctech images, though not with nearly the same clarity as medical CT images (Tables 12 and 13).

Example frequency plots of pixel values are also shown in Tables 12 and 13 to demonstrate the ability to differentiate tissue types within these images based on pixel values. In medical CT images these frequency distributions show the expected differentiation of fat and lean tissue, with separate peaks at about -60 and +60 Hounsfield unit values aligning with fat and muscle tissue, and the bone pixel values being distributed above this level. The frequency distributions of Nuctech image pixel values also demonstrate some separation into pixel value peaks corresponding to fat and lean tissue, though the separation of these peaks is more obvious in fatter primals such as short loin 11 and 12(Table 12), or rib sets 9 and 10 (Table 13), than the leaner primals. Promisingly, the values of the peaks were relatively consistent between different Nuctech primal scans, both between short loins and rib sets and between individual primals (Tables 11 and 12).

The precision with which different fat to lean thresholds in Nuctech CT images could predict CT fat and lean % are shown in Table 10. A fat: lean threshold pixel value of 26700 produced the most precise prediction of CT lean and fat% in short loins, while a threshold of 26300 produced the most precise prediction of CT lean and fat % in rib sets, though only very minor differences in precision were observed between lean: fat thresholds ranging from 26100 to 26700 HU. Similarly, only very small shifts in precision were seen with variation in the lean: bone threshold between 29000 and 30000 HU (Table 11). The precision of fat % prediction was very high and changed little when fat: air thresholds in Nuctech CT images were tested from 6000 to 7000 HU (Table 12).

Table 10. The precision (R-squared and root mean square error or RMSE) of Nuctech fat: lean pixel value thresholds predicting CT fat and lean % of beef short loins and rib sets. A lean: bone pixel threshold of 29500 was consistently applied.

Nuctech fat to lean threshold	Short loins				Rib sets			
	CT fat %		CT lean %		CT fat %		CT lean %	
	R^2	RMSE	R^2	RMSE	R^2	RMSE	R^2	RMSE
25800	0.923	1.638	0.857	2.031	0.981	0.845	0.925	1.160
26000	0.932	1.534	0.890	1.782	0.986	0.718	0.962	0.828
26100	0.937	1.484	0.903	1.673	0.987	0.681	0.971	0.721
26200	0.939	1.451	0.910	1.608	0.988	0.657	0.975	0.666
26300	0.944	1.401	0.921	1.512	0.989	0.641	0.979	0.614
26500	0.948	1.345	0.934	1.380	0.987	0.683	0.978	0.626
27000	0.949	1.332	0.943	1.279	0.980	0.855	0.966	0.783

Table 11. The precision (R-squared and root mean square error or RMSE) of Nuctech CT lean: bone pixel value thresholds predicting CT lean and bone % of beef short loins and rib sets. A fat : lean pixel threshold of 26200 was consistently applied.

Nuctech lean to bone threshold	Short loins				Rib sets			
	CT lean %		CT bone %		CT lean %		CT bone %	
	R^2	RMSE	R^2	RMSE	R^2	RMSE	R^2	RMSE
29000	0.901	1.690	0.993	0.146	0.971	0.720	0.994	0.158
29200	0.905	1.653	0.994	0.141	0.973	0.697	0.994	0.169
29400	0.909	1.619	0.994	0.140	0.975	0.675	0.992	0.188
29500	0.910	1.608	0.994	0.143	0.975	0.666	0.991	0.197
29600	0.912	1.593	0.993	0.147	0.976	0.654	0.990	0.209
29800	0.915	1.565	0.992	0.163	0.978	0.635	0.987	0.238
30000	0.918	1.539	0.989	0.186	0.979	0.619	0.983	0.272

Table 12. The precision (R-squared and root mean square error or RMSE) of Nuctech CT fat: air pixel value thresholds predicting CT fat % of beef short loins and rib sets. A fat : lean pixel threshold of 26200 was consistently applied.

Nuctech fat to air threshold	Short loins		Rib sets	
	CT fat %		CT fat %	
	R^2	RMSE	R^2	RMSE
6000	0.939	1.451	0.988	0.657
6200	0.939	1.451	0.988	0.657
6400	0.939	1.451	0.988	0.657
6500	0.939	1.453	0.988	0.657
6600	0.939	1.455	0.988	0.656
6800	0.939	1.458	0.988	0.654
7000	0.939	1.462	0.988	0.652

Based on these results, thresholds of 6400 (to differentiate fat from air); 26400 (to differentiate lean and fat); and 29200 (to differentiate lean from bone) were determined to give the most precise tissue differentiation in Nuctech CT scans of bone-in beef primals. Nuctech CT scans analysed using these thresholds were able to predict CT fat, lean and bone % of the beef short loins and rib sets with excellent precision (Fig. 20). Nuctech CT scans predicted CT bone % with the highest precision, with an R^2 of 0.994 in all primals and only slightly less error (RMSE of 0.141 bone % units) in the shortloin than in rib sets (RMSE of 0.141 bone % units). The Nuctech CT scans were also able to predict medical CT fat % and lean % with excellent precision, though rib sets were predicted with higher precision (than the short loins (Fig. 20). Images demonstrating how these thresholds differentiate tissue types in Nuctech CT scans are shown in Tables 12 and 13, along with the corresponding medical CT image of each primal cross-section, where tissues have been differentiated according to established thresholds.

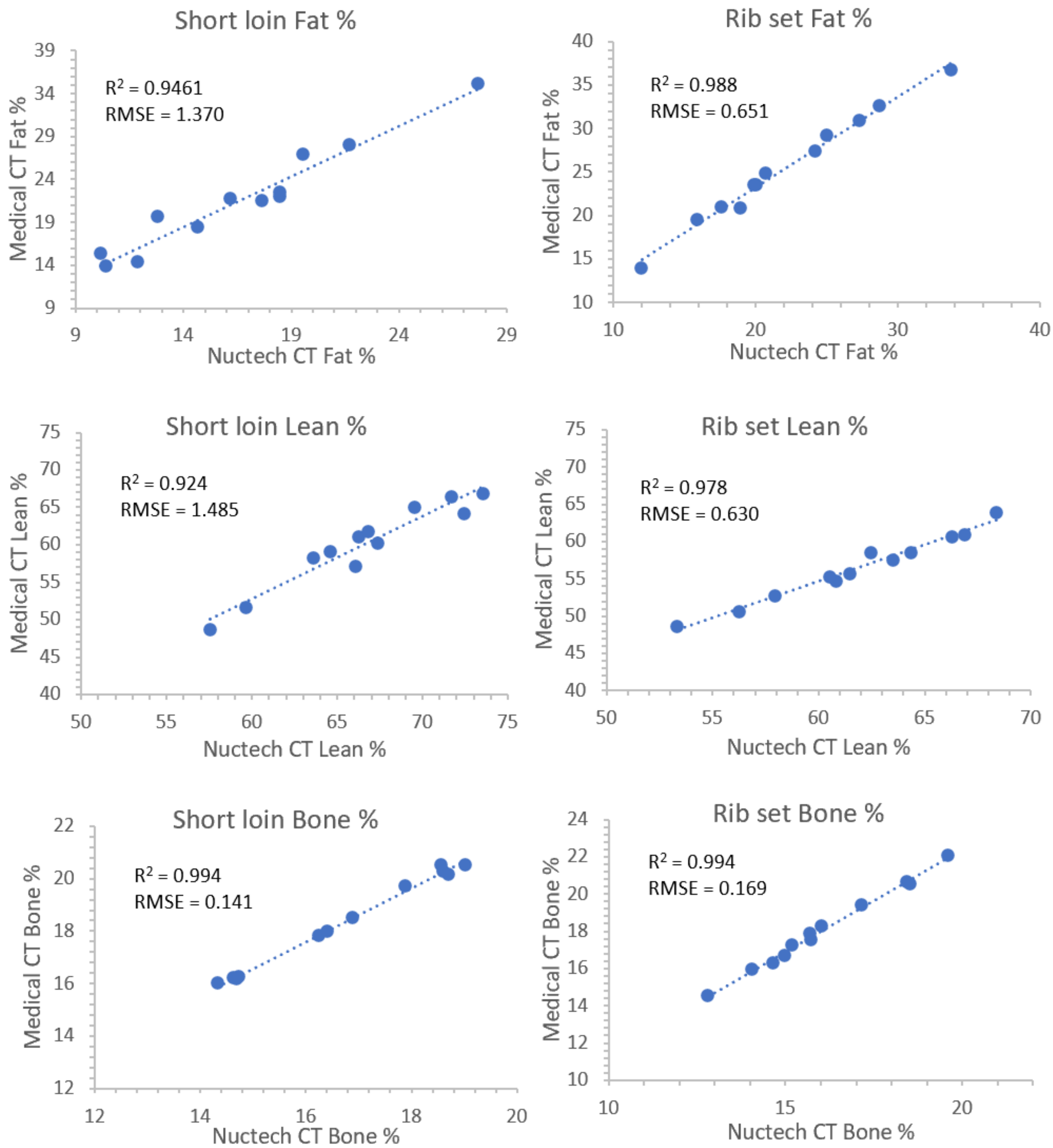
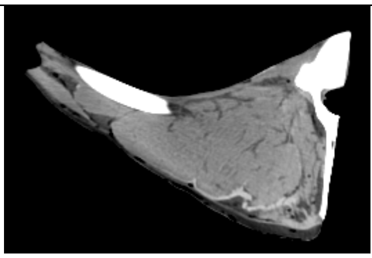


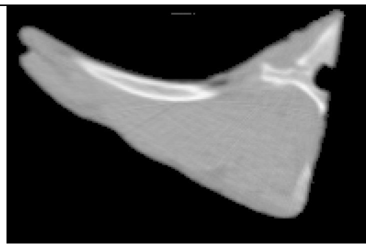
Figure 20. The relationships between Nuctech CT and medical CT estimates of bone, fat and lean % in beef short loins and rib sets. Points represent individual beef primal estimates; the line represents the line of best fit while the R^2 and root mean square error (RMSE) demonstrate the precision of each prediction.

Table 12. Example medical CT and Nuctech CT image slices of the same anatomical site in four short loin primals sourced from carcases phenotypically diverse in weight and fatness. Frequency distributions of pixel values within the selected image slices are shown, in addition to images demonstrating the thresholding of fat, lean and bone tissue in the selected slices.

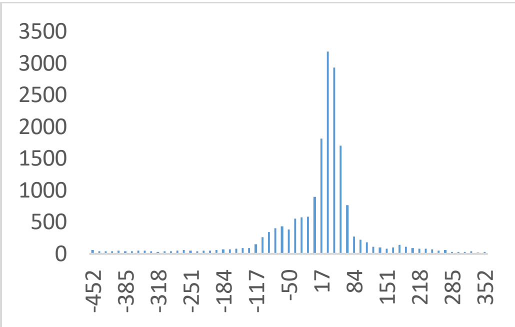
Medical CT	Nuctech CT

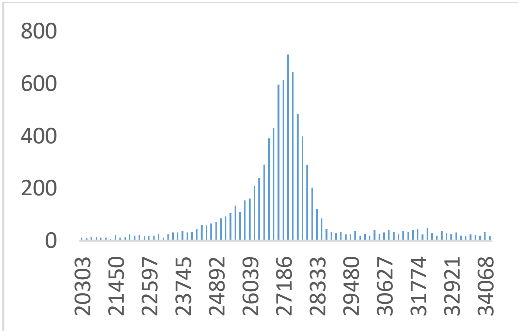
Short loin 1



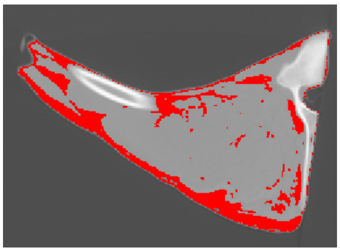


Pixel count

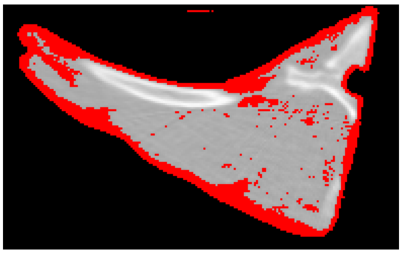




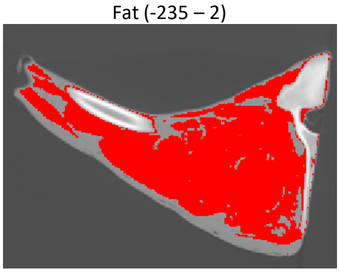
Tissue thresholding



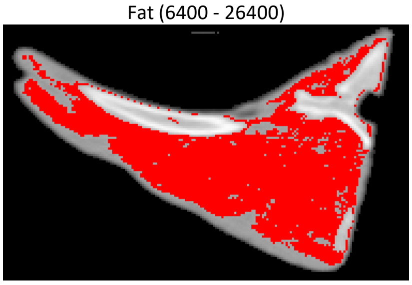
Fat (-235 – 2)



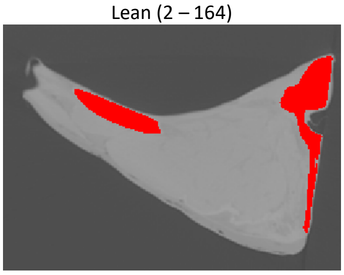
Fat (6400 - 26400)



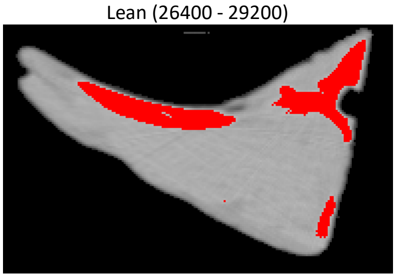
Lean (2 – 164)



Lean (26400 - 29200)

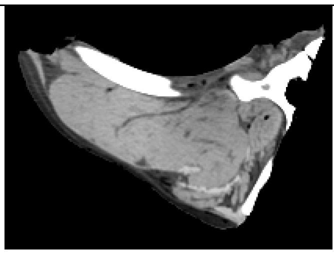


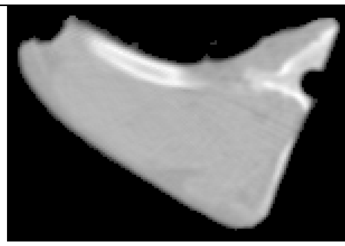
Bone (164 – 32767)



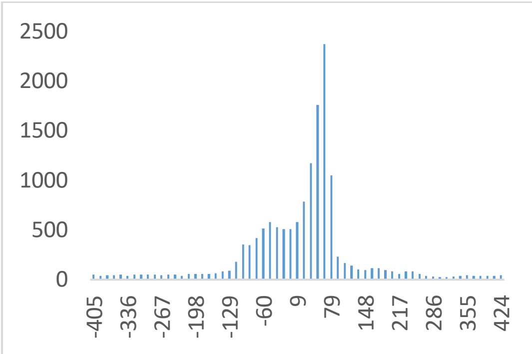
Bone (29200 – 65535)

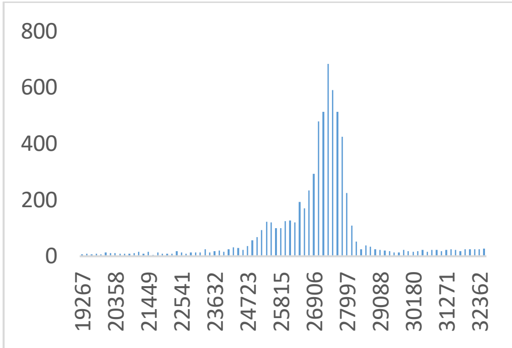
Short loin 7



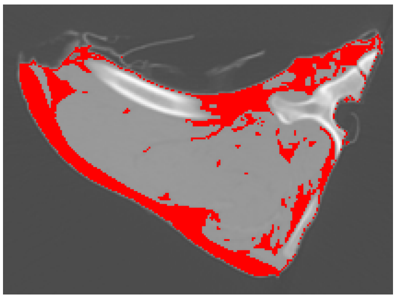


Pixel count

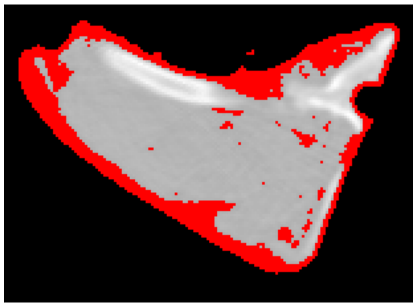




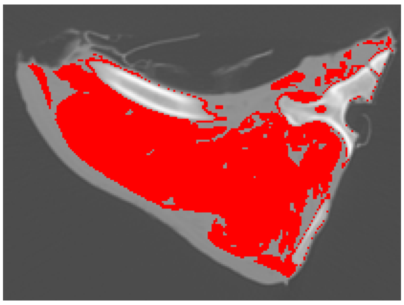
Tissue thresholding



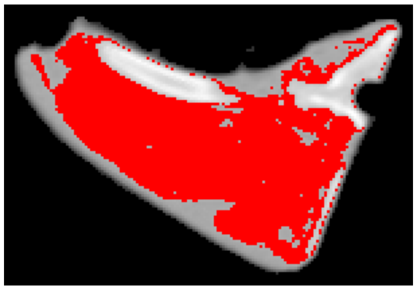
Fat (-235 – 2)



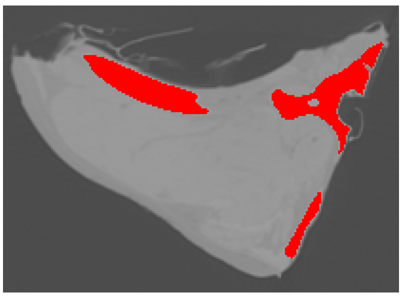
Fat (6400 - 26400)



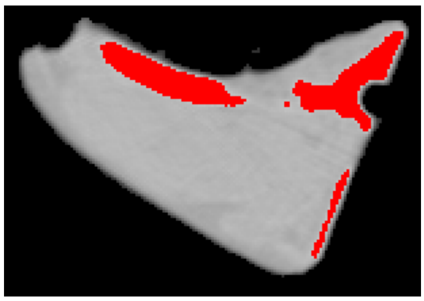
Lean (2 – 164)



Lean (26400 - 29200)

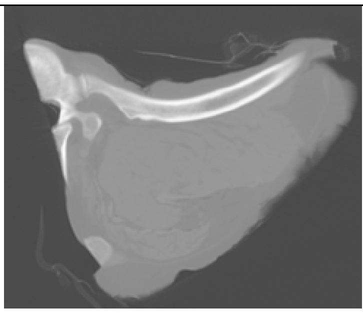


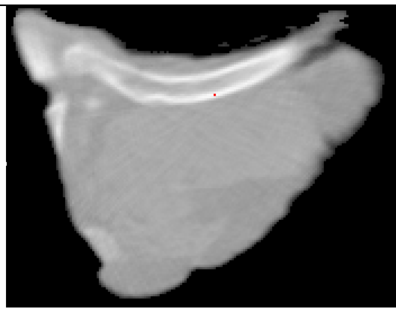
Bone (164 – 32767)



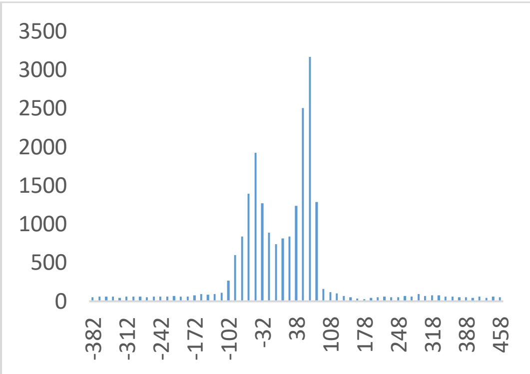
Bone (29200 – 65535)

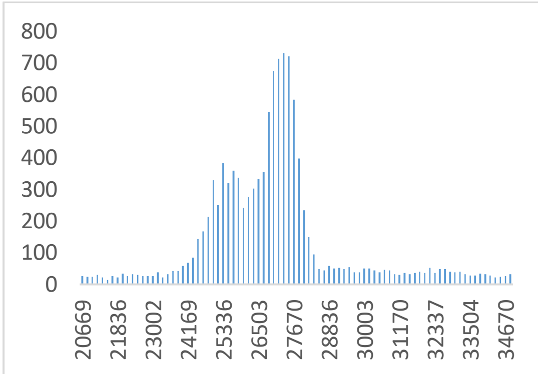
Short loin 11



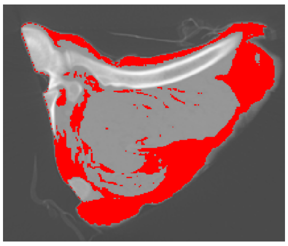


Pixel count

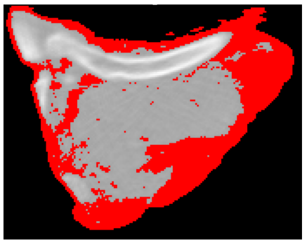




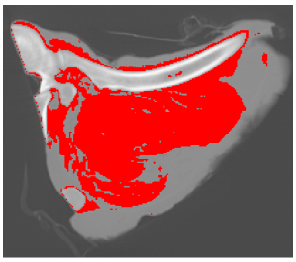
Tissue thresholding



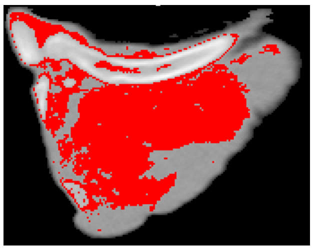
Fat (-235 – 2)



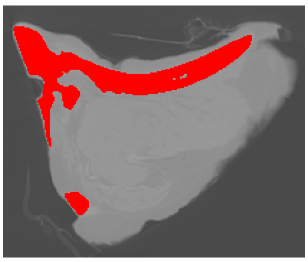
Fat (6400 - 26400)



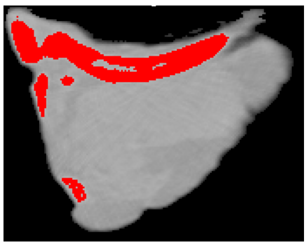
Lean (2 – 164)



Lean (26400 - 29200)

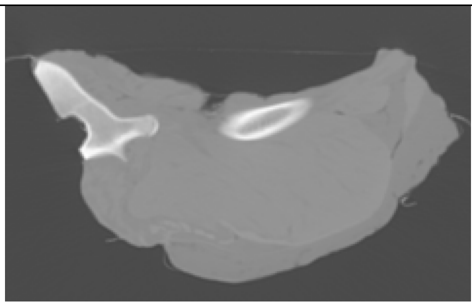


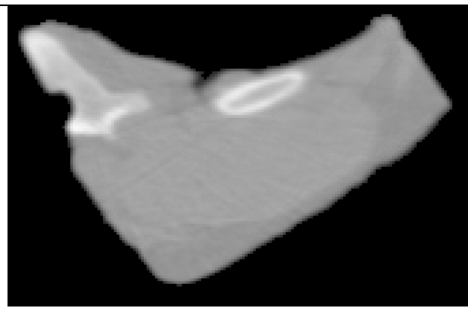
Bone (164 – 32767)



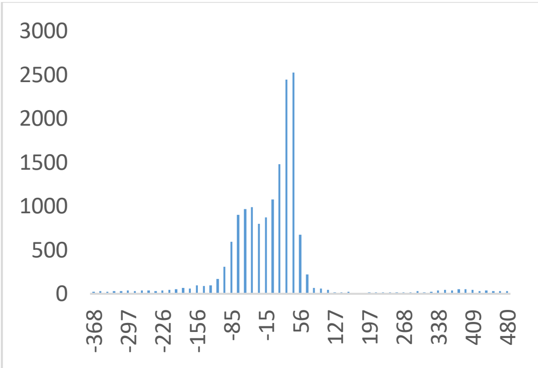
Bone (29200 - 65535)

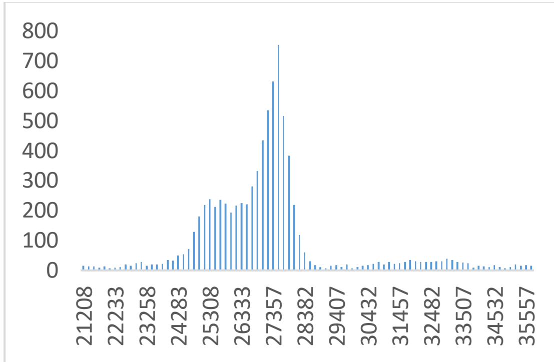
Short loin 12



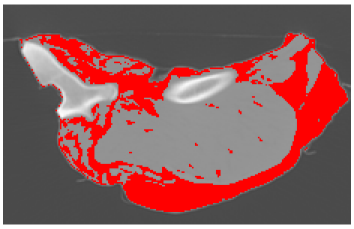


Pixel count

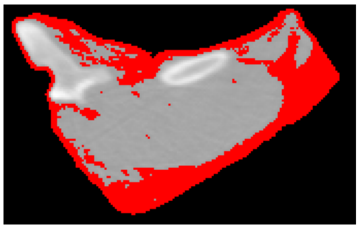




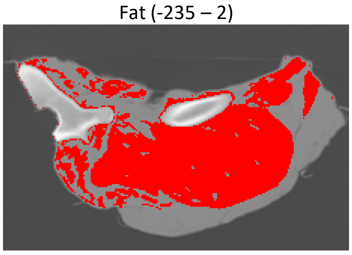
Tissue thresholding



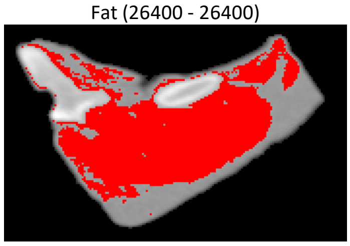
Fat (-235 – 2)



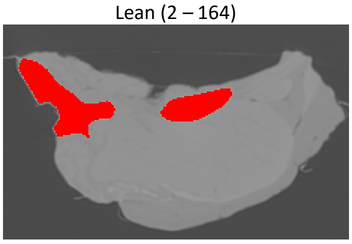
Fat (26400 - 26400)



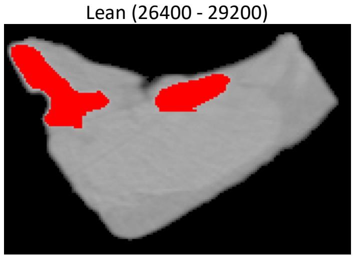
Lean (2 – 164)



Lean (26400 - 29200)

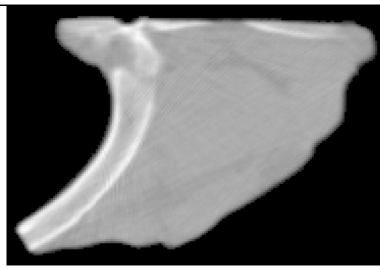
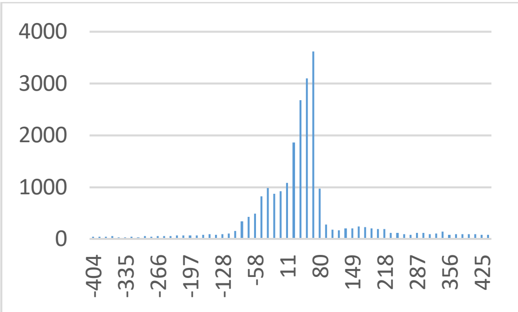
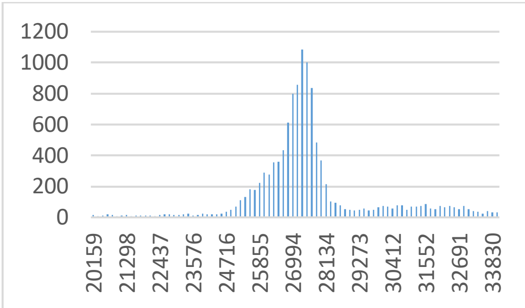
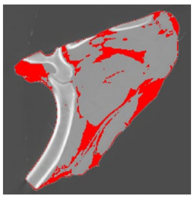
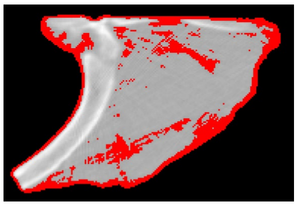
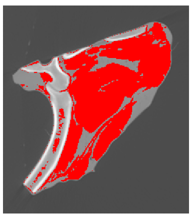
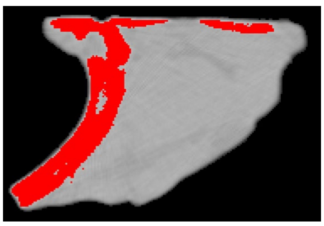


Bone (164 – 32767)

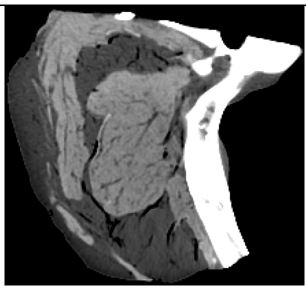


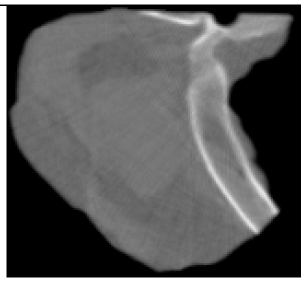
Bone (29200 – 65535)

Table 13. Example medical CT and Nuctech CT image slices of the same anatomical site in 4 rib set primals sourced from carcasses phenotypically diverse in weight and fatness. Frequency distributions of pixel values within the selected image slices are shown, in addition to images demonstrating the thresholding of fat, lean and bone tissue in the selected slices.

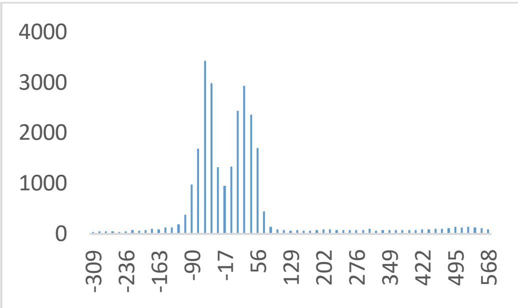
	Medical CT	Nuctech CT
	Rib set 1	
		
Pixel count		
issue thresholding	 Fat (-235 – 2)	 Fat (6400 – 26400)
	 Lean (2 – 164)	 Lean (26400 – 29200)
	 Bone (164 – 32767)	 Bone (29200 – 64535)

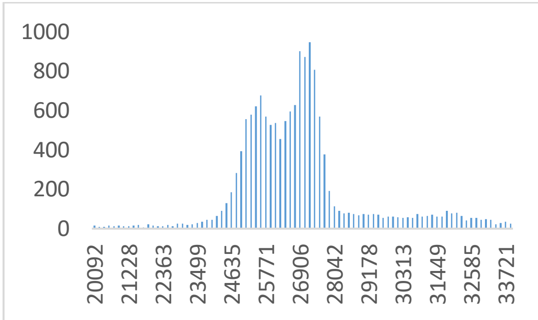
Rib set 9



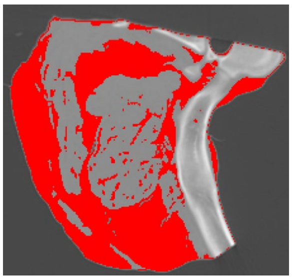


Pixel count

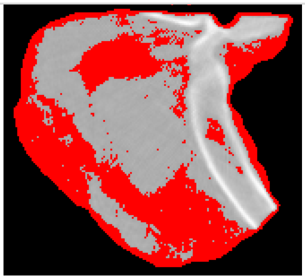




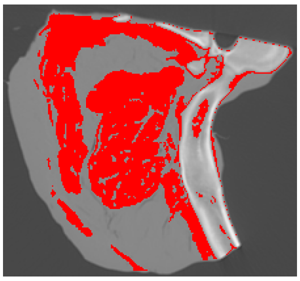
Tissue thresholding



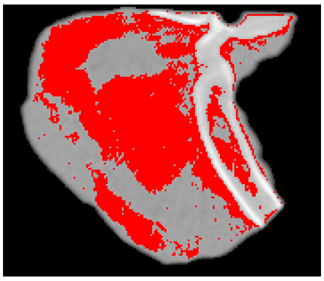
Fat (-235 – 2)



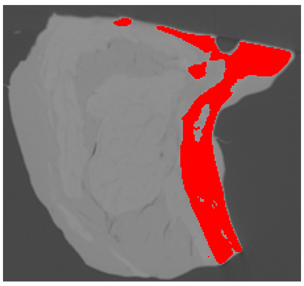
Fat (6400 – 26400)



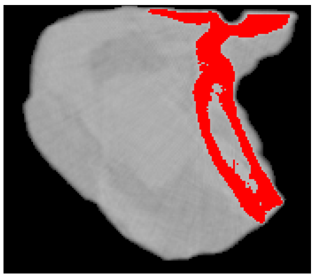
Lean (2 – 164)



Lean (26400-29200)

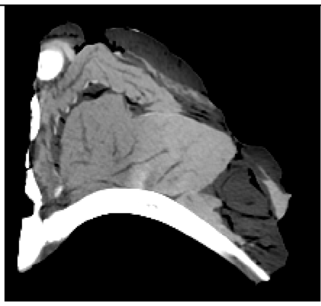


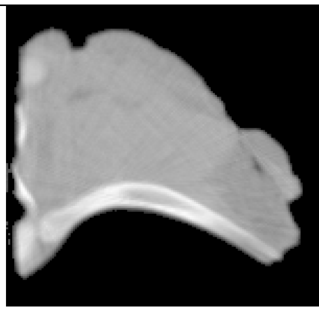
Bone (164 – 32767)



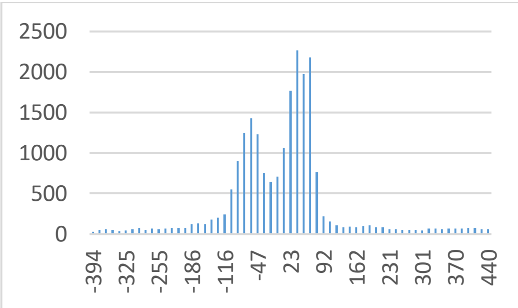
Bone (29200- 64535)

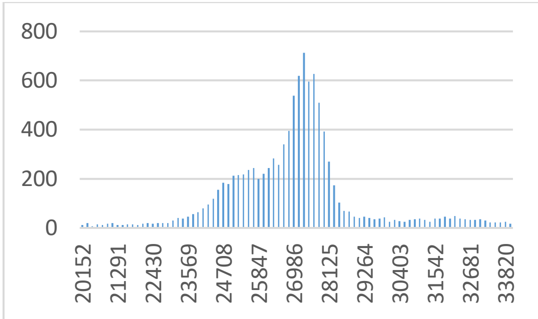
Rib set 10



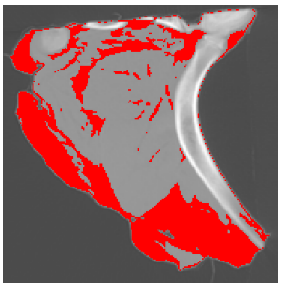


Pixel count

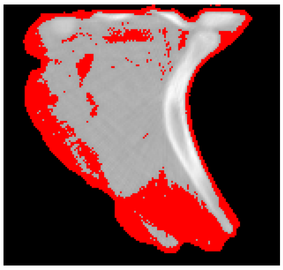




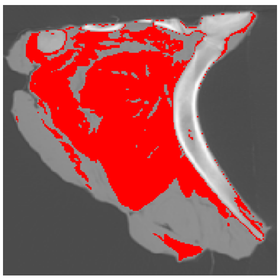
Tissue thresholding



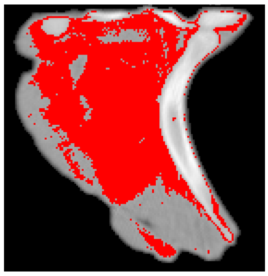
Fat (-235 – 2)



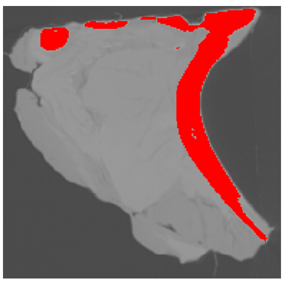
Fat (6400 – 26400)



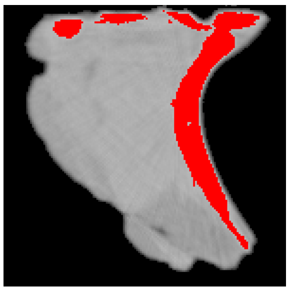
Lean (2 – 164)



Lean (26400 - 29200)

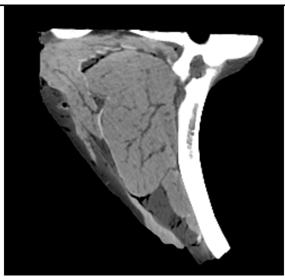


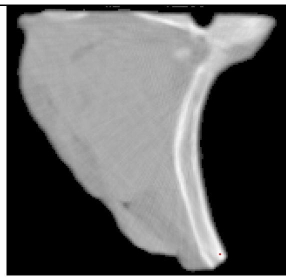
Bone (164 – 32767)



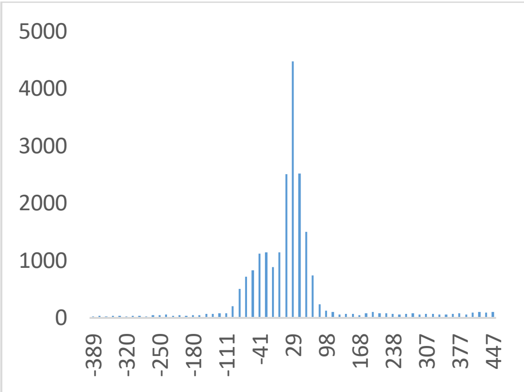
Bone (29200 – 65535)

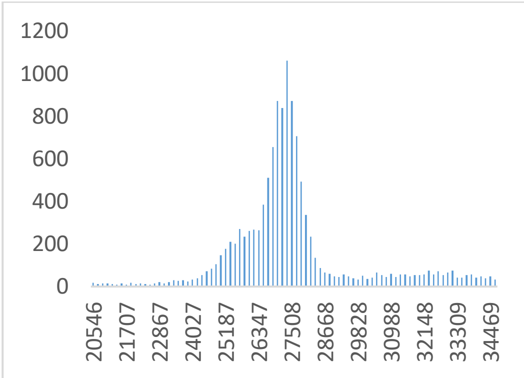
Rib set 11



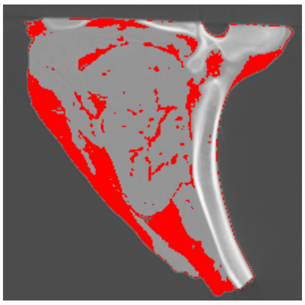


Pixel count

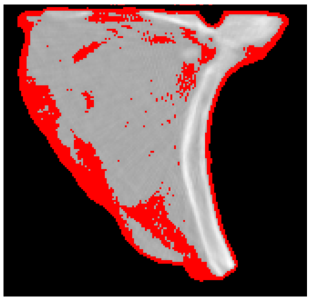




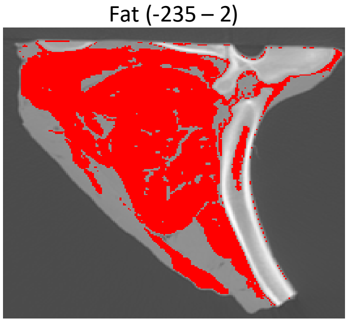
Tissue thresholding



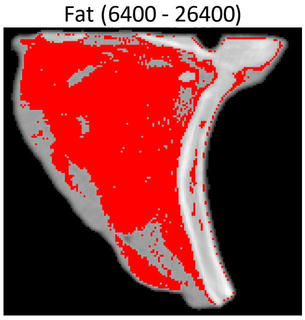
Fat (-235 – 2)



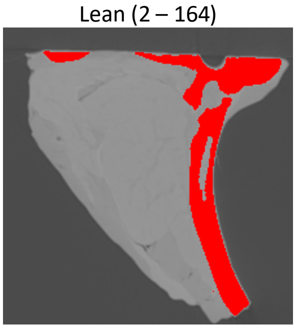
Fat (6400 - 26400)



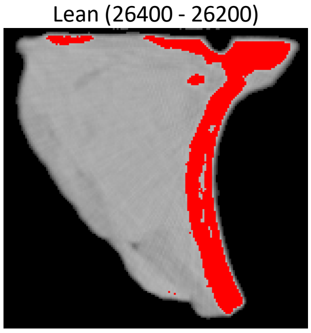
Lean (2 – 164)



Lean (26400 - 26200)



Bone (164 – 32767)



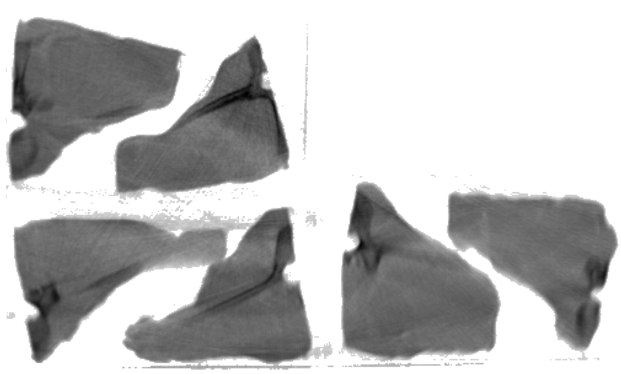
Bone (29200 – 65535)

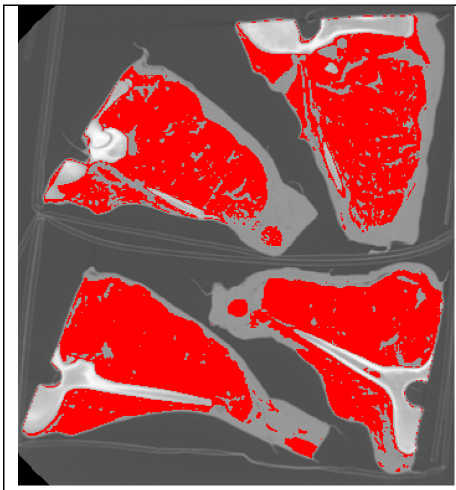
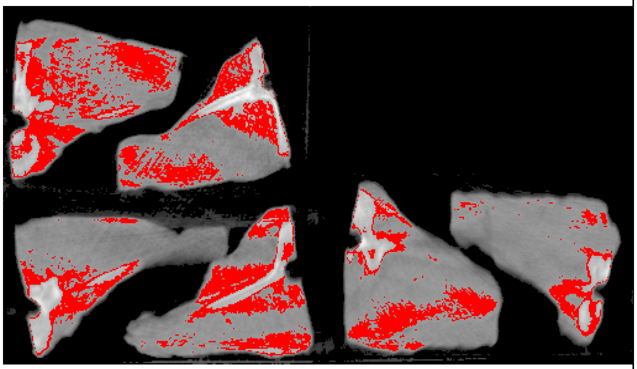
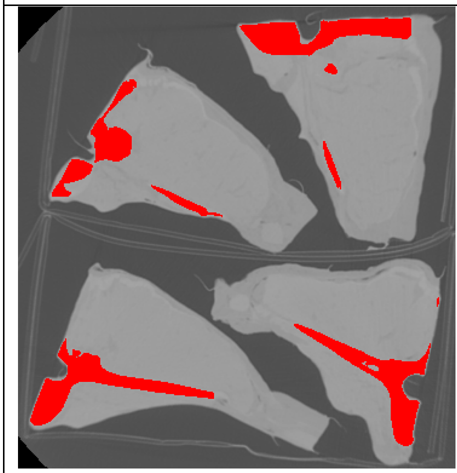
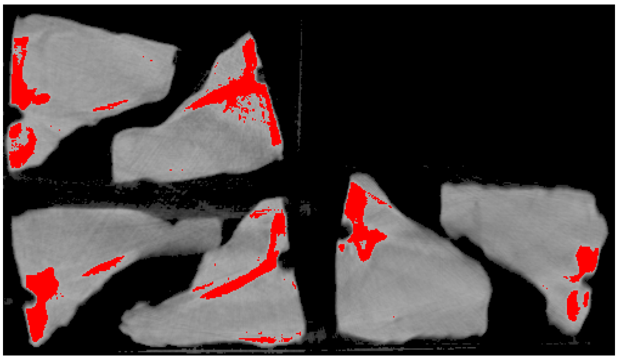
4.3.2 Boxed beef primal scanning

Configuration 1. – 2 boxes high, 2 wide

When boxes of primals were stacked on top of each other for CT scanning the quality of Nuctech CT images were impacted. For Nuctech CT scanning the boxes of primals were scanned 2 boxes wide (720 mm) and 2 boxes high on one side (360mm high), as described in section 3.2.4. This was not able to be exactly replicated in the medical CT, given the limited dimensions of the aperture in this system. Instead, the boxes were scanned 2 boxes high and only 1 box wide (360mm high and wide). The example CT images of short loin boxes from the Medical and Nuctech CT systems shown in Table 15 are not therefore an entirely fair comparison, though the high quality of the medical CT image and continued ability to differentiate fat, lean and bone% in these images is evident, compared to the markedly reduced quality of the Nuctech CT image. Marked shadowing is evident in the Nuctech CT image of the 6 short loins. This is particularly evident when the lean tissue thresholds are applied, which fail to differentiate lean and fat tissue in the short loins given the thickness of the tissue. Alternatively, the Nuctech CT is still able to differentiate bone from soft tissue in this image despite the tissue thickness scanned – a result that is crucial for the automated cutting of soft-tissue from bone.

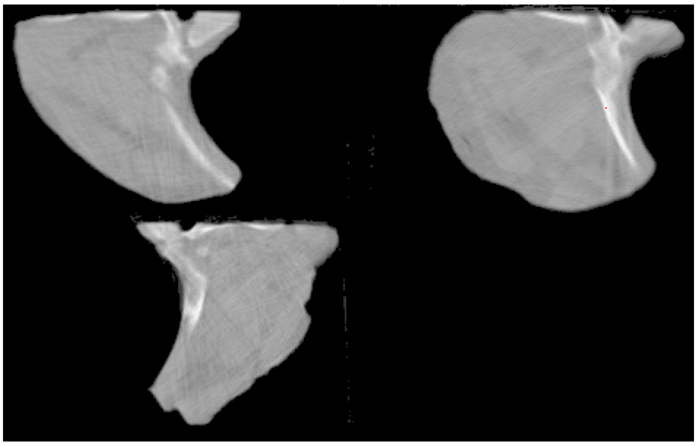
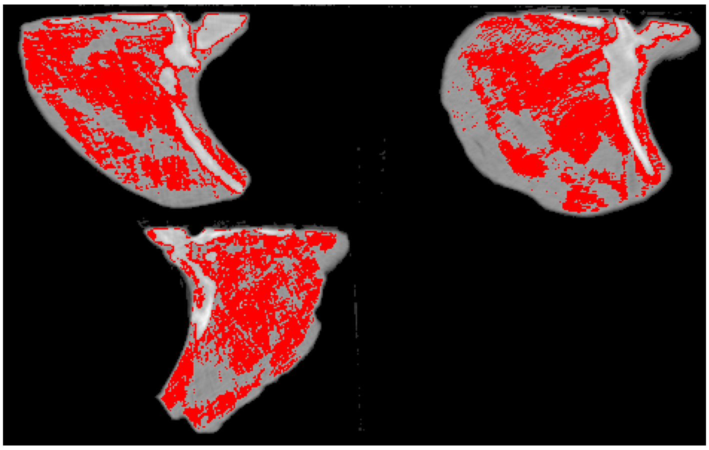
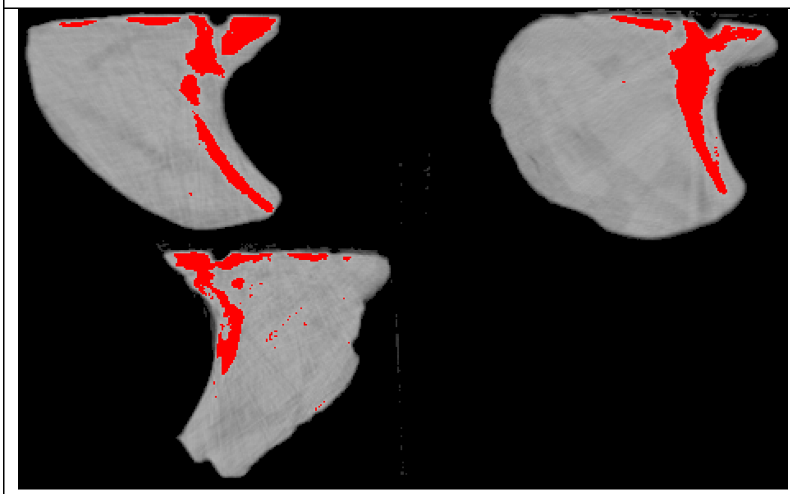
Table 15. Example medical and Nuctech CT image slices when boxes of short loins (containing 2 primals) were stacked 2 boxes high, and in the case of Nuctech images were scanned 2 boxes wide on the lower level. Example image slices are shown, in addition to images demonstrating the thresholding of lean and bone tissue in the selected slices.

Medical CT scan of 4 short loins	Nuctech CT scan of 6 short loins
	
Lean tissue thresholding (2-164)	Lean tissue thresholding (26400 – 29200)

	
Bone tissue thresholding (164 - 32767)	Bone tissue thresholding (26400 – 65535)
	

Given that only 1 rib set was able to fit in each box, stacking the boxes 2 high on one side and 2 boxes wide for Nuctech CT scanning resulted in only 3 rib set primals being scanned at one time as shown in Table 16. Though some shadowing was evident in these images, the Nuctech CT maintained its ability to differentiate lean, fat and bone tissues via pixel value thresholding (Table 16).

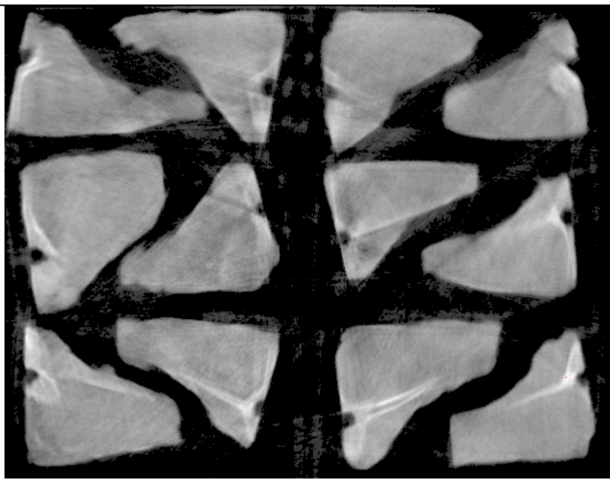
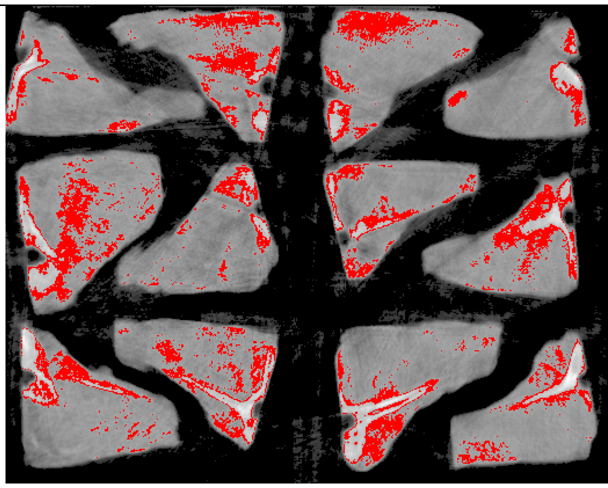
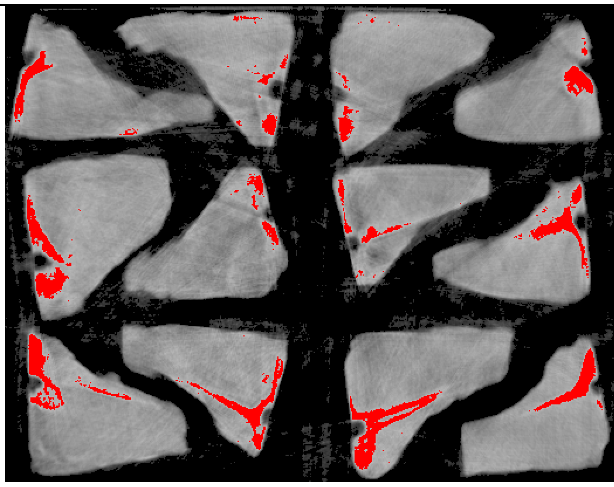
Table 16. Example Nuctech CT scan image of short loin primals in boxes (2 primals per box) stacked 3 boxes high and 2 boxes wide. An example image slice is shown, as well as the thresholding of that same image to identify lean and bone tissue.

Nuctech CT scan of 3 rib sets

Lean tissue thresholding (26400 – 29200)

Bone tissue thresholding (26400 – 65535)


Configuration 3. – 3 boxes high, 2 wide

When boxes containing 2 short loins were scanned 3 boxes high (540mm) and 2 boxes wide (720mm) through the Nuctech CT, the image quality was substantially reduced as shown in Table 17. This is expected given the substantial tissue thickness of this scan. The 6 boxes scanned contained 12 bone-in short loin primals, totalling 107.8kg. The substantial shadowing in the images negated the ability to use pixel value thresholding to differentiate lean tissue from fat and bone, though the ability to differentiate bone from soft tissue was reasonably well maintained (Table 17). The medical CT scanner was not able to replicate this scan given the 500mm limit of the aperture in this system.

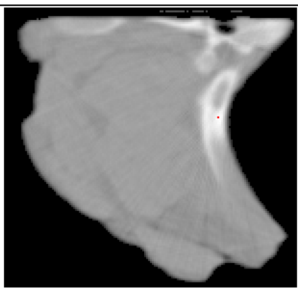
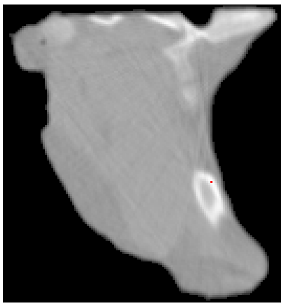
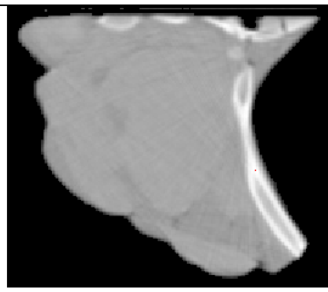
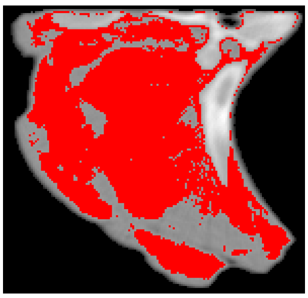
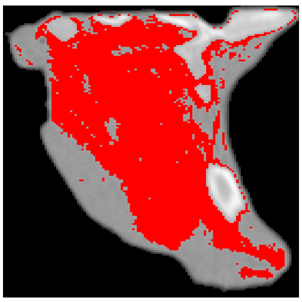
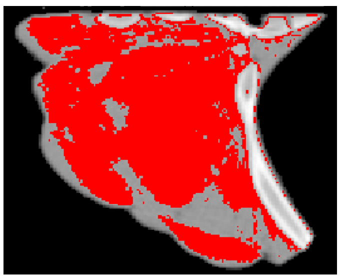
Table 17. Example Nuctech CT scan image of short loin primals in boxes (2 primals per box) stacked 3 boxes high and 2 boxes wide. An example image slice is shown, as well as the thresholding of that same image to identify lean and bone tissue.

Nuctech CT scan of 12 short loins

Lean tissue thresholding (26400 – 29200)

Bone tissue thresholding (26400 – 65535)


Configuration 2. – Continuous scanning

Qualitative assessment of boxed rib-sets scanned continually for 5 minutes in the Nuctech CT demonstrated that neither image quality nor the ability to differentiate fat, lean and bone tissue were influenced by continuous scanning over 5 minutes, as demonstrated in Table 18. An example rib set is shown at the start, mid-point and end of the 5 minute continuous scan period in Table 18, illustrating both a raw slice image and the thresholding of lean tissue in the same image. Though the thresholding of lean tissue appears to be highly precise in these images, the rib set numbers were not able to be tracked during the continuous scanning, thus it is not possible to qualitatively assess the ability of the Nuctech CT scans to predict CT fat, lean and bone% for these scans. Given rib set numbers were not tracked, the example images shown in Table 18 are likely of different primals, though could also represent the repeat scanning of the same primal.

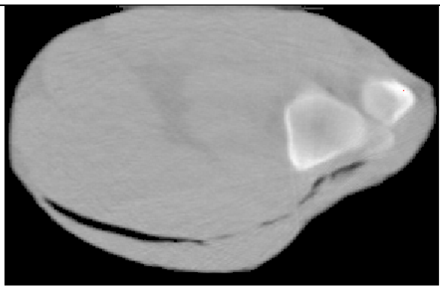
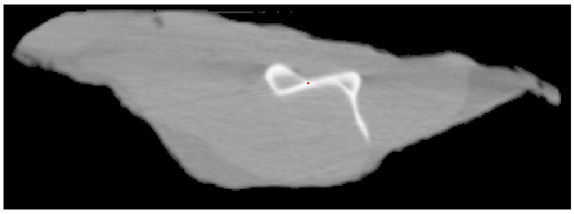
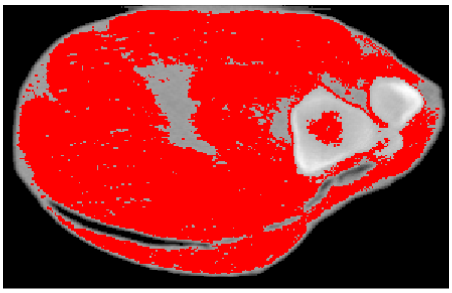
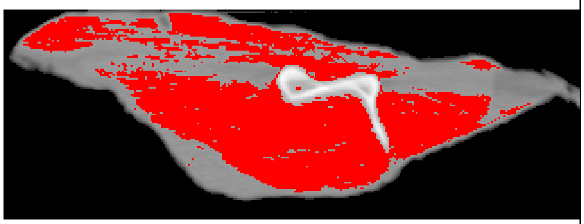
Table 18. Example Nuctech CT image slices of rib sets at the start, mid-point and end of the 5 minute continuous scanning of rib sets in boxes through the Nuctech CT. An example image slice is shown, as well as the thresholding of that same image to identify lean tissue. Rib set numbers were not tracked so these examples are likely different primals.

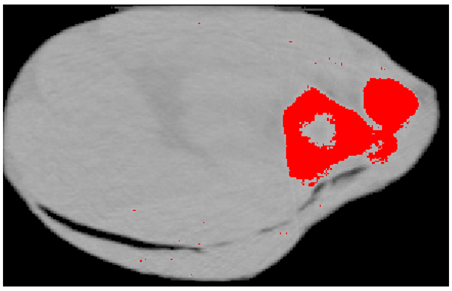
First Scan (10 sec)	Mid point (2.5 min)	Last scan (5 min)
Raw images (example slices of 3 rib sets)		
		
Lean tissue thresholding (26400 – 29200)		
		

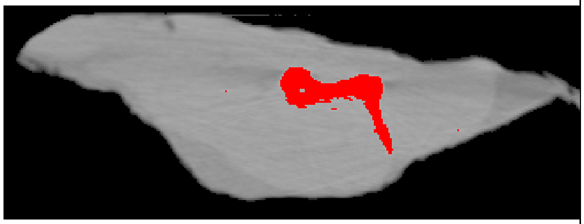
4.3.3 Entire beef sides

Qualitative assessment of the Nuctech CT images of 3 beef sides of varying weights (146, 186 and 208kg) cut into 5 sections for scanning demonstrate that the Nuctech CT is capable of differentiating bone, fat and lean tissue in diverse primal sections. Examples of Nuctech CT images of the larger hind limb and forelimb sections from the lightest and heaviest beef sides are shown in Table 19. While bone is uniformly well differentiated from soft tissues in all sections, in the larger beef side the ability to identify lean tissue in the heaviest sections was reduced using the established pixel value thresholds of 26400 to 29200. However, isolation of lean tissue improved with reduction of this fat: lean threshold to a pixel value of 25750 (Table 19). The ability of the Nuctech CT to precisely estimate medical CT lean, fat and bone % in entire beef carcases cut into minimal sections needs to be investigated using medical CT as the gold standard, with corrections to the Nuctech CT predictions potentially needed for larger carcase sections.

Table 19. Example Nuctech CT image slices of large fore and hind limb sections scanned and the ability to identify lean and bone tissue using existing pixel threshold values.

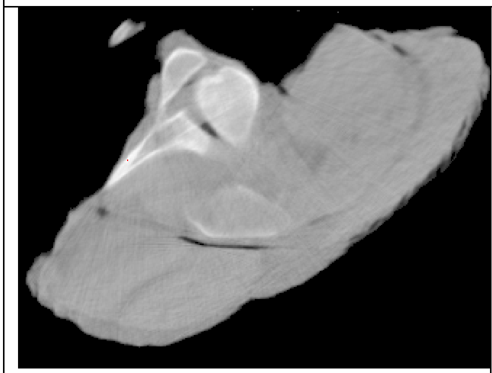
Beef side # 1 (146 kg)	
Raw images (example slices of 3 rib sets)	
 Hind leg (femur and patella)	 **Forelimb (scapula)**
Lean tissue thresholding (26400 – 29200)	
	
Bone tissue thresholding (29200)	



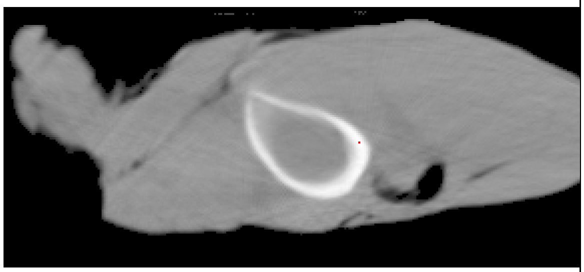


Beef side # 3 (208.5 kg)

Raw images (example slices of 3 rib sets)

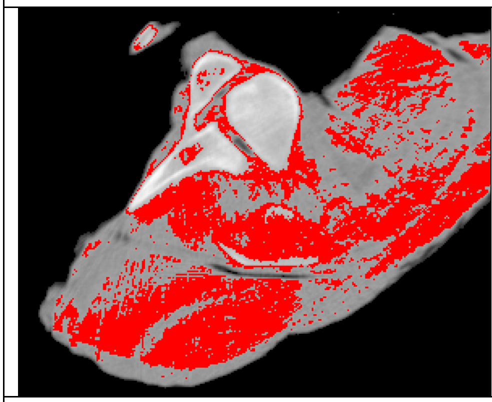


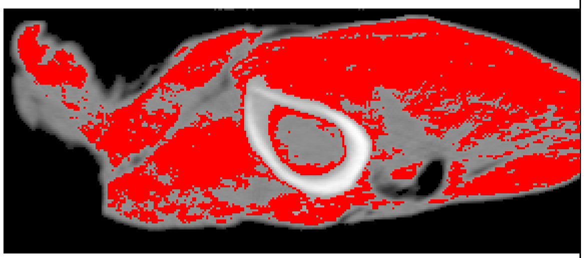
Upper hind (femur and pelvis)



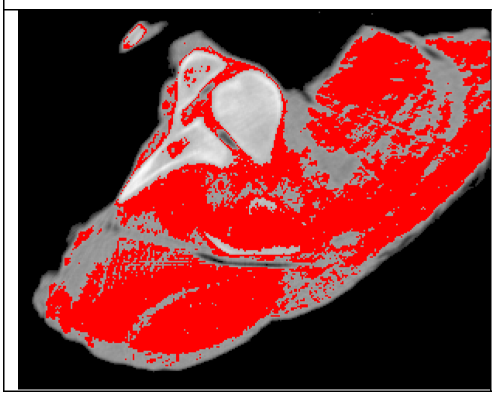
Forelimb (mid humerus)

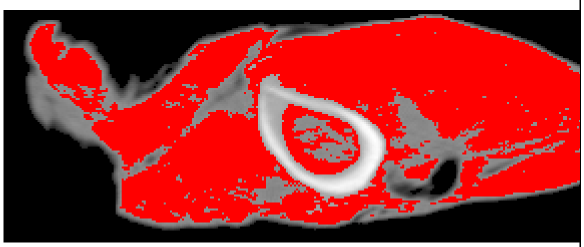
Lean tissue thresholding (26400 – 29200)



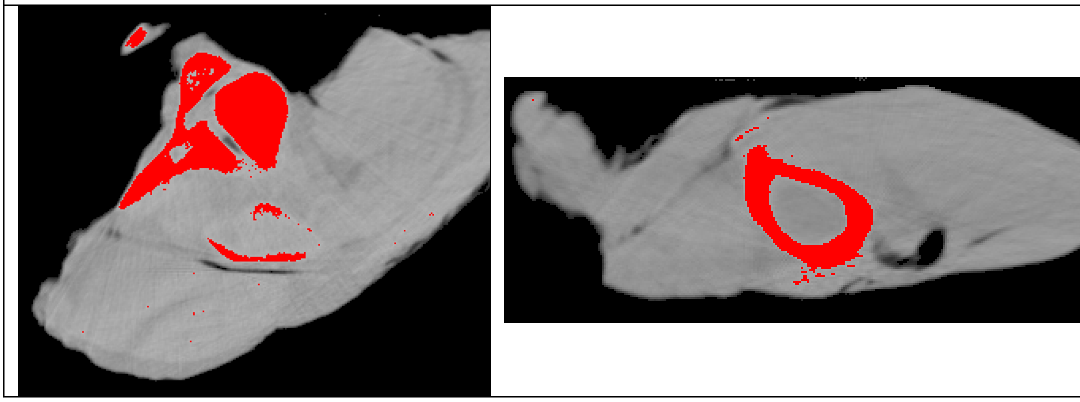


Alternative lean threshold of 25750





Bone tissue thresholding (29200)



5. Discussion

This study demonstrates that the Nuctech CT system has good image resolution and the ability to measure dimensions in a scaled and highly repeatable fashion, as demonstrated through scans of the XTE-CT test piece. The XTE-CT test piece allows a comprehensive testing of CT imaging systems, having been adopted as the calibrating device for CT scanners that provide reference data for technologies seeking commercial accreditation to predict lamb carcase lean and fat% in Australia. Based on the Nuctech CT performance in XTE-CT scanning, we anticipate the Nuctech CT system will provide imagery suitable for identifying 3-dimensional skeletal landmarks in beef for automation.

The resolution tests of the XTE-CT phantom estimated the Nuctech CT has an image resolution of 2 to 2.5 mm, not far exceeding the 1mm resolution achieved by medical CT scanners. The resolution of the Nuctech CT scanner was highly repeatable, with a standard deviation of only 0.22 mm between the repeat measures of the same scan. If additional resolution were required to differentiate tissue types within portions of beef, edge detection analysis would likely further enhance existing Nuctech images.

The Nuctech CT measures of thickness in the XTE-CT was highly accurate, precise and repeatable, aligning with medical CT performance. However, the dimension measures of the XTE-CT were relatively inaccurate though highly precise and repeatable. The Nuctech CT measures the 200mm XTE-CT diameter test as 179mm, compared with medical CT measures of 201mm. This inaccuracy suggests the need to apply scale calibration to Nuctech CT images.

The Nuctech CT successfully differentiated materials of differing density within the XTE-CT test piece, where Nuctech CT Hu values demonstrated a strong linear relationship with density similar to medical CT. Furthermore, analysis of the raw Nuctech CT XTE-CT images demonstrated that the

Nuctech CT can provide highly repeatable and consistent density measures that are not influenced by the positioning of the XTE-CT in the CT aperture.

This study has also demonstrated the excellent ability of the Nuctech CT system to differentiate bone from soft tissue and furthermore lean from fat tissue in bone-in beef portions of variable size and composition. While initial qualitative assessment of tissue thresholding in Nuctech CT scans to differentiate tissue types did produce a range of possible 'optimal' thresholds for processing these images, the subsequent analyses demonstrated that the Nuctech CT scans could predict CT composition with excellent precision right across the range of thresholds identified (Tables 10 – 12). This excellent result is underpinned by the ability of the Nuctech CT to produce pixel values highly consistent with tissue types in the bone-in short loin and rib sets of diverse weight and fat content scanned. It would be valuable to further validate the precision of these predictions further in greater numbers of primals with maximal weight and fatness ranges and in diverse primals. While this was done to a certain extent by scanning 3 beef sides cut into pieces in this study, this beef was not medical CT scanned and therefore the gold standard measure is not available to validate the Nuctech CT predictions.

The stacking of primal boxes (2 wide and 2 to 3 high) to increase the density or thickness of tissue scanned did reduce the quality of Nuctech CT images. Shadowing could be observed in these Nuctech CT images which reduced the ability to differentiate lean from fat tissue via pixel value thresholds, however differentiation of bone from soft tissue was well maintained despite the substantially increased scan thickness. Unsurprisingly the shadowing and ability to differentiate lean and fat tissue were further reduced when boxes were scanned 3 boxes high and 2 wide, where the Nuctech CT was effectively scanning 12 bone-in short loins at the same time. When the Nuctech CT images of beef side sections were assessed, there was some reduction in differentiation of lean and fat tissue in the heaviest hind and forelimb carcase portions. Differentiation of bone from soft tissue remained excellent, while manipulation of the lean: fat thresholds did improve the ability to differentiate lean tissue even in these heavy carcase sections. Therefore, further investigation is warranted into the effect of tissue thickness (of bone-in and bone-out product) on the ability of Nuctech CT to predict the medical CT composition of beef and particularly to identify muscle seams in larger sections. The consistent ability of the Nuctech CT to differentiate bone from soft tissue in scans of all thicknesses in this study is very promising for use of this imaging system to drive automated beef boning.

6. References

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