final report

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3D X-Ray Developments

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ABSTRACT

This report details the 3D x-ray trials undertaken by Scott Technology Australia (STA), supported by Meat and Livestock Australia (MLA) and Australian Meat Processor Corporation (AMPC), to enable a platform to be developed for Objective Carcase Measurements to be acquired real-time within processing facilities. The research was focused on Hardware and not Software understanding. The research has demonstrated that there are a significant number of meat processing attributes that can be measured, within the required processing time frame, with 3D x-ray hardware platforms.

1 Executive Summary

Along with others, Scott Technology Ltd (Scott) has identified certain carcase measurements that are vital to be measured more accurately (i.e. objectively) to assist in the long term sustainability and competiveness of the Australian red meat supply chain.

Form all aspects it has appeared for many years that 3D X-ray hardware was the most suitable and ready for the purpose of objective measurement. However, it was a large leap of faith (i.e. expensive with some technical unknowns) to commit to developing and installing a system within and Australian processing company.

1.1 Research Project

Scott supported by the Australian Meat Processing Corporation and Meat and Livestock Australia, worked with a research arm within Siemens to undertake mitigating some of the technical unknowns.

Hence the purpose of this research project was to determine the hardware specifications (not software) of the required 3D x-ray platform to objectively measure identified Attributes and defined Uses. In addition the research aimed at understanding which of the two current 3D x-ray platforms best suited the industry (industrial vs. medical).

1.2 Meat Processing Attributes for Objective Measurement

Scott identified the following attributes that are required to be objectively measured within the meat industry.

Meat CT Attributes → Measurements, Calculations and Inferences

	M	C	I		M	C	I		M	C	I
Skeletal Mapping	●			Marktet Cuts/Weights		●		Dentition	●		
Determination fo E.M.A		●		Ossification/Age	●			Meat colour			●
GR Score (Rib Fat)	●			Cysts	●			Skin Quality	●		
Location of Seams	●			Abscess	●			Glycogen			●
Marbling (hot/cold)	●			Disease (i.e. liver)	●			Juiciness			●
Lean meat yield		●		Eating quality			●	Gender	●		
Hump height	●			Ext. contamination	●			Growth (Live)	●		
Determination of SMY		●		Tenderness			●	Arthritis	●		

1.3 USES

Some of the above attributes are only applicable to Australia and some only easily acquired by being located on a processing plant (i.e. cysts). As a result the research undertaken was limited to determination of the 3D x-ray hardware specifications that could be determined from acquisition and testing of meat from a butcher in Europe.

Of these the following Uses where defined and researched.

Use	**Sheep / Lamb**		**Beef**
	Fan Beam (Medical)	**Cone Beam (Industrial)**	**Fan Beam (Medical)**
Automated cutting between bones	🟢	🟢	🟢
Automated cutting between primals	🟢	🔴	🟢
Lean Meat Yield	🟠	🔴	🟠
Saleable Meat Yield	🟢	🟢	🟢
Marbling	N/A	N/A	🟢
Eye Muscle Area	🟢	🔴	🟢
Hump Height	N/A	N/A	🟢
Subcutaneous Fat & GR	🟢	🟢	🟢

A successful outcome was deemed to be achieved based on current industry testing standards and a scan being within a reasonable meat processing cycle time. For beef the cycle time was taken at 20 seconds and for lamb at 6-7 seconds. A green light indicates that the Siemens hardware could objectively determine the required Use (and hence Attribute(s)). An orange light indicates that the time was slightly higher than the 'standard' Processor processing time, although the Attribute/Use could be objectively measured. Red indicates a failure to measure the Attribute/Use.

1.4 Fan Beam (Medical) Summary

Both beef and lamb constituents can be successfully objectively measured using a fan beam (Medical) scanner at the required industry processing rates of one beef carcase every 20 seconds and one lamb carcase every 6-7 seconds.

1.5 Cone Beam (Industrial) Summary

Although the cone beam scanner cannot categorically be removed from consideration as a result of these trials, Scott believe that it is highly unlikely that further work in the cone beam area will prove viable for the processing sector.

1.6 Hardware Specifications

The following summarises the hardware specifications required to objectively measure the identified Uses.

	Fan Beam		Cone Beam
Use	**Lamb**	**Beef**	**Lamb**
Automated cutting between bones	Voltage (kV) = 140 Scan time < 3 sec	Voltage (kV) = 140 Scan time < 7 sec	Voltage (kV) = 130 Scan time < 53 mins
Automated cutting between primals	Voltage (kV) = 140 Scan time = 5-9 sec	Voltage (kV) = 140 Scan time <7 sec	
Lean Meat Yield	Voltage (kV) = 140 Scan time < 3 sec	Voltage (kV) = 140 Scan time < 7 sec	
Saleable Meat Yield	Voltage (kV) = 140 Scan time = 14-28 sec	Voltage (kV) = 140 Scan time = 15-30 sec	Voltage (kV) = 130 Scan time = 53 mins
Marbling		Voltage (kV) = 140 Scan time = 15 sec	
Eye Muscle Area	Voltage (kV) = 140 Scan time = 5-9 sec	Voltage (kV) = 140 Scan time 15-20 sec	
Hump Height		Voltage (kV) = 140 Scan time < 7 sec	
Subcutaneous Fat	Voltage (kV) = 140 Scan time = 5-9 sec	Voltage (kV) = 140 Scan time 7-15 sec	
GR	Voltage (kV) = 140 Scan time 5-9 sec		Voltage (kV) = 130 Scan time < 53 mins

Scott's best estimate of a system that could objectively measure Lean Meat Yield in the required Processor cycle time is depicted in the following table.

	Hardware Upgrades		Software Upgrades
	Lamb	Beef	
Lean Meat Yield	Voltage (kV) = 200 Scan time = 6 sec	Voltage (kV) = 140 Scan time = 9 sec	Development of an algorithm to interpolate results more accurately.

1.7 FUTURE RESEARCH

Industry should consider a 3D x-ray development program over the next 3-4 years.

The first two years would require an indicative budget of AUD$1.5 million to develop, install, operate and modify a beef side hardware platform, based on fan beam (i.e. Medical) platform.

Years 3-4 (an on) would then focus on the required software development, although some of this could commence in years 1-2. An indicative budget of AUD$500,000 – 1,000,000 may be required for software development.

Development of a full side Beef system would lead to the development of one off uses on primals, offals, trim and waste.

Hence one large system installed as a research platform will enable a plethora of other uses that require smaller (and hence cheaper) hardware and software solutions all based on the same 3D x-ray platform.

Contents

2 BACKGROUND

Along with others, Scott Technology Ltd (Scott) has identified the following carcase measurements that are vital to measure more accurately (i.e. objectively) to ensure the long term sustainability and competiveness of the Australian red meat supply chain.

Table 1: Meat supply chain attributes of relevance.

Meat CT Attributes → Measurements, Calculations and Inferences											
	M	C	I		M	C	I		M	C	I
Skeletal Mapping	●			Marktet Cuts/Weights		●		Dentition	●		
Determination fo E.M.A		●		Ossification/Age	●			Meat colour			●
GR Score (Rib Fat)	●			Cysts	●			Skin Quality	●		
Location of Seams	●			Abscess	●			Glycogen			●
Marbling (hot/cold)	●			Disease (i.e. liver)	●			Juiciness			●
Lean meat yield		●		Eating quality			●	Gender	●		
Hump height	●			Ext. contamination	●			Growth (Live)	●		
Determination of SMY		●		Tenderness			●	Arthritis	●		

Scott has investigated various measurement techniques to determine theoretically which technology should be able to objectively measure the largest number of carcase measurements identified in Table 1.

Table 2: Possible objective measurement techniques.

1 Visual ('Camera' System)	7 2D x-ray	13 Microwave
2 Ultrasound	8 DEXA	14 pH
3 Radar / Sonar	9 2D-3D X-ray continuum	15 Shear Forces
4 Thermography	10 3D x-ray	16 Fluroscopy
5 MRI (or NMRI)	11 Molecular Imaging	17 PET
6 NIR	12 Weight Systems	18 SPECT

Of the eighteen technologies investigated in Table 2, Scott identified that 3D x-ray was the technology which theoretically could measure the most number of carcase measurements.

The development of a supply chain business model incorporating the use of 3D x-ray systems, taking into account current unknowns pertaining to 3D x-ray application in the meat industry, has resulted in an independent organisation[1] calculating a weighted benefit to a typical Australian beef processing company of $18/head.

There are various hardware platforms and configuration within platforms of the 3D x-ray

[1] Greenleaf Enterprises

family. After lengthy discussions with various medical and non-medical (aka industrial) hardware suppliers of 3D x-ray platforms, not one supplier was either able to, or interested in, providing Scott with a solution that was guaranteed to deliver accurate measurements of the identified attributes at line speed and with a duty cycle that suited operations in the Australian processing sector.

Suppliers and Scott identified that there were significant concerns and unknowns pertaining to the trade-offs between too much and too little power, speed versus capital cost and full or part carcase applications that all required consideration and additional information.

After additional on-going discussion with Siemens, Siemens suggested that Scott use their German based 3D x-ray development lab. This lab is utilised by Siemens when developing new or evolving existing solutions for newly identified 3D x-ray opportunities in both the medical and non-medical fields.

The Siemens lab is used predominantly by Siemens global group to x-ray samples using either a cone beam (typically known as an industrial scanner) or helical scanner (typically known as a medical scanner). Within the Siemens lab the technicians have infinite control over x-ray power, rotation speed, and distance between sensors and parts. Having access to the ‘back end’ of the initial x-ray image compilation software also ensures the Siemens’ lab has an additional level of image interrogation and manipulation at their disposal.

Typically the output from the Siemens lab provides the internal Siemens hardware manufactures and x-ray system builders with the required hardware and software parameters to build and commercialise new 3D x-ray solutions.

Scott and Siemens agreed that upon the initial meat developments being successful, Siemens would be able to provide initial indicative pricing for the required number of identified meat solution platforms and secondly to be able to build the required systems, either as one-off prototypes or as production runs for global supply and commercialisation.

3 INTRODUCTION

To progress the demonstration of the potential benefits of 3D x-ray to the Australian processing sector and identified potential application and integration issues of 3D x-ray within a processing environment, Scott submitted two projects for consideration to the Australian Meat Processor Corporation Technical Committee.

The first project was aimed at demonstrating a system that could measure beef marbling whilst the carcase was still hot. The second system was aimed at differentiating meat, bone and fat. This second application could be used for multiple purposes within a boning room such as advanced automated beef deboning. However, initially Scott were proposing to the developed and demonstrate its benefits as either a more accurate Chemical Lean analysis solution or application on the waste belt to measure and determine a value on lost meat and fat to a Processor's rendering facility. This last application, if successful, would enable Australian Processors to undertake continuous mass balances (i.e., yield), something which is not currently practicable to do. These two applications were chosen for strategic reasons.

Application 1, **automated beef marbling**, required a system that could:

1. Differentiate between inter-muscular and intra-muscular fat, and
2. Measure inter-muscular fat (i.e. marbling) content hot (i.e. at 37^{o}C), and
3. Have the power to penetrate through the thickest cross-sectional area of a beef side (~ 800 mm) and still retain the required clarity of image, and
4. Acquire an image every twenty(20) seconds, and
5. Run continuously for up to 20 hours, and
6. Arguably have the hardware rotate around the carcase whilst the carcase is held in a vertical position, or alternatively
7. Have the hardware remain idle from a rotation perspective and have the carcase rotate and the hardware move in the vertical orientation only.

It was believed that this solution would most likely be an industrial 3D x-ray scanner platform as depicted in Figure 1.

Figure 1: Cone Beam (aka Industrial) 3D x-ray scanner

Application 2, **beef meat, fat, bone automated differentiation**, required a system that could:

1. Differentiate between meat, fat and bone, and
2. Have a continuous conveyer run through the hardware, i.e. not be the current 'in and out' patient table typically associated with medical 3D x-ray platforms,
3. Have a duty cycle that enable up to 20 hours of continuous operation, and
4. Have the ability to process 'lumps' of meat from a large striploin to a small 'chunk of meat' nearing 50mm in diameter, and
5. Report on each individual piece of meat that traverses through the scanner, not provide an average across an accumulated sample.

It was believed that this solution would most likely be a medical 3D x-ray scanner platform as depicted in Figure 2.

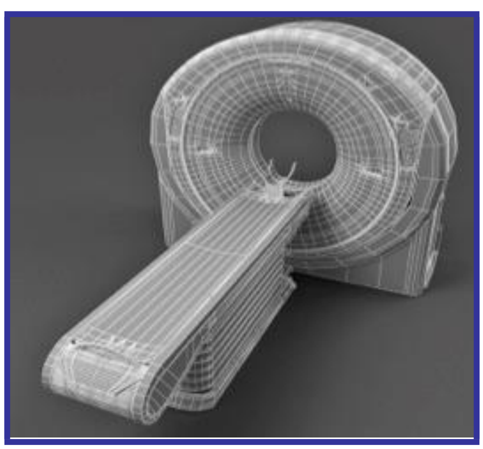


Figure 2: Helical (Medical) 3D x-ray scanner.

Scott believed that by undertaking both of these projects, the lessons learnt, would effectively provide the information required to develop a 3D x-ray platform for any beef (and small stock) application whereby differentiation between meat, fat (inter and intramuscular) and bone was required.

Scott proposed that the additional attributes such as cartilage, seams, sinew, cysts, ligaments, tendons, and diseases could be evaluated more cost effectively once the two proposed platforms had been installed within an Australian Processor's facility.

In addition to determining the required hardware specifications it was vital that Scott ensure that the optimum hardware specifications did not result in different attributes (i.e. meat and fat) having the same or overlapping 3D x-ray 'density' values

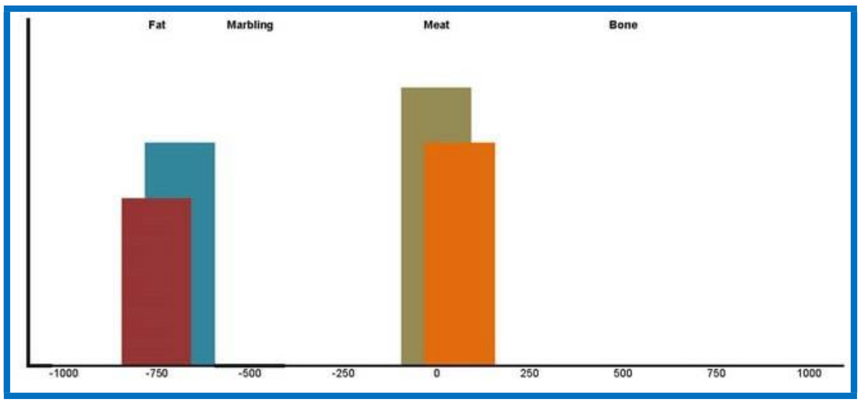


Figure 3: Fictitious meat attributes with overlapping 'density' values (a bad outcome)

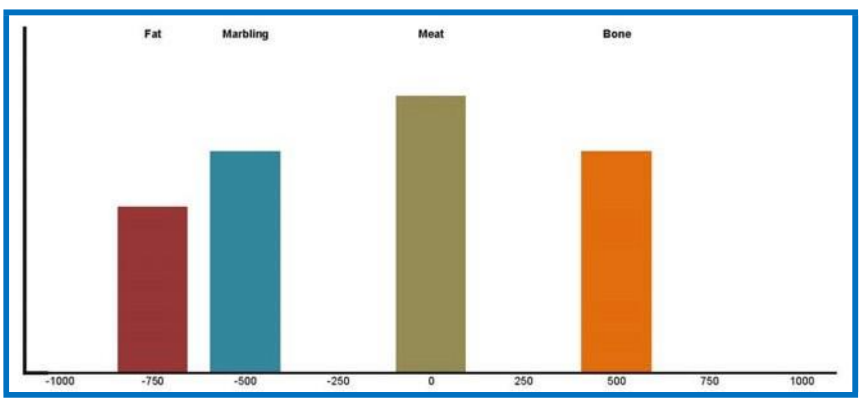


Figure 4: Fictitious meat attributes with non-overlapping 'density' values (a good outcome)

Setting and defining these 'density' values are later discussed in the report under the descriptor of threshold values (refer Section 5.4.3).

4 AIM

The original aim of the project approved by the AMPC Technical committee was two separate projects to develop and demonstrate two platforms operating as pilots in an Australian meat processing operation(s) that could enable further evaluation of 3D x-ray on beef marbling, beef cut analysis and beef chemical lean for application on the waste belt to enable continuous closed mass balances to be undertaken by the processing sector.

Initially Scott proposed to evaluate an industrial scanner for beef marbling and a medical scanner for chemical lean. Both projects initial steps where to evaluate the optimum settings to enable a purpose built (industrial) or second hand scanner (medical) to be acquired for installation into a processing plant.

Subsequent to the approval of both projects by the AMPC Technology Committee, Scott had undertaken further discussions with Siemens in Germany, and after discussions with MLA it was agreed to merge both approved projects into a single project from a first Phase perspective. Hence under the guise of a single project known as Phase 1, Scott aimed to identify the scanner hardware settings to enable the required demonstration scanners to be specified from an engineering/technical perspective.

The overall aim for Phase 1 was to identify the minimum specifications for a machine such that a system could measure desired product characteristics; meat, bone, and fat (intra-muscular and inter-muscular).

Information from Phase 1, would then enable the specification of a prototype(s), that could either be sourced as a second hand unit, or manufactured, for installation into a processing facility.

Phase 2 would enable Scott to evaluate and demonstrate at line speed the various hardware platforms providing the required attribute measures as well as evaluate the developed platform(s) capability at measuring the other meat attributes identified in Table 1.

Whilst at Siemens, it was prudent to also undertake lamb scanning research.

5 METHODOLOGY

This methodology section provides a summary of the type of meat analysed, meat analysis preparation, hardware utilised, image analysis operations, software utilised and images obtained.

5.1 MEAT SAMPLES

A full lamb carcase cut into two pieces and forequarter of beef were used for analysis.

5.2 MEAT PREPARATION

Due to fresh meat being used and the abnormal shape and hence non-uniform centre of gravity, the meat samples were required to be wrapped (to protect the equipment) and packaged into a 'holder' to ensure that the sample being analysed did not 'topple' or move excessively whilst being scanned.

5.2.1 Lamb Preparation

Lamb scanned in the cone beam scanner was packed into a small plastic bin and surrounded with foam and bubble wrap (Figure 5).

Figure 5: Lamb forequarter packaged for scanning.

Lamb scanned on the fan beam scanner the lamb was retained in its 'cone beam scanner bin' and strapped to the patient table (Figure 6).

Figure 6: Lamb in the bin and strapped to the patient table.

5.2.2 Beef Preparation

Beef scanned on the cone beam scanner was supported firmly within a purpose built crate. The crate was supported from an overhead hoist to take a large portion of the carcase weight off the cone beam scanners rotating platform as the platform, as the drives could not support the weight of the beef forequarter (Figure 7).

Figure 7: Beef packaged for cone beam scanning.

Beef was wrapped in plastic for processing in the fan beam scanner (Figure 8).

Figure 8: Beef packaged for fan beam scanning.

5.3 HARDWARE

The Siemens lab comprised both an industrial (cone beam) and medical (helical/fan beam) scanner. Both scanners were configured with servo motors on all moving axis that could be infinitely controlled in addition to the power of the tubes emitting/generating the x-rays. Typically a scan that took one hour on a cone beam (industrial) machine, took one minute on a fan beam machine.

5.3.1 Cone Beam Scanner

The cone beam machine (refer Figure 9) scanned at an average rate of 500 slices/hour.

X-ray Detector – Digital detector was a Perkin-Elmer with 2048x2048 pixels at 200x200 µm², mounted on a moveable platform, allowing variable distance between detector and object..

X-ray Source (x-ray tube) – Cone beam x-ray tube, with a maximum power of 11.2 kilowatts.

Rotational Platform (Turntable) – A platform with 3 degrees of movement.

Processing – A total of eight (8) computers with dual core processors.

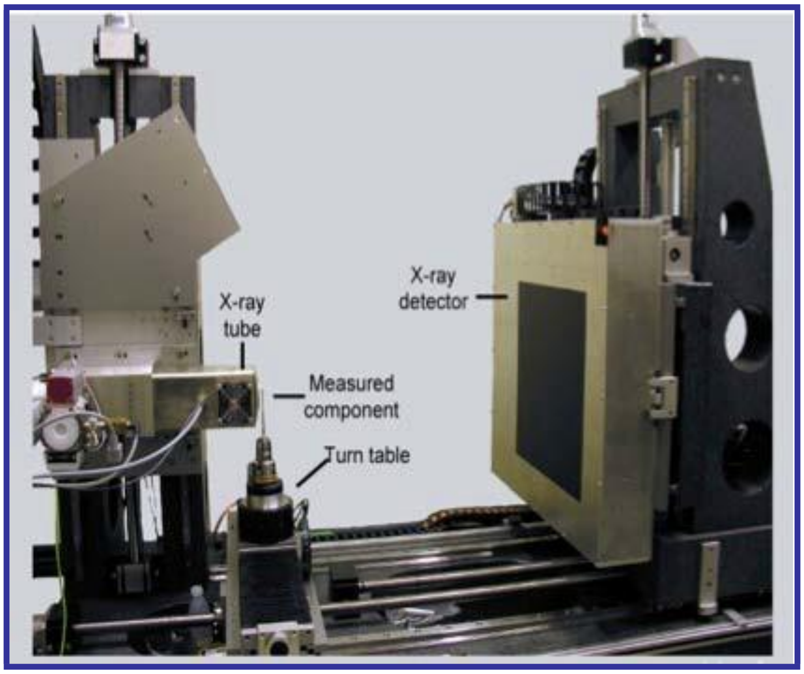


Figure 9: Siemens Cone Beam (Industrial) Scanner.

5.3.2 Helical (Fan Beam) Scanner

Figure 10 depicts the Siemens helical scanner.

Figure 10: Siemens helical scanner

Digital Detector – Two digital detectors rotating on the same axis as the x-ray tube and always maintained the same distance from the source (Figure 11).

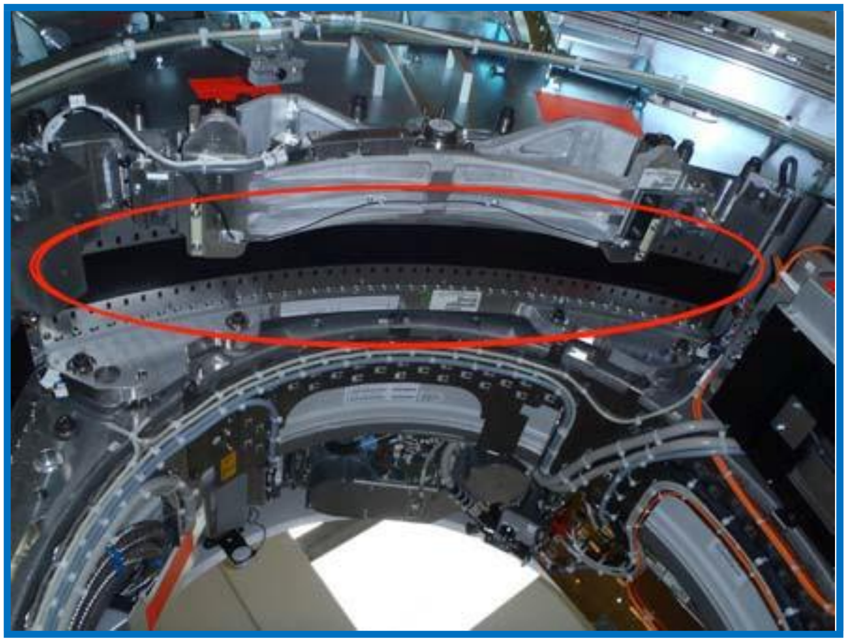


Figure 11: X-ray detector.

X-ray source – A fan beam x-ray source producing up to 80 kilowatts of power (Figure 12).

Figure 12: Fan beam x-ray source.

Translational platform – The object being scanned was placed on a flat platform, with two degrees of movement, up/down and left/right (Figure 13).

Figure 13: Directions of platform movement.

Processing power – In contrast to the cone beam setup, there was a single computer which controlled the procedure, including the segmentation process.

5.4 IMAGE ANALYSIS

The Aim of Phase 1 was to determine the platform hardware that was the optimum setting to objectively measure the required meat attributes. To enable this to occur the best image was utilised to determine the 'thresholding' values and then these thresholding values applied to all scans. When a scan with lower contrast was analysed and the scan could no longer clearly identify the required meat attributes to the required level, the applicable hardware settings were deemed not acceptable and the next highest quality scan hardware settings are determined to be the most optimum.

Image analysis involved the following steps:

1. Pre-analysis
2. Segmentation / Thresholding (best quality single slice)
3. Threshold value determination
4. Segmentation (all scans)
5. Hardware specification selection

5.4.1 Pre-analysis (Cone beam only)

The output files from the cone beam platform are raw image files (.RAW format). These files cannot be directly uploaded into a volume analysis tool such as Analyze. Therefore the files must be converted into a software 'friendly' file format that contains scan properties. This process is undertaken separately using specialised conversion software (refer Section 5.4.5).

The generic output for a medical CT machine is a .DCM (DICOM) file. This file format does not require conversion for the analysis process.

5.4.2 Segmentation & Thresholding (Single scan)

Segmentation is the process of differentiation and separating required attributes. This separation can be undertaken using a number of complex techniques. These techniques differ in complexity and accuracy. Thresholding was chosen as the segmentation technique, being a compromise between accuracy and ease of use.

Thresholding is segmentation based on attribute Gray levels within an image. The varying Gray levels within an image are as a result of the differences in attribute densities. The lighter the colour in the scan image the denser the attribute.

The maximum and minimum Gray levels for a certain attribute are defined and all objects that fall within those maximum and minimum values are grouped and extracted as the same attribute.

With the vast majority of 3D x-ray scans being conducted on human patients, the majority of the software available is designed and pre-calibrated to human density (Gray level) values. Using human threshold values for analysing animal scans gave an inaccurate output.

5.4.3 Threshold Value Determination

For the Australian meat industry the different threshold values had to be identified using a logic deduction method, involving; tweaking maximum and minimum threshold values to isolate only the required attributes.

5.4.4 Segmentation (all scans)

Using the threshold values each scan acquired using the various platforms and specification configurations where analysed to determine at which setting did the image not portray the required meat attributes to the required level that would provide a Processing company with valuable information (refer Figure 14).

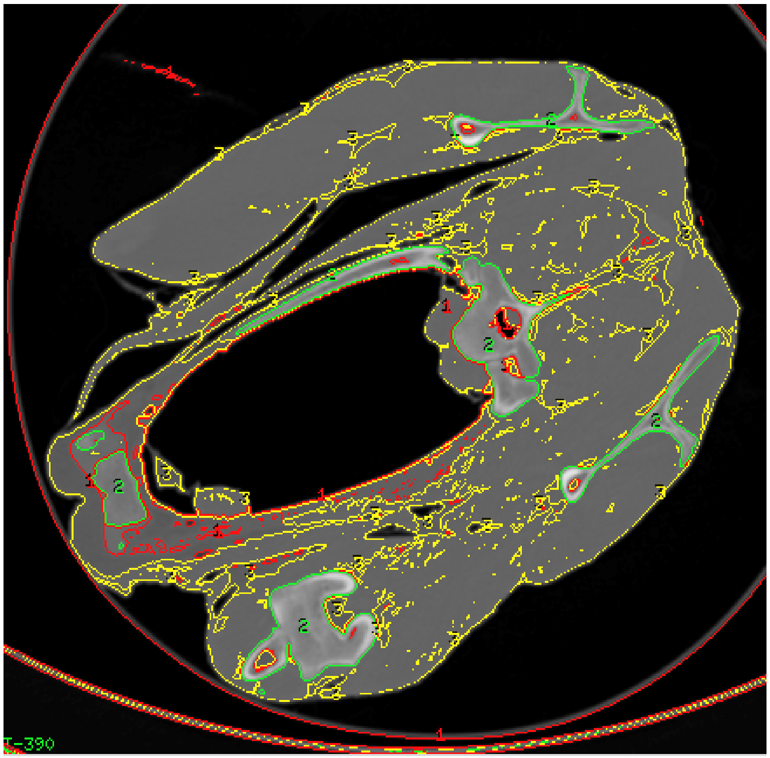


Figure 14: Segmented Beef Scan (Green = bone, Red = meat and Yellow = fat).

5.4.5 File conversion (using VGStudio Max 2.1)

The raw image files (.RAW) obtained from the cone beam scanner, were converted into DICOM files (.DCM). The properties required, for the conversion process were manually extracted using VGStudio Max version 2.1

5.5 SOFTWARE UTILISED

5.5.1 VG Studio Max (Version 2.1)

VG Studio is a volume[2] viewing software converts multiple image files into a single volume file. VGS was used to view and convert raw image files obtained from the cone beam platform, into single volume files (refer Section 5.4.1).

[2] Volume: A collection of individual scan images combined to form a collection of images stacked accordingly

5.5.2 Analyze (Version 10.0)

Analyze is x-ray analysis software for segmenting converted volume files. This segmentation process differentiated between the required meat properties. Analyze was one of the few available software platforms which allowed the use of custom threshold values in the segmentation process. This was vital for an application in the non-human analysis field.

5.6 Images Obtained

3D x-ray platforms and associated image analysis software can generate images for various functions. Figure 15 depicts the typical types of images used in this report.

The 2D cross sectional images are obtain from different axis of the original 3D image, and further processed to segment the different tissue types. The different colours in the scan coincide with different tissues types, fat as yellow, meat as red and bone as green. The front view was the main view utilised within the report specifically pertaining to the segmentation process.

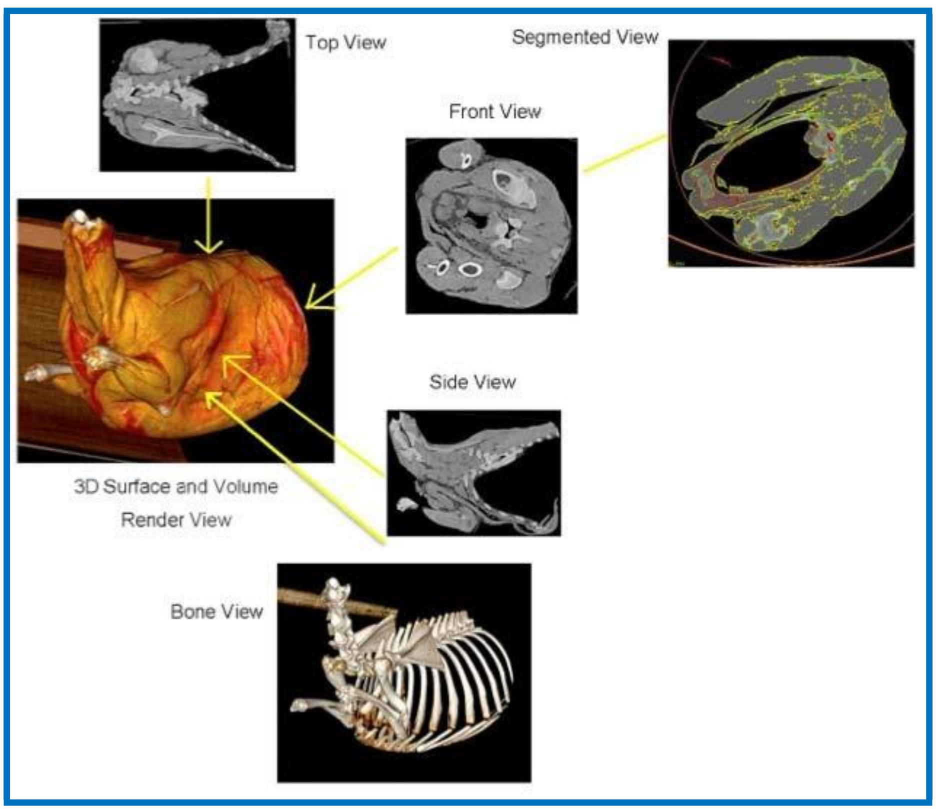


Figure 15: Various images acquired from scans.

6 RESULTS AND DISCUSSION

At a high level Table 3 identifies the types of use applications each image was analysed against.

Table 3 - Potential 3D X-Ray Uses

Possible Task/Use	Lamb or Beef
Automated cutting between bones	Lamb and beef
Automated cutting of between primals	Lamb and beef
Lean Meat Yield	Lamb and beef
Saleable Meat Yield & GR Score	Lamb and beef
Marbling	Beef
Eye Muscle Area	Lamb and beef
Subcutaneous Fat (Rib Fat) Hump Height	Beef

To determine acceptable system specifications for these uses, Scott was required to develop a test for each attribute being investigated. These tests where then applied to each increasing or decreasing image clarity to determine whether the hardware settings that produced that scan were acceptable or not.

Each developed Scott test was compared for compatibility to be the equivalence or better than the current industry standard of measurement for each measurement. Hence, the current industry standard method for each use is compared to a possible 3D x-ray method of measure. The error involved with both the current standard and a 3D x-ray version are outlined and the recommended specifications are outline based on maximum accuracy and minimum scan time.

Table 4 - Standard Measurements vs. 3D X-ray

Use	Standard	Test
Automated cutting between bones	Currently the operator visually identifies the bones and their positions. He or she then cuts between the 5^{th}-6^{th} & 10^{th}-11^{th} rib bones. *Level of error: Varies depending on operator vision and handling.*	• Identify and differentiate rib bones • Isolate required rib bones (5^{th}-6^{th} & 10^{th}-11^{th}) • Measure the distance between 5^{th}-6^{th} & 10^{th}-11^{th} rib bones *Allowable level of error: ±4mm*

Automated cutting between primals	Currently the primals are cut by an operator who relies on his or her vision to identify the seams that separate primals.
	
	Level of error: dependent on operator vision and experience
		• Identify meat, fat and bone (MFB).
		• Identify Seam
		    ○ Seam between two pieces of meat.
		    ○ Seam between Meat-Fat-Meat.
		• Measure seam continuity.
		    ○ Compare measured lengths with (GS)
		
		Allowable variation of ±10%

Lean Meat Yield	Visible fat trimmed from cut of meat and weight recorded and compared to cold weight of full carcase Level of error ±10%	• Threshold values identified • Threshold values applied to scans and data stored *Allowable level of error: ±10%*
Saleable Meat Yield	Currently the outer fat of a carcase is measured using a measuring device (ruler) by a trained operator. The operator relies on his or her vision to detect the edges of the fat and meat. The operator can have a varied accuracy depending on training level, experience, age, visibility and many other factors. *Level of error: ±2mm*	• Identify and isolate meat and fat • Identify position to measure from • Ensure measurements are taken from identical locations for each scan *Allowable level of error: ±2mm*
Marbling	Currently the carcase is chilled for a number of days after which an operator scores the carcase by visually comparing the meat with a reference score card. This is a proven subjective measurement which can be influenced by many factors including time chilled and light conditions.	• Identify rib bones • Identify meat and fat • Segment fat from meat • Isolate given area • Take measurement of fat in selected isolated area

Use	Standard	Test
	Level of error: ±4%	*Allowable level of error: ±4%*
Eye Muscle Area	Currently an operator makes a cut at the required section of a carcase and then uses a measuring device (either a ruler or electronic grid) to measure the muscle area collected. *Level of error: ±5% (manual measurement)* *Level of error: ±1% (electronic grid measurement)*	• Identify threshold values • Identify and locate required rib bone • Isolate required muscle • Obtain surface area measurement *Allowable level of error: ±5%*
Hump Height	Currently an operator measures the fat thicknesses using a measuring device (ruler), where the operator relies on his or her vision to identify fat thickness. *Level of error: ±2mm*	• Meat and fat isolated • Co-ordinate for measurement position identified • Measurements taken from identical position and distance recorded *Allowable level of error: ±1mm*
Subcutaneous Fat & GR	Currently an operator measures the fat thicknesses using a measuring device (ruler), where the operator relies on his or her vision to identify fat thickness. *Level of error: ±2mm*	• Meat and fat isolated • Co-ordinate for measurement position identified • Measurements taken from identical position and distance recorded *Allowable level of error: ±1mm*

6.1 AUTOMATED CUTTING BETWEEN BONES

Automated cutting would allow robotic processing of a carcase by accurately identifying rib bone positions and dimensions.

6.1.1 Current industry standard

Beef quartering and scribing, and lamb primal cutting requires an operator to visually identify the bones and their positions. The operator then cuts between the 5th-6th & 10th-11th rib bones for beef quartering, various other locations for beef scribing and between either the 3rd-4th, 4th-5th or 5th-6th rib bones on lamb depending upon the number of ribs within the lamb rib cage.

Level of error: Varies depending on operator vision and handling.

6.1.2 Test applied

Initially bone positions were located, then the required bones were identified and the distance between them measured.

- Identify and differentiate rib bones.
- Isolate required rib bones (For example in beef, 5th-6th & 10th-11th, and lamb 3rd-4th ribs).
- Measure the distance between 5th-6th & 10th-11th rib bone for beef and 3rd-4th for lamb.

Allowable level of error: ±4mm

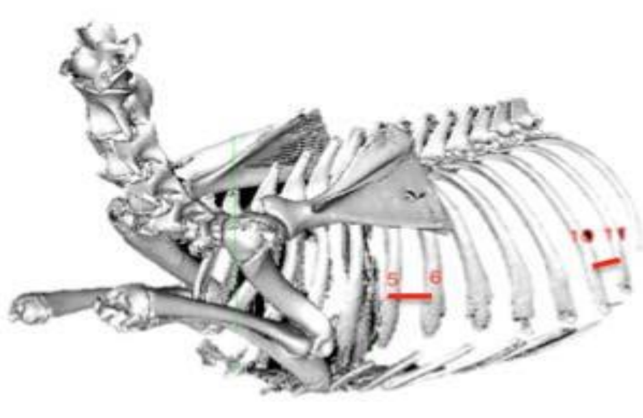


Figure 16 - Lamb bone structure indicating measured points

6.1.2.1 Lamb

The lamb results are separated into fan beam and cone beam, with each being compared to a separate reference. The twenty-eight (28) second scan is the reference or 'gold standard' for the fan beam scans and the three-thousand (3000) slice image is the reference for the cone beam scans. The error is calculated as both a percentage deviation from the respective reference scan and a measurement in millimetres.

6.1.2.1.1 Fan Beam (Medical)

Scan Time	28 sec	14 sec	9 sec	5 sec	3 sec
5th – 6th					
Distance (mm)	16.78	17.32	16.38	13.62	13.92
Error (mm)	0	+0.54	-0.4	-3.16	-2.86
% Error	0%	+3.22%	-2.38%	-18.83%	-17.04%
10th – 11th					
Distance	8.54	8.65	7.08	5.26	9.29
Error (mm)	0	+0.11	-1.46	-3.28	+0.75
% Error	0%	+1.29%	-17.1%	-38.41%	+8.78%

6.1.2.1.2 Cone Beam (Industrial)

Scan Time (Slices)	3h 30m (3000)	1h 45m (1500)	53m (750)
Distance	13.20	14.39	15.54
Error (mm)	0	+1.19	+2.34
% Error	0%	+9.02%	+17.73%

The differences in results are due to the variations in resolution. Resolution refers to the ability to distinguish between two points in an image. A low-resolution image is coarse, which makes it difficult to identify the outline points of the rib bone(s). The lower the resolution image, the lower the accuracy and the higher the variation from the reference. This is illustrated with the figures below.

Figure 17 – High Resolution Image

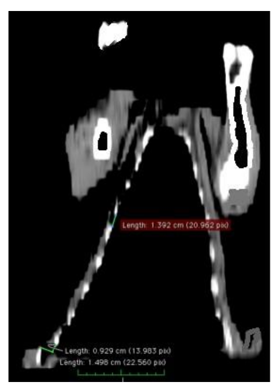


Figure 18 – Low Resolution Image

Figure 17 displays a high-resolution image (28 second scan) where a fine and clear outline of the rib bone is visible. Conversely, Figure 18 presents a low-resolution image (3 second scan) with a coarse and grainy quality, where the rib bone outlines are difficult to see.

6.1.2.2 Beef

The beef results are calculated in the same manner as the lamb results. A reference scan is identified and the percentage deviation from the reference is recorded, along with an error in millimetres. Hardware restraints during the experimental stage of the trial, limited the beef scans to fan beam only. The measurements were taken between the 5^{th}-6^{th} rib bones with the results tabulated below.

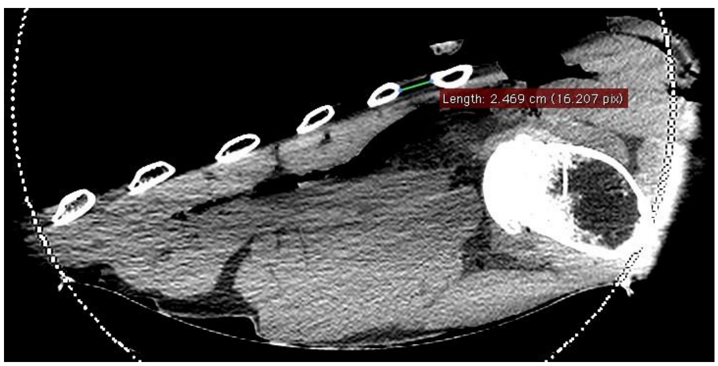


Figure 19 - Example beef measurement

6.1.2.2.1 Fan Beam (Medical)

Scan Time	30 sec	15 sec	7 sec
Distance (mm)	24.69	23.29	22.69
Error (mm)	0	-1.4	-2.0
% Error	0%	-5.67%	-8.10%

6.1.3 Discussion

Specials	Proven	Indicative Speed	Notes
Lamb (medical)		<3 seconds	
Lamb (industrial)		< 53 minutes	It is unknown what reasonable time, from a processing perspective this could be reduced to.
Beef		< 7 seconds	

6.2 AUTOMATED CUTTING BETWEEN PRIMALS

Automated cutting between primals would allow a system to recognise primals and allow automatic processing of carcases at the deboning or primal from primal separation stage within a boning room. Primal identification would also feed into and enable a cut recognition program that could be used for pre-empting which cuts within a carcase would suit which market destination best and hence be the enabler of a pre-emptive feed forward customer make to order system. A first for the meat industry.

6.2.1 Current Industry Standard

Currently the primals are cut by an operator who relies on his or her vision to identify the seams that separate primals.

Level of error: dependent on operator vision and experience

6.2.2 Test Applied

The meat and fat of a scan was separated. Then seams were identified and the length of a chosen seam was measured. The error in seam continuity would determine the accuracy of the scan.

- Identify meat and fat.
- Identify and isolate seam.
- Measure seam length.

Allowable level of error: ±10% continuity.

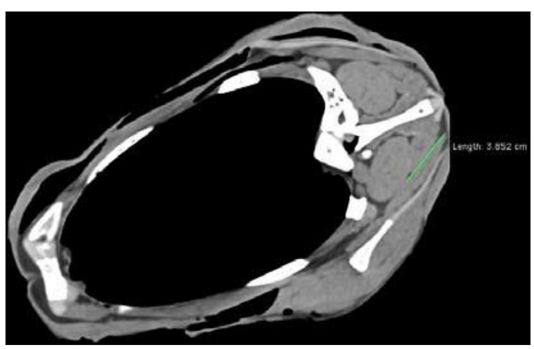


Figure 20 - Example lamb seam measurement

6.2.2.1 Lamb

The lamb results are separated into fan beam and cone beam, with each being compared to a separate reference. The twenty-eight (28) second scan is the reference or 'gold standard' for the fan beam scans and the three-thousand (3000) slice image is the reference for the cone beam scans. The error is calculated as both a percentage deviation from the respective reference scan and a measurement in millimeters.

6.2.2.1.1 Fan Beam (Medical)

Scan Time	28 sec	14 sec	9 sec	5 sec	3 sec
Seam Length (mm)	38.52	38.20	37.57	Not visible	Not Visible
Error (mm)	0	-0.32	-0.95	38.52	38.52
% Error	0	0.83%	2.5%	100%	100%

6.2.2.1.2 Cone Beam (Industrial)

Scan Time (Slices)	3h 30m (3000)	1h 45m (1500)	53m (750)
Seam Length (mm)	26.5	22.14	Not visible
Error (mm)	0	-4.36	26.5
	0	-16.45%	100%

6.2.2.2 Beef

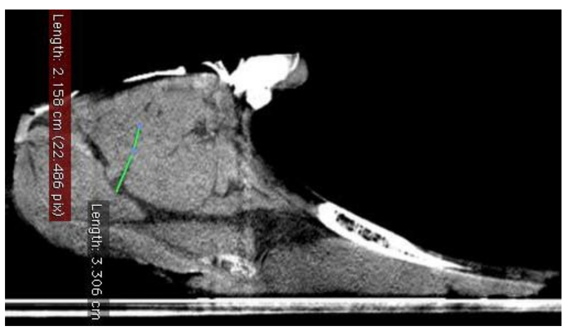


Figure 21 - Example beef seam measurement

The beef results are calculated in the same manner as the lamb results. A reference scan is identified and the percentage deviation from the reference is recorded, along with an error in millimetres. Hardware restraints during the experimental stage of the trial, limited the beef scans to fan beam only.

6.2.2.2.1 Fan Beam (medical)

Scan Time	30 sec	15 sec	7 sec
Seam Length (mm)	54.64	53.56	52.90
Error (mm)	0	-1.08	-1.74
% Error	0	-1.98%	-3.18%

6.2.3 Discussion

Specials	Proven	Indicative Speed	Notes
Lamb (medical)		Between 5-9 seconds	
Lamb (industrial)			
Beef		< 7 seconds	

6.3 Lean Meat Yield

This test involves identifying and segmenting three different tissue types; meat, fat and bone. Then calculating the overall meat volume of the full carcase (i.e. without the bone and fat).

6.3.1 Current industry standard

Currently lean meat yield is calculated by weighing muscle tissue that has been trimmed free of visible fat and comparing it to the cold carcase weight. The answer is expressed as a percentage of the total cold carcase weight.

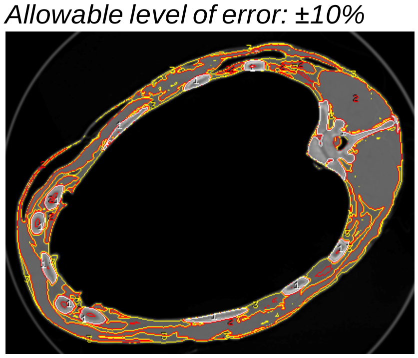
Level of error: ±10%

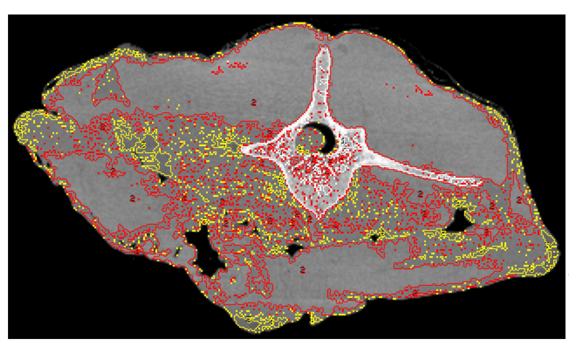
6.3.2 Test applied

A common threshold value was calculated from the gold standard scan, then applied to all other scans to ensure standardisation of results. The scans were then segmented and values for each tissue type recorded.

- Threshold values identified
- Threshold values applied to scans and data stored

Allowable level of error: ±10%





6.3.2.1 Lamb

The lamb results are separated into fan beam and cone beam, with each being compared to a separate reference. The twenty-eight (28) second scan is the reference or 'gold standard' for the fan beam scans and the three-thousand (3000) slice image is the reference for the cone beam scans. The error is calculated as both a percentage deviation from the respective reference scan and a measurement in millimetres cubed.

6.3.2.1.1 Fan Beam (Medical)

Scan Time	28 sec	14 sec	9 sec	5 sec	3 sec
Volume (mm^3)	2310108	2000108	1013840	181315	171315
Error (mm^3)	0	-310000	-1296268	-2128793	-2138793
% Error	0%	13.41%	56.11%	92.15%	92.58%

6.3.2.1.2 Cone Beam (Industrial)

Scan Time (Slices)	3h 30m (3000)	1h 45m (1500)	53m (750)
Volume (mm^3)	235625	195625	165001
Error (mm^3)		-40000	-70624
% Error	0%	-16.98%	-29.97%

6.3.2.2 Beef

The beef results are calculated in the same manner as the lamb results. A reference scan is identified and the percentage deviation from the reference is recorded, along with an error in millimetres cubed. Hardware restraints during the experimental stage of the trial, limited the beef scans to fan beam only.

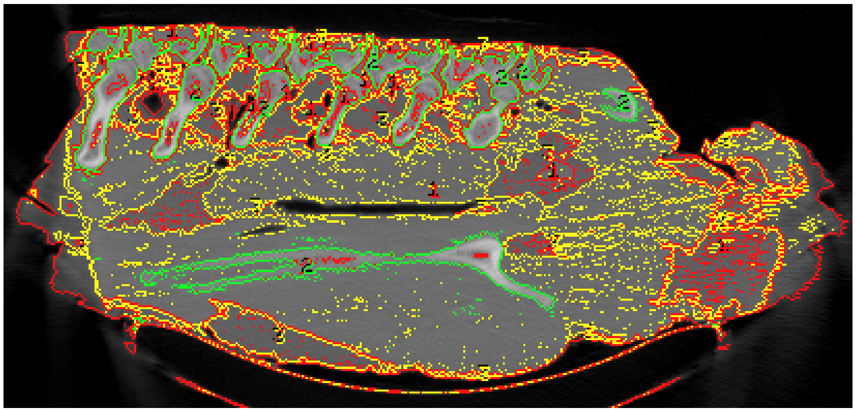


Figure 22 - Example beef lean meat yield measurement

6.3.2.2.1 Fan Beam (Medical)

Scan Time	30 sec	15 sec	7 sec
Volume (mm^3)	5410108	4010108	3510108
Error (mm^3)	0	-1400000	-1900000
% Error	0%	-25.88%	-35.12%

6.3.3 Discussion

Specials	Proven	Indicative Speed	Notes
Lamb (medical)		Between 14-28 seconds	If the 28 second scan is an accurate measurement of the carcase then this would be a green light not orange.
Lamb (industrial)			
Beef		Between 15-30 seconds	If the 30 second scan is an accurate measurement of the carcase then this would be a green light not orange.

6.4 Saleable Meat Yield & GR score

This would allow a processor to determine the saleable meat yield before purchase and without having to cut a carcase. This would also allow an objective measurement method as opposed to the current subjective techniques explained below.

6.4.1 Current industry standard

Currently the outer fat of a carcase is measured using a measuring device (ruler) by a trained operator. The operator relies on his or her vision to detect the edges of the fat and meat. The operator can have a varied accuracy depending on training level, experience, age, visibility and many other factors.

Level of error: ±2mm

6.4.2 Test applied

The outer fat thickness of a carcase was to be measured. The meat and fat were segmented and the fat thickness perpendicular to the meat surface was measured. The outer fat in lamb was less than one 1mm therefore the measurement was simulated with a measurement taken from the inner stomach region of the carcase.

- Identify and isolate meat and fat.
- Identify position to measure from.
- Ensure measurements are taken from identical locations for each scan.

Allowable level of error: ±2mm

Figure 24 - Example Lamb GR measurement

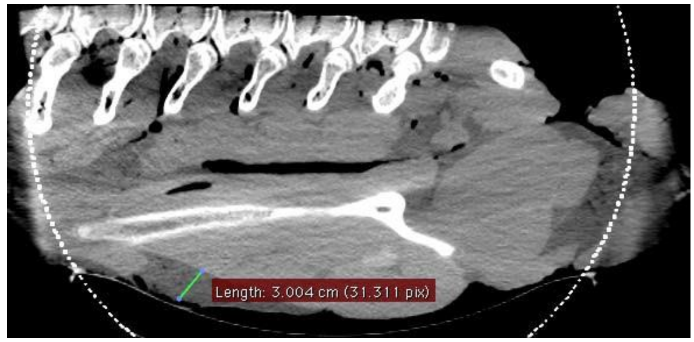


Figure 23 – Example Beef Saleable meat yield measurement

6.4.2.1 Lamb

The lamb results are separated into fan beam and cone beam, with each being compared to a separate reference. The twenty-eight (28) second scan is the reference or 'gold standard' for the fan beam scans and the three-thousand (3000) slice image is the reference for the cone beam scans. The error is calculated as both a percentage deviation from the respective reference scan and a measurement in millimetres.

6.4.2.1.1 Fan Beam (Medical)

Scan Time	28 sec	14 sec	9 sec	5 sec	3 sec
Thickness (mm)	8.38	9.95	9.22	13.58	19.75
Error (mm)	0	+0.57	+0.84	5.2	11.37
% Error	0%	+6.80%	+10.02%	+62.05%	+135.68%

6.4.2.1.2 Cone Beam (Industrial)

Scan Time (Slices)	3h 30m (3000)	1h 45m (1500)	53m (750)
Thickness (mm)	3.64	3.54	3.47
Error (mm)	0	-0.1	-0.17
% Error	0%	-2.75%	-4.67%

6.4.2.2 Beef

The beef results are calculated in the same manner as the lamb results. A reference scan is identified and the percentage deviation from the reference is recorded, along with an error in millimetres. Hardware restraints during the experimental stage of the trial, limited the beef scans to fan beam only.

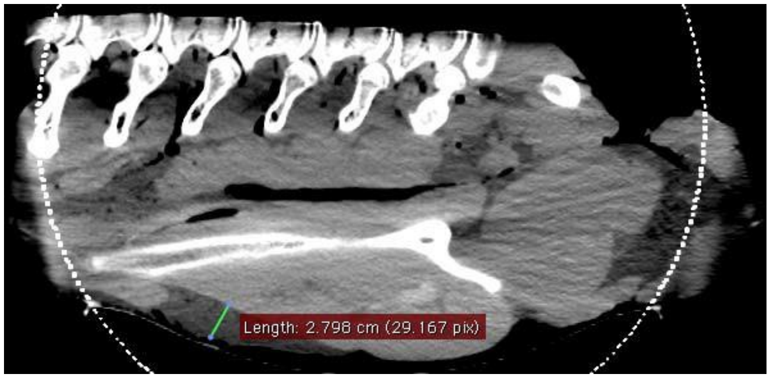


Figure 25 - Beef

6.4.2.2.1 Fan Beam (Medical)

Scan Time	30 sec	15 sec	7 sec
Thickness (mm)	30.04	27.98	26.23
Error (mm)	0	-2.06	-3.81
% Error	0%	-6.86%	-12.68

6.4.3 Discussion

Specials	Proven	Indicative Speed	Notes
Lamb (medical)		Between 5-9 seconds	
Lamb (industrial)		< 53 minutes	It is unknown what reasonable time, from a processing perspective this could be reduced to.
Beef		Between 7-15 seconds	

6.5 Marbling (Beef Only)

This test would identify the potential of 3D x-ray in identifying marbling scores of carcases without chilling (hot marbling score).

6.5.1 Current industry standard

Currently the carcase is chilled for a number of days after which an operator scores the carcase by visually comparing the meat with a reference score card. This is a proven subjective measurement which can be influenced by many factors including time chilled and light conditions.

Level of error: ±4%

6.5.2 Test applied

The meat, fat and bone of the carcase was identified and the bone tissue removed. A common preselected area had been chosen and the percentage marbling inside the common area recorded. The preselected area was placed on identical sites for each scan to ensure uniformity of results.

- Identify rib bones.
- Identify meat and fat.
- Segment fat from meat.
- Isolate given area.
- Take measurement of fat in selected isolated area.

Allowable level of error: ±4%

Figure 26 - Example marbling measurement

6.5.2.1 Beef

A reference scan is identified and the percentage deviation from the reference is recorded, along with an error in millimetres squared. Hardware restraints during the experimental stage of the trial, limited the beef scans to fan beam only.

6.5.2.1.1 Fan Beam (Medical)

Scan Time	30 sec	15 sec	7 sec
Area (mm²)	57.59	54.84	53.17
Error (mm²)	0	-2.75	-4.42
% Error	0%	-4.78%	-7.67%

6.5.3 Discussion

Specials	Proven	Indicative Speed	Notes
Beef	●	15 seconds	

6.6 Eye Muscle Area

This test involved identifying and isolating the eye muscle in a carcase and measuring the eye muscle area.

6.6.1 Current industry standard

Currently an operator makes a cut at the required section of a carcase and then uses a measuring device (either a ruler or electronic grid) to measure the muscle area collected.

Level of error: ±5% *(manual measurement)(most common)*
Level of error: ±1% *(electronic grid measurement)*

6.6.2 Test applied

The threshold values for the gold standard scan were determined, then applied to all other scans to ensure equivalent segmentation results. Once segmented the eye muscle was identified and isolated using the muscle seam. The surface area of the isolated eye muscle was then calculated and recorded.

- Identify threshold values.
- Identify and locate required rib bone.
- Isolate required muscle.
- Obtain surface area measurement.

Allowable level of error: ±5%

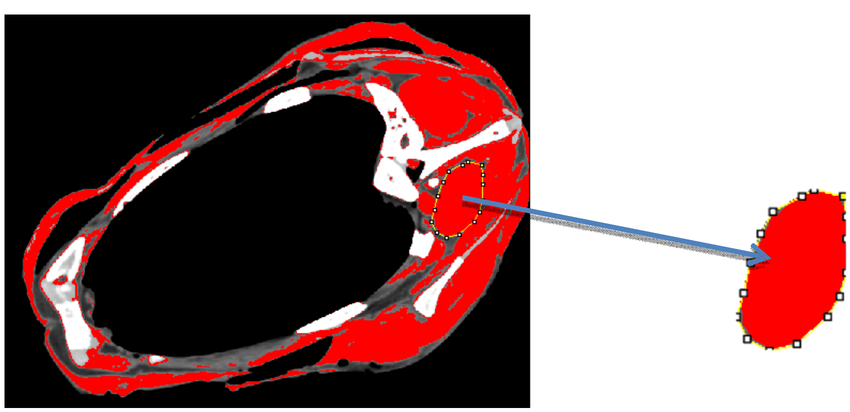


Figure 27 - Lamb eye fillet area

6.6.2.1 Lamb

The lamb results are separated into fan beam and cone beam, with each being compared to a separate reference. The twenty-eight (28) second scan is the reference or 'gold standard' for the fan beam scans and the three-thousand (3000) slice image is the reference for the cone beam scans. The error is calculated as both a percentage deviation from the respective reference scan and a measurement in millimetres squared.

6.6.2.1.1 Fan Beam (Medical)

Scan Time	28 sec	14 sec	9 sec	5 sec	3 sec
Area (mm^2)	865.56	860.36	803.12	907.66	943.24
Error (mm^2)	0	-5.2	-62.44	42.1	77.68
% Error	0	-0.60%	-7.21%	5.86%	8.97%

6.6.2.1.2 Cone Beam (Industrial)

Scan Time (Slices)	3h 30m (3000)	1h 45m (1500)	53m (750)
Area (mm^2)	1582.77	1579.32	1575.41
Error (mm)	0	-3.45	-7.36
% Error	0%	0.21%	0.5%

6.6.2.2 Beef

The beef results are calculated in the same manner as the lamb results. A reference scan is identified and the percentage deviation from the reference is recorded, along with an error in millimetres squared. Hardware restraints during the experimental stage of the trial, limited the beef scans to fan beam only.

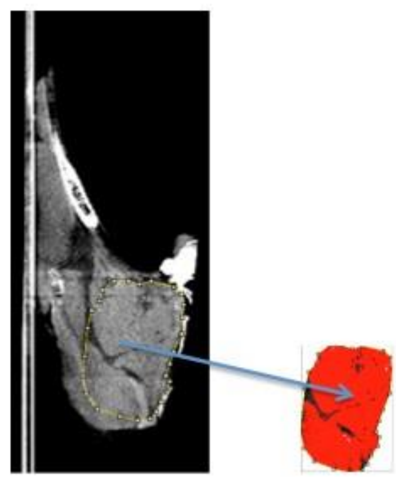


Figure 28 - Beef eye fillet area

6.6.2.2.1 Fan Beam (Medical)

Scan Time	30 sec	15 sec	7 sec
Area (mm^2)	19020	17560	17325
Error (mm^2)	0	-1460	-1695
% Error	0%	-7.67%	-8.91%

6.6.3 Discussion

Specials	Proven	Indicative Speed	Notes
Lamb (medical)		Between 5-9 seconds	
Lamb (industrial)			
Beef		Between 15-20 seconds	

6.7 Subcutaneous Fat & Hump Height (Beef Only)

This test includes two (2) uses, which involve measuring the same tissue type (fat) in varying locations. Subcutaneous fat and hump height are both are measure of fat thickness in different locations on a beef carcase. The equivalent to subcutaneous fat for lamb is the GR. The beef carcase scanned did not have a hump, as a result, there is no measurement for hump height. However, we know that hump height is the same type of measurement as subcutaneous fat (fat thickness measurement) therefore we can make an assumption that the accuracy for both uses will be equal.

6.7.1 Current industry standard

Currently an operator measures the fat thicknesses using a measuring device (ruler), where the operator relies on his or her vision to identify fat thickness.

Level of error: +/- 2mm

6.7.2 Test applied

The meat and fat of the scan had to be isolated and a high contrast image used to allow maximum contrast between tissue types. A measurement was then taken perpendicular to a single meat pixel and directed toward the edge of the carcase. All measurements were taken from the same position or as close to as possible.

- Meat and fat isolated.
- Co-ordinate for measurement position identified.

- Measurements taken from identical position and distance recorded.

  Allowable level of error: +/- 1mm

Figure 29 - Beef Subcutaneous fat

6.7.2.1 Beef

A reference scan is identified and the percentage deviation from the reference is recorded, along with an error in millimetres. Hardware restraints during the experimental stage of the trial, limited the beef scans to fan beam only.

6.7.2.1.1 Fan Beam (Medical)

Scan Time	30 sec	15 sec	7 sec
Thickness (mm)	32.03	31.81	31.72
Error (mm)	0	-0.22	-0.31
% Error	0%	-0.7%	-0.97%

6.7.3 Discussion

Specials	Proven	Indicative Speed	Notes
Beef	●	<7 seconds	

7 SUMMARY OF RESULTS

7.1 KNOWN HARDWARE SPECIFICATIONS FOR PROVEN USES

Table 5 summarises whether the Siemens hardware could objectively measure the identified uses.

Table 5: Summary of whether Siemens hardware could objective measure the uses within a reasonable Beef (20s) and Lamb (7s) processing time

Use	Sheep / Lamb		Beef
	Fan Beam (Medical)	Cone Beam (Industrial)	Fan Beam (Medical)
Automated cutting between bones	🟢	🟢	🟢
Automated cutting between primals	🟢	🔴	🟢
Lean Meat Yield	🟠	🔴	🟠
Saleable Meat Yield	🟢	🟢	🟢
Marbling	N/A	N/A	🟢
Eye Muscle Area	🟢	🔴	🟢
Hump Height	N/A	N/A	🟢
Subcutaneous Fat & GR	🟢	🟢	🟢

7.2 RECOMMENDED HARDWARE SPECIFICATIONS

Table 6 outlines the minimum hardware requirements for each lamb and beef use, divided into cone and fan beam systems. Where applicable minimum requirements are given, if the current hardware specifications did not meet the required standards for measure, then an upgraded recommended specification is given in

Table 6: Uses than could be measured on Siemens Laboratory Hardware

	Fan Beam		Cone Beam
Use	**Lamb**	**Beef**	**Lamb**
Automated cutting between bones	Voltage (kV) = 140 Scan time < 3 sec	Voltage (kV) = 140 Scan time < 7 sec	Voltage (kV) = 130 Scan time < 53 mins
Automated cutting between primals	Voltage (kV) = 140 Scan time = 5-9 sec	Voltage (kV) = 140 Scan time <7 sec	
Lean Meat Yield	Voltage (kV) = 140 Scan time < 3 sec	Voltage (kV) = 140 Scan time < 7 sec	
Saleable Meat Yield	Voltage (kV) = 140 Scan time = 14-28 sec	Voltage (kV) = 140 Scan time = 15-30 sec	Voltage (kV) = 130 Scan time = 53 mins
Marbling		Voltage (kV) = 140 Scan time = 15 sec	
Eye Muscle Area	Voltage (kV) = 140 Scan time = 5-9 sec	Voltage (kV) = 140 Scan time 15-20 sec	
Hump Height		Voltage (kV) = 140 Scan time < 7 sec	
Subcutaneous Fat	Voltage (kV) = 140 Scan time = 5-9 sec	Voltage (kV) = 140 Scan time 7-15 sec	
GR	Voltage (kV) = 140 Scan time 5-9 sec		Voltage (kV) = 130 Scan time < 53 mins

7.3 Predicted Hardware Specifications for Better Use Determination

Table 7: Predicted hardware settings for Uses that couldn't be measured on Siemens laboratory hardware

	Hardware Upgrades		Software Upgrades
	Lamb	**Beef**	
Lean Meat Yield	Voltage (kV) = 200 Scan time = 6 sec	Voltage (kV) = 140 Scan time = 9 sec	Development of an algorithm to interpolate results more accurately.

8 Recommendations and Conclusions

The overall goal of the research was to determine the minimum (or optimum) specifications for a machine to be able to:

- View, identify and quantify; meat, fat and bone in lamb and beef
- View, identify and quantify marbling in beef

The two projects that were originally submitted to AMPC Technical Committee proposed using a Fan Beam (Medical) scanner to undertake Beef fat, meat and bone differentiation and a Cone Beam (Industrial) scanner to undertake Beef Marbelling determination.

8.1 FAN BEAM (MEDICAL) SUMMARY

It has been conclusively demonstrated that at most levels a Fan Beam scanner can differentiate between all three constituents although additional work should be undertaken pertaining to hardware and software to ensure a more accurate saleable meat yield can be determined to the required industry standard. Scott believe that with modification to the Siemens hardware platform that increase accuracy for determination of lean meat yield would be achievable.

Both beef and lamb constituents can be successfully objectively measured using a fan beam (Medical) scanner are required industry processing rates of one beef carcase every 20 seconds and one lamb carcase every 6-7 seconds.

8.2 CONE BEAM (INDUSTRIAL) SUMMARY

Unfortunately with the issues experienced scanning beef on the cone beam (Industrial) scanner, there are no beef results to scientifically analyse the application of a cone beam scanner on beef. The lamb results depicted three(3) of six (6) Uses being objectively measured by the cone beam system, however this was at a 53 minute scan time.

Although the cone beam scanner cannot categorically be removed from consideration as a result of these trials, Scott believe that it is highly unlikely that further work in the cone beam area will prove viable for the processing sector.

8.3 Possible Next Steps

There are three considerations for the next steps as follows:

1. Have all of the required Attributes/Uses for objective measurement been tested/proven?
2. Is sufficient knowledge known to develop / buy a 'meat specific' hardware solution?
3. Is the required software available for the next phase(s)?

Taking each one of these at a time, the following is Scott's recommendations.

8.3.1 Attributes & Uses

The following are the attributes (which as themselves or combined with others become Uses) that have been identified as valuable to the Australian red meat processing sector.

Meat CT Attributes → Measurements, Calculations and Inferences

	M	C	I		M	C	I		M	C	I
● (green) Skeletal Mapping	●			● (green) Marktet Cuts/Weights		●		● (green) Dentition	●		
● (green) Determination fo E.M.A		●		● (green) Ossification/Age	●			● (yellow) Meat colour			●
● (green) GR Score (Rib Fat)	●			● (yellow) Cysts	●			● (yellow) Skin Quality	●		
● (green) Location of Seams	●			● (yellow) Abscess	●			● (yellow) Glycogen			●
● (green) Marbling (hot/cold)	●			● (yellow) Disease (i.e. liver)	●			● (yellow) Juiciness			●
● (green) Lean meat yield		●		● (yellow) Eating quality			●	● (green) Gender	●		
● (green) Hump height	●			● (yellow) Ext. contamination	●			● (green) Growth (Live)	●		
● (green) Determination of SMY		●		● (yellow) Tenderness			●	● (yellow) Arthritis	●		

All of the Attributes with a green indicator have been successfully demonstrated to be able to be measured for both beef and lamb are the required beef and lamb indicative processing rates with a fan beam (Medical) scanner.

The remaining Attributes ideally from a cost effectiveness point of view need to be measured by having a scanner located within a meat processing facility.

8.3.2 Hardware Unknowns

The current research project has developed a concise determination of the hardware spefications for the tested uses. A system can now be design and installed in a Beef (and Lamb) processing facility. Siemens has provided an indicative estimate of $600,000 Euro to develop a Beef system for installation into an Australian meat processing location.

In addition to this an allowance of an addition AUD$250,000 for site installation and modifications and $250,000 for labour and operating costs. This indicative budget will enable all of the required meat and other samples to be analysed and the final hardware specification for all uses developed and refined.

8.3.3 Software Development

Additional software will required development to enable images to be automatically analysed for the Uses identified within this research. Companies such as the Mayo Clinic with their Analyze program and other software companies and software researchers/developers will need to be engaged for these developments. However first the hardware needs to be developed to enable the required images to be obtained to then enable the software developers to develop the requisite software.

8.4 PATH FORWARD

Industry should consider a 3D x-ray development program over the next 3-4 years.

The first two years would require an indicative budget of AUD$1.5 million to develop, install, operate and modify a beef side hardware platform, based on fan beam (i.e. Medical) platform.

Years 3-4 (an on) would then focus on the required software development, although some of this could commence in years 1-2. An indicative budget of AUD$500,000 – 1,000,000 may be required for software development.

Development of a full side Beef system would lead to the development of one off uses on primals, offals, trim and waste. Hence one large system installed as a research platform will enable a plethora of other uses that required small (and hence cheaper) hardware and software solutions all based on the same 3D x-ray platform.

9 APPENDIX A - EXPERIMENTAL PROBLEMS ENCOUNTERED:

9.1 OBTAINING MEAT

Obtaining the meat (lamb/beef) served as a problem as there were few wholesalers of meat near the Siemens research facility. This required additional time and costs to locate, purchase and transfer the meat to the laboratories for testing.

9.2 CALIBRATION TIME

After each scan, both systems (cone beam/fan beam) required recalibration, Due to the meat position changing slightly with machine vibrations. The calibration process required; 1-5 minutes for the fan beam system and 30 mins to 1 hour for the cone beam system. Coupled with other time consuming tasks consumed valuable scanning time.

9.3 STORING MEAT

Once the meat was transferred to the Siemen's Munich facility, the additional problem of storage became apparent. With no accessible facilities to store the meat at a sufficiently low temperature, the only identified location was the complex' cafeterias. With the cafeteria open between the hours of 8am - 2pm, all scanning and testing had to be conducted between the 6 hour time period, and after the 1 hour of calibration was conducted. This allowed a maximum scanning time of 5 hours per day.

9.4 SCANNING TIME

Medical x-ray machines (fan beam) operate on a quicker time frame than the industrial machines (cone beam). This is undertaken to reduce x-ray exposure and avoid health risks to the human patient being scanned. In contrast the industrially designed cone beam machines do not have the same exposure risks, therefore they are designed to operate at much slower speeds.

9.5 CONE BEAM (INDUSTRIAL)

Due to the low power output of the cone beam machine in the Siemens research facilities, no results could be extracted from the beef cone beam scans. Although disappointing, nil results indicate that, a significantly higher tube power is required for scanning beef (in comparison with lamb). The cone beam machine used for the trials, requires at least a 10 fold increase in power, to be able to measure the desired properties.

This increase in speed comes at a price to the medical machines. As the scan speed is increased the scan resolution decreases accordingly. A typical medical CT machine can scan at a rate of 30.58 cm/sec but only has a maximum resolution of 1mm. Conversely, an industrial CT machine can have a resolution of up to 200 μm but can only scan at a maximum rate of 0.001 cm/sec[3].

In order to measure the meat attributes listed in section 4, a minimum resolution of one (1) mm is required.

As a result each cone beam scan could take anywhere between 1 - 6 hours (depending on the number of projections required) and coupled with all the other time-obligated procedures detailed in this section, it greatly reduced the amount of scans that could be conducted on any single day.

9.6 AVAILABILITY OF THE HELICAL (MEDICAL) SCANNER

The helical scanner located in the research laboratory in Munich, was not functioning due to unforeseen circumstances, which meant that the nearest available helical scanner was located 200km's from Munich. This required the meat to be transferred to the other laboratory, as quickly as possible to stop the meat from decomposing.

[3] All times are calculated based on trialed machines and can vary depending on chosen settings

9.7 SCANNING OF BEEF

The beef carcase was packaged into a custom built container (Figure 2), packed with foam and other soft material to stop the meat from moving whilst being rotated during the scan. Due to the sheer size and weight of the beef, and the design of the container, the jig was unable to rotate in a controlled manner.

To allow the platform to rotate as required, the container had to be held up by an overhead crane. The setup of the crane, took up valuable time (7 hours). This was then followed by an extensive calibration process, which required calibration of the x-ray system and calibration of the rotational platform, all taking up considerable time.

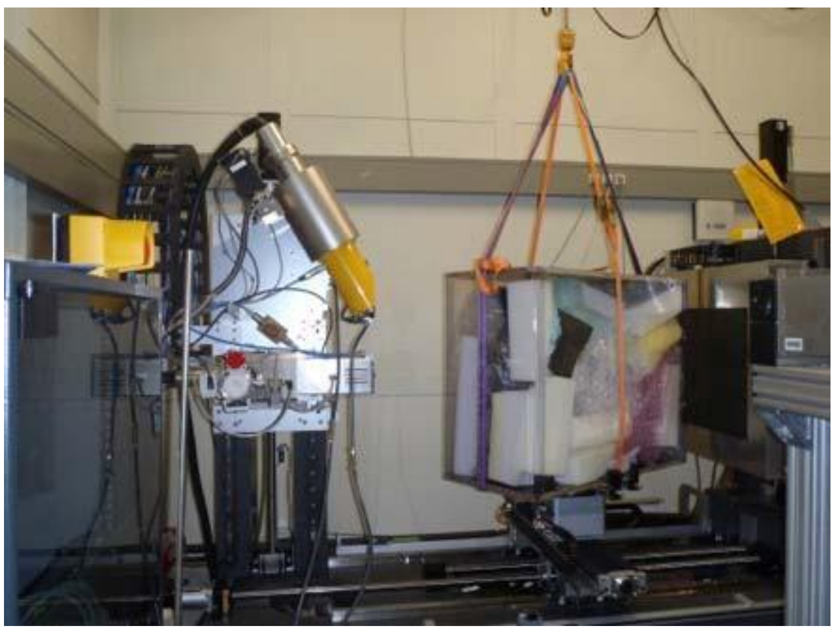


Figure DD - Beef Scanning Setup

10 APPENDIX B - TECHNICAL PROBLEMS ENCOUNTERED

10.1 CUPPING

Cupping is an artefact in the volume data where the Gray levels towards the centre of an object are lower than the Gray levels around the outer layers of an object. The Gray levels in an object should remain constant, as the material is homogenous. This phenomenon is called cupping due to the shape of the line created in the Gray level vs. position graph (Figure 16), where there is a dip effect in the middle of the graph similar to a cup shape.

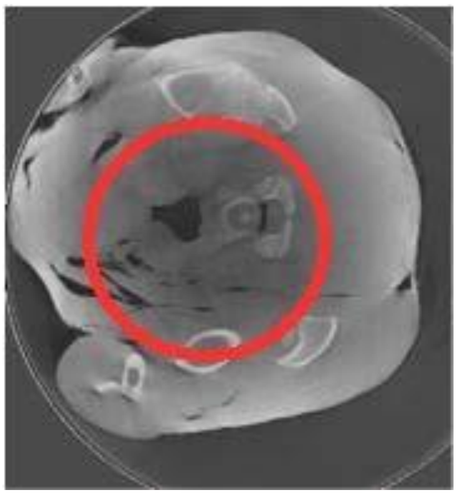


Figure EE - Example of X-ray with cupping (affected area highlighted). As the X-ray gets closer to the centre of the object the image gets darker due to higher absorption of X-rays

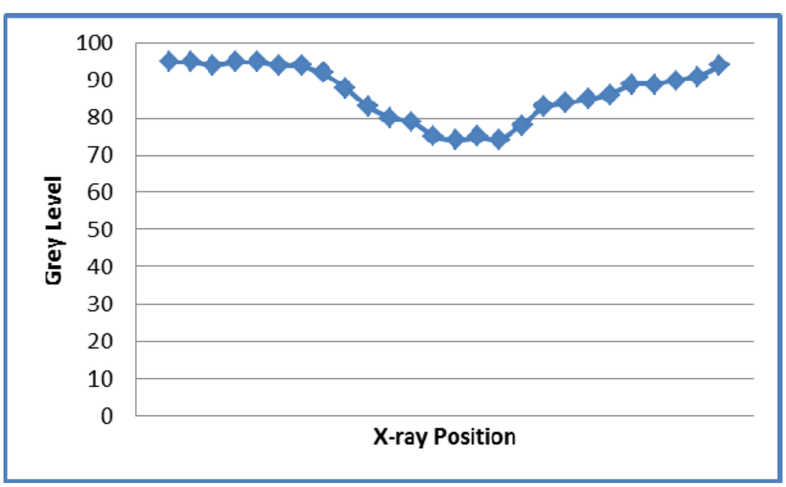


Figure FF - Example of Cupping Graph

Cupping causes a difference in the overall intensity of the X-ray. This results in a lower quality image where only low accuracy segmentation is possible.

10.1.1 How to counteract cupping

It is possible to counteract cupping by filtering the image (post scan), but this can result in unwanted changes in the image, which can result in false results. In order to remove cupping the cause must be determined and then eliminated.

10.1.2 Causes of cupping

Cupping is caused by 3 phenomena;

- Beam hardening
- Scatter
- Material thickness

10.1.2.1 Beam hardening

The soft X-rays are eliminated in the first few centimetres of the object being scanned. Travelling through the material the x-ray beam gets harder causing the average intensity of the photons to increase. This allows the photons to penetrate longer distances and pollutes the image quality as the pixels are over intensified.

10.1.2.2 Scatter

The x-ray beams travelling through the material are, ideally, supposed to be removed by absorption in the atoms of the material, a phenomena known as the photo effect. This difference in absorption levels causes the image(s) to appear on the detector.

The energy in the x-ray photon travelling through the material is not absorbed, rather, the energy is maintained as the photon passes through the material. This extra intensity in the photon causes the photon to change direction when leaving the atom and the photon moves in an uncontrollable manner which creates interference in the results.

10.1.2.3 Material thickness

The X-rays cannot penetrate the object because the x-ray intensity/power is not high enough to pass through the object thickness. This also causes streaks and other artefacts. Both beam hardening and scatter increase the intensity levels on the detector creating false images and polluting the image.

10.2 SCATTER

Scattering is when the x-rays produced, move through atoms, of the material being scanned and for an unknown reason, change their path of travel. Ideally, x-rays should lose energy when passing through an atom and continue moving in the same direction as when entering the atom. This loss of energy is then recorded by the detector. There are 2 types of scatter.

Compton scattering - The X-ray(s) photon loses intensity and changes direction. This loss of energy causes the photon to change direction and results in the photon rebounding of other objects and returning towards the detector, providing false results.

Rayleigh scattering –The X-ray(s) photon loses a significant amount of intensity but maintains the original path. This loss in intensity doesn’t allow the x-ray photons to reach the detector or they reach the detector with a weak signal which results in an unreadable image.

10.2.1 How to counteract scatter

There are 2 techniques to eliminate scatter;

- Removing scatter *before* it reaches the detector
- Countering the scatter in post image processing

10.2.1.1 Before taking X-ray:

Reduce the source of the scatter through use of collimation; this can be done by going from a cone beam to a fan beam. As the beam is only directed in straight lines which minimises the amount of scatter in surrounding material (e.g. bouncing off walls). Alternatively, scatter grids can be used. Scatter grids are lead grids, which are placed in front of a detector to blocks x-rays coming from unwanted angles.

10.2.1.2 Post X-ray:

Record the background scatter by blocking the x-ray from going to the detector. Thus allowing only background scatter to be detected, this background scatter image is then subtracted from the final x-ray image, resulting in an image with less scatter. This is an iterative process and requires a great deal of time and processing power.

10.3 NOISE

10.3.1 What is noise?

Noise is interference that causes unwanted effects on the generated photons and on the detector. Noise is caused by; Cosmic rays, electromagnetic noise from the X-ray tubes or motors and white noise.

10.3.2 Why does noise occur?

Noise is uncontrollable and is in every measurement on the earth. Noise can only be minimised, not eliminated.

10.3.3 How to counteract noise

Noise from X-ray equipment can be calculated and minimised from the x-ray image. Background noise can be measured and minimised in post x-ray processing.

Noise can be minimised by increasing the signal to noise ratio. By increasing the x-ray signal quality, or by increasing the x-ray power output, the effect of noise on the image is decreased. This is because the ratio of signal to noise is higher, resulting in more x-ray photons reaching the detector than noise interference.

The best ways to increase signal to noise ratio is to (and/or):

- Increase the tube current.
- Increase the intensity.
- Increase the number of projections.

All of these techniques increase the average signal per image, while simultaneously reducing the interference from surrounding noise.

10.4 BINNING

An alternative method of counteracting noise is binning.

10.4.1 What is binning?

Binning is where a number of small pixels on a detector are combined together using software integration to form one large pixel (Figure 17). Each smaller pixel has a Gray scale value and these individual Gray scale values are combined and averaged to give the Gray scale value of the larger 'binned' pixel.

This technique allows a reduction in noise, as it takes an average value of each of the pixels, therefore the effect of the noise on the larger pixel is minimised.

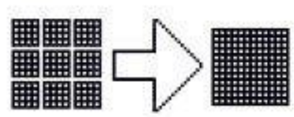


Figure GG - Binning

10.5 SOFTWARE LEARNING ISSUES

Whilst Analyze is widely used within the medical industry, the task of importing the data into the software was more technologically challenging than anticipated. Loading the files into Analyze was a complex process and required third party technical assistance to complete successfully. The files needed to be uploaded in a sequential order and if one file was misplaced or mislabelled, a system error would occur.

Once the files were correctly uploaded into the software, technical details about the files were required. This involved entering detailed technical specifications about the scanned object *and* about the x-ray detector. If any of the specifications were entered incorrectly the image(s) would not be visible. Once uploaded and with all specifications entered correctly, the files were converted from individual (.RAW) image files to a single volume file. This volume file could then be analysed using a volume analysis tool (Analyze 10.0).

10.6 SOFTWARE ANALYSIS PROBLEMS

The software thresholding process involved a significant amount of logic deduction, where the maximum and minimum values for each tissue type had to be defined. This was particularly difficult when trying to separate meat and fat, as the two tissue types were similar in density and had similar Gray levels.

The differentiation process between meat and fat, involved overlap of data resulting in fat tissue being recognised as meat and vice versa. To counteract this inaccuracy the threshold limits were refined making each range more precise and removing as much overlap as possible.

10.7 SOFTWARE COST AND CAPABILITIES

Specialised medical software was required to analyse and segment the scan data. The software was expensive and required extensive computer hardware upgrades to meet the minimum operating requirements.

Despite Analyze being at the leading edge of development software, it was incapable of analysing the collected data automatically using software pre-set values. The software had been designed for *human analysis* and any variation in density or volume required a complete recalibration of software variables. This was a major issue with the overall analysis process, as the software(s) used did not allow for variations in Gray level values. As result, a new system of Gray level values had to be identified and established. These values were then manipulated to allow the software to analyse accordingly.

10.8 LIMITATIONS OF X-RAY

X-ray works on the bases of photon collision. As an x-ray photon collides with an atom, the atom absorbs some of the photon's energy. Hydrogen, due to its electrochemical nature, absorbs wavelengths of x-ray more easily than other atoms. This causes a major problem when measuring material with high levels of hydrogen, which more commonly exists as water (H_2O).

10.8.1 Non-Organic Material

When compared to organic material, non-organic materials have significantly lower levels of Hydrogen. This insignificant Hydrogen presence allows x-rays of non-organic material to be clearer and more defined. This is one of the reasons why industrial (cone beam) machines do not operate at the same high power levels as medical (fan beam) machines.

10.8.2 Organic Material

Organic material have higher levels of hydrogen (present as H_2O) in their composition and as x-ray photons pass through an organic object, the Hydrogen atoms absorb the majority of x-ray photons and only a small amount of x-ray radiation is allowed to pass through and enter the detector. This results in blurry and poorly defined x-ray images.

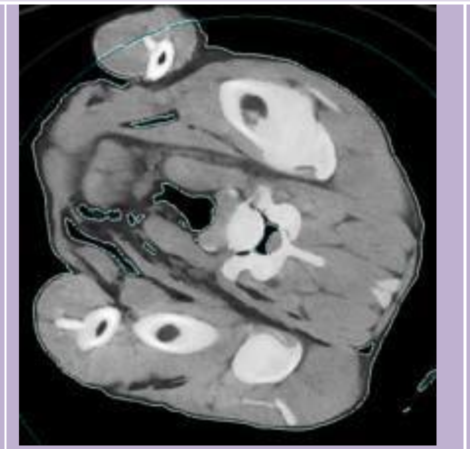
In order to counter the effects of the absorption, a high power x-ray source is required. A higher power source outputs more x-ray photons, which results in more photons colliding with Hydrogen atoms and only some being fully absorbed. This allows the other photons to pass through and reach the detector. The higher the x-ray source, the more x-ray photons produced resulting in a more defined x-ray image.

11 APPENDIX C – EXPERIMENTAL RESULTS

11.1 LAMB RESULTS

11.1.1 Helical (Fan beam)

Table 8 - Fan Beam Lamb Results

Time	3 seconds	5 seconds	9 seconds	14 seconds	28 seconds
Voltage	140	140	140	140	140
Current (mA)	595	556	547	300	489
Power (kW)	83	77.8	76.6	42	68.5
Resolution (pixel/mm)	1.506	1.506	1.506	1.431	1.438
Pixel size (mm)	0.66x0.66	0.66x0.66	0.66x0.66	0.70x0.70	0.70x0.70
istance Source to object (mm)	595	595	595	595	595
2D Cross sectional View					

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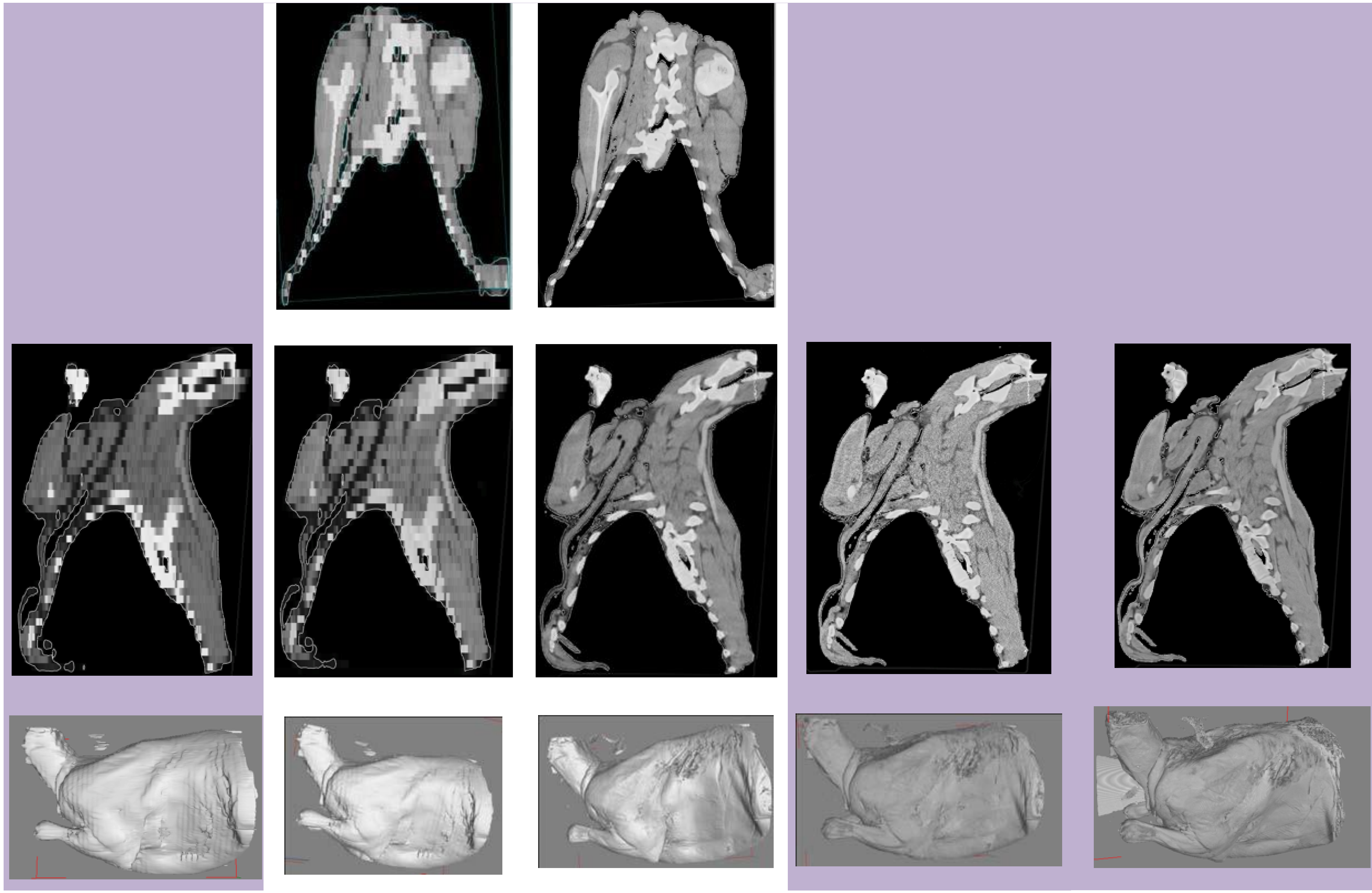

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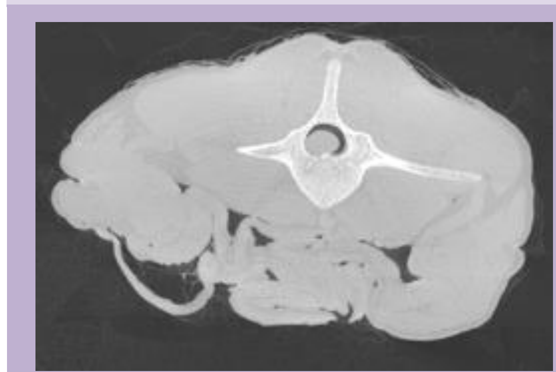
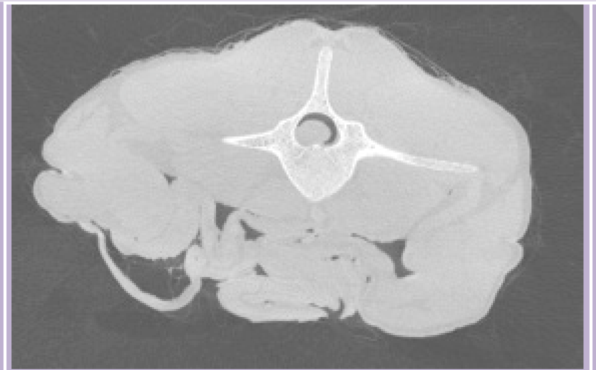
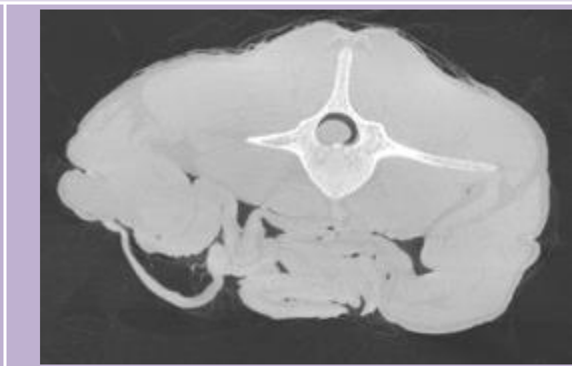
11.1.2 Industrial (Cone Beam)

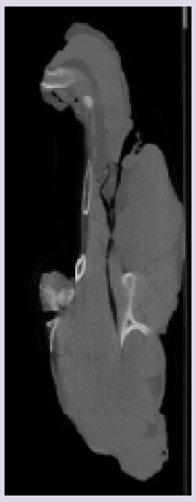
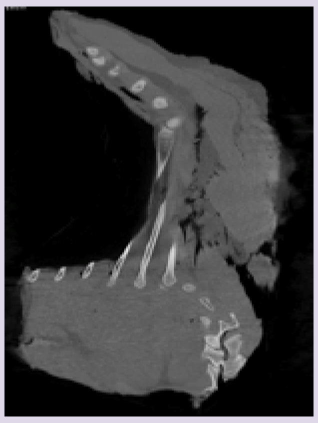
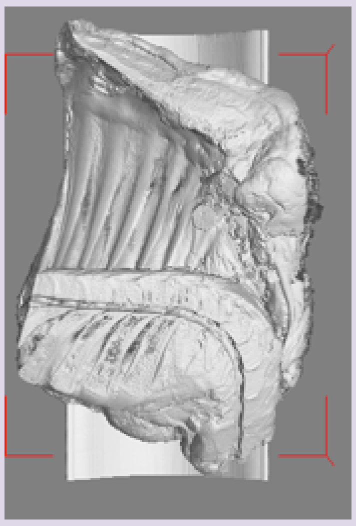
Table 9 - Cone Beam Lamb Results

(Binning) Number of Slices/Images	(2x2) 750	(4x4) 750	(2x2) 3000	(4x4) 3000
Voltage	130	130	130	130
Current (mA)	80	80	80	80
Power (kW)	10.4	10.4	11.2	11.2
Resolution (pixel/mm)	0.27130	0.27130	0.27130	0.27130
Pixel size (mm)	0.2	0.2	0.2	0.2
Distance Source to object (mm)	746	746	746	746
				

11.2 BEEF RESULTS

11.2.1 Medical/Helical (Fan beam)

Table 10 - Fan Beam Beef Results

Time	7 Sec	15 sec	30
Voltage	140	140	140
Current (mA)	551	529	485
Power (kW)	77.2	74.1	68
Resolution (pixel/mm)	0.656	0.656	0.656
Pixel size (mm)	1.52x1.52	1.52x1.52	1.52x1.52
	  		

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