final report

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Computed Tomography Beef Experiments

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Contents

1 Project description

This experimental series is designed to determine the feasibility of IMTEC's industrial X-ray computed tomography (CT) ability to rate the quality of meat samples. Experimental qualification parameters are defined through interaction with Meat and Livestock Australia (MLA). MLA has high interest in automation of the surveying and statistical profile of beef and lamb carcasses with high volume throughput. IMTEC's ability to CT scan, process and analyse meat samples with existing equipment and software on a small scale is under evaluation. Meat samples are rated statistically in percentage of fat, meat and bone. Experimental results and the ability to distinguish fat, meat and bone in test samples will determine future interest in this solution.

The experimental series direction consisted of five experiments on beef and five on lamb. The series is intended to identify CT ability to consistently distinguish fat, meat, and bone in various conditions, different cuts, different animals, different temperatures, and different age. This summary reviews the beef experiments performed. CT results are compared to surface pixilation and sample dissection weight measurements.

2 HYTEC facility

The HYTEC Technology Center is located in Los Alamos, NM, USA. HYTEC is the CT component of IMTEC, a 3M Company. HYTEC is the scientific and engineering center where its CT systems were developed and commercialized.
Data acquisition for this series utilized HYTEC's Commander CT system. The Commander utilizes a convention 450 kV 4 kW X-ray source with a 25cm x 20 cm amorphous silicone detector. The Commander system operates in a walk-in cabinet which is sealed for X-ray containmnent during X-ray operations. Beef samples are placed on a rotary stage for CT scanning and data acquisition. CT data sets are processed on-site on a multi-processor computer. Data analysis is performed with a beta/early release of IMTEC's new ILUMA Industrial Vision software for volume rendering and, meat statistics.

2.1 CT overview

X-ray CT imaging is setup by initially reviewing two dimensional radiographs of the sample object to confirm proper X-ray intensity and beam collimation for the sample size object to be scanned. The collimation is set to window the object image onto the digital recording detector during the entire 360 degree rotation of the object. Metallic pre-filters placed on the X-ray source output to reduce low energy X-ray intensity with direct open beam path to the detector. This allows X-ray penetration through the sample object with out over exposing the imaging detector in open beam areas.
The CT scan consists of recording many digital radiographs of the object as it is rotated 360 degrees. The digital radiographs are then processed to generate a 3-D volume reconstruction. Density of fat, meat and bone are distinguishable in the reconstructed volume. Statistical volume content of fat, meat and bone are then reported to calculate volume percentage of fat, meat and bone.

3 Experimental setup

3.1 Process control

IMTEC personnel organised a Prep and Process Lab where the beef samples could be stored at sub zero centigrade temperatures. Process Control technicians inserted a calibrated K thermocouple into each beef sample prior to storage at sub zero (-10 deg C). The thermocouples were inserted to a depth of about 17 mm in the mid height of the beef sample upon arrival in the lab. IMTEC purchased two 4 channel thermocouple data converters to monitor sample temperatures, freezer temperature, refrigerator temperature and experimental temperatures in the Commander cabinet. These data converters were ported into the computer in the Prep and Process Lab and the computer residing in the Commander control rack. The converters were checked for accuracy using a millivolt source and classical techniques of ice bath and boiling water comparison to thermometers. Some channels were found to have relatively gross temperature errors of 3 or 4 degrees C. These channels were adjusted and calibrated. All reporting channels were thought to be within -I-/- 1 deg C.

These resources were sufficient to track the temperatures of all samples from dry ice delivery, through storage regimes and scanning, right up to the cutting board. Process Control technicians used a warmer refrigerator set at 0 deg C to warm samples up to the approximate scanning temperatures. Samples could be warmed to 5 deg C or 10 deg C by storing at ambient lab temperatures. High temperature samples were warmed to 37 deg C using a precision oven. All samples retained their inserted thermocouple, so any sample could be plugged in and checked at any point in process life.

3.2 X-ray collimation

Lead shielding is used to reduce X-ray scatter in the Commander cabinet. Low X-ray scatter is important in recording good quality radiographs. An object mask is built to collimate the X-ray line of sight from the source through the meat sample to the detector. Figure 1 is a block diagram of the cabinet setup and shielding. Initial tests early in 2008 revealed the need to improve detector shielding. Figure 1 through 3 illustrate the developments in this area. The object mask results in low noise radiography.

3.3 X-Ray Scatter Reduction – Rev B

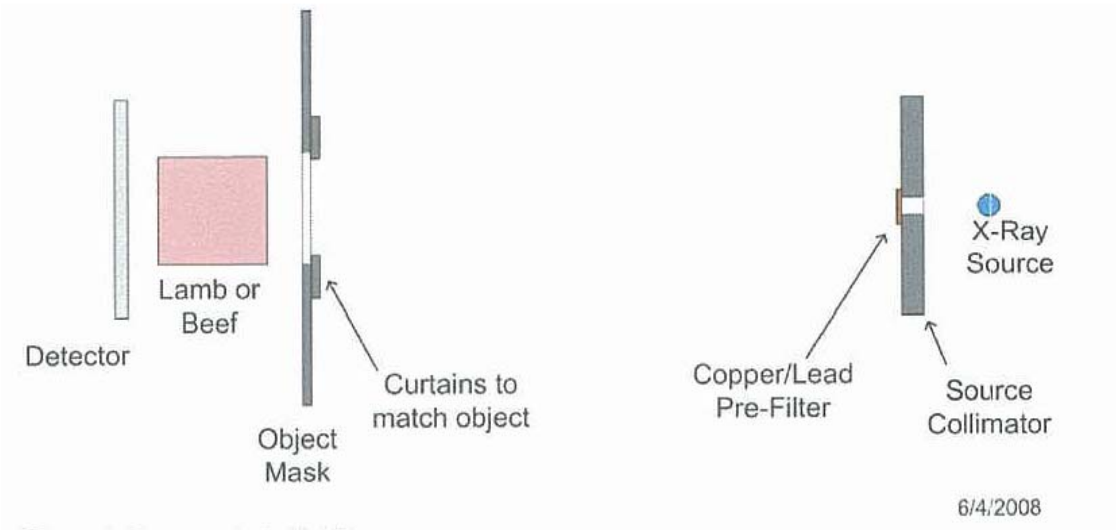

Figure I. X-ray cabinet shielding

Figure 2. Object mask as seen from X-ray source

Figure 3. Meat sample windowed in object mask

Figure 4. Meat sample on rotation stage in front of detector.

The experimental setup was in flux during initial stages of experiment one. Data acquisition and processing were reviewed to establish a sequence for the series. This included CT sample rate, beef streak orientation, establishing Hounsfield Unit calibration, and statistical volume sample rate.

4 Data acquisition and processing

4.1 CT sample rate

CT sample frame rate is the number of images recorded as the object rotates through 360 degrees. The optimum number of frames to be recorded for the best quality reconstruction is referred to as the 'full Nyquest' frame rate. Reduced frame sampling is desired if sufficient statistical results are achieved. This reduces data acquisition time, processing time and disk storage space. Half Nyquist scans achieved nearly identical results as full Nyquist. Half Nyquist frame sampling is used for the series. This results in approximately 600 frames for each CT scan.

	Full Nyquist CT Statistics (voxels)	%	Half Nyquist CT Statistics (voxels)	%
Steak test				
Fat	12,145,442	32.5	12,049,093	32.7
Meat	21,677,032	58,1	21,268,460	57.7
Bone	3,502,729	9.4	3,562.011	9.7
total	37,325,203	100	36,879,564	100

Figure 5. Nyquist sampling results.

4.2 Beef density profile and scatter correction

Density profiles are checked across the meat volume. This shows several indicators on data quality. We are looking for flat profiling across the meat volume with no rounded dishing or sloped shape. Flat profiles will allow for good statistical reporting. This requires meat density to appear uniform across the volume. Scatter correction is applied to flatten the density profile. A good result is shown in figure 6. We are looking for steps in the profile in fat to meat to bone transitions.

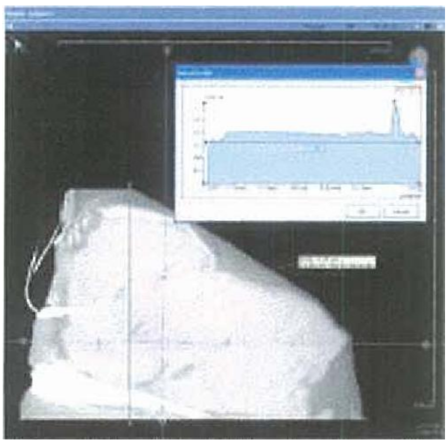

Figure 6. Exp I B2 SC I8 — density profile, flat in meat with steps in fat and bone.

4.3 Hounsfield unit calibration

Hounsfield unit, HU, calibration is performed by pre-scanning a water sample. A water container is CT scanned and processed. The CT values of air and water are mapped to - 1000 and 0 respectively for conversion to HU. This offset and scale factor is then applied to the meat scans. Water pre-scan was performed before each data run with slight variation run to run. The current calibration is a single value scaling applied to the entire image. Typical scale factor ranged around 70. Figure 7 is an HU scaled histogram of the density range of fat, meat and bone.
In going through this process it is noted that the CT value of water varies slightly over the object area, Improvements in HU calibration may be possible by mapping the scaled calibration by detector area location versus a single point referenced calibration.

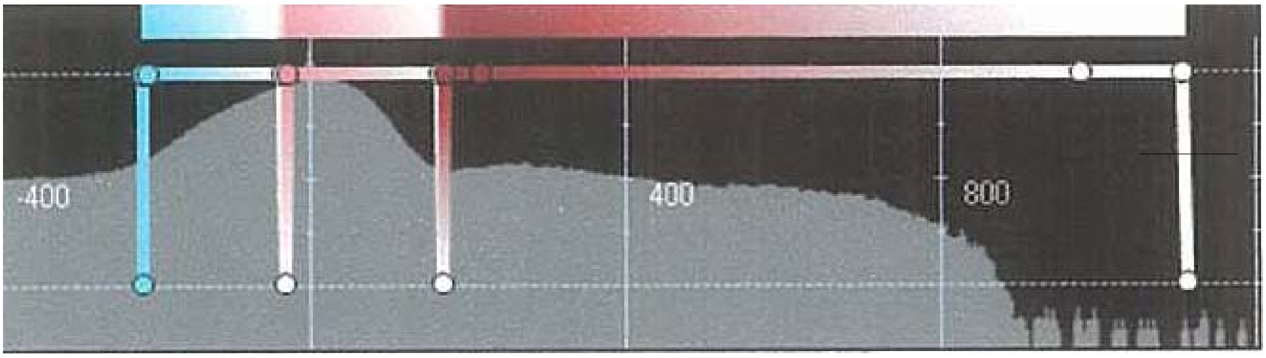

Figure 7. Volume, exp4131 sc24 hu70, fathneat/bone HU range

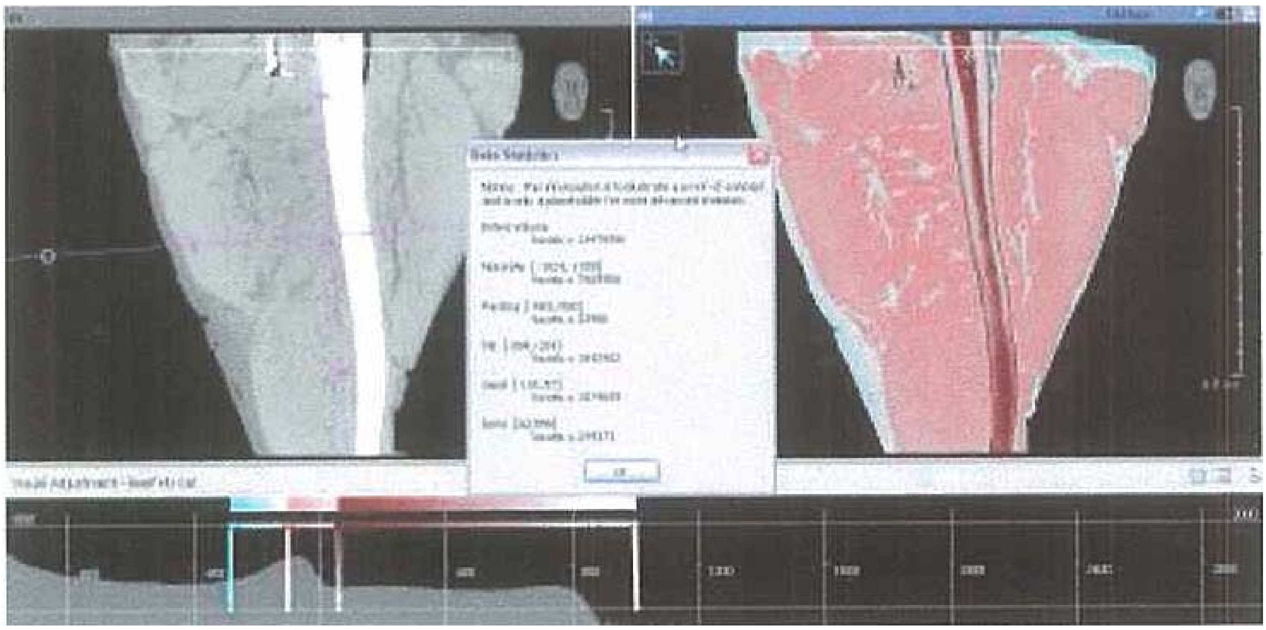

Figure 8. Volume exp I B5V HU cal 1, volume statistics.

Figure 8 shows a XY cross section of the reconstruction data set on the left and a cut section of the 3D volume rendered on the right. The color look up table over the density histogram in the lower section is applied to the 3D rendering. The look up table is adjusted to match the volume rendering to the reconstruction cross section. Statistics of the defined density ranges are shown.

4.4 Density gauge measurement

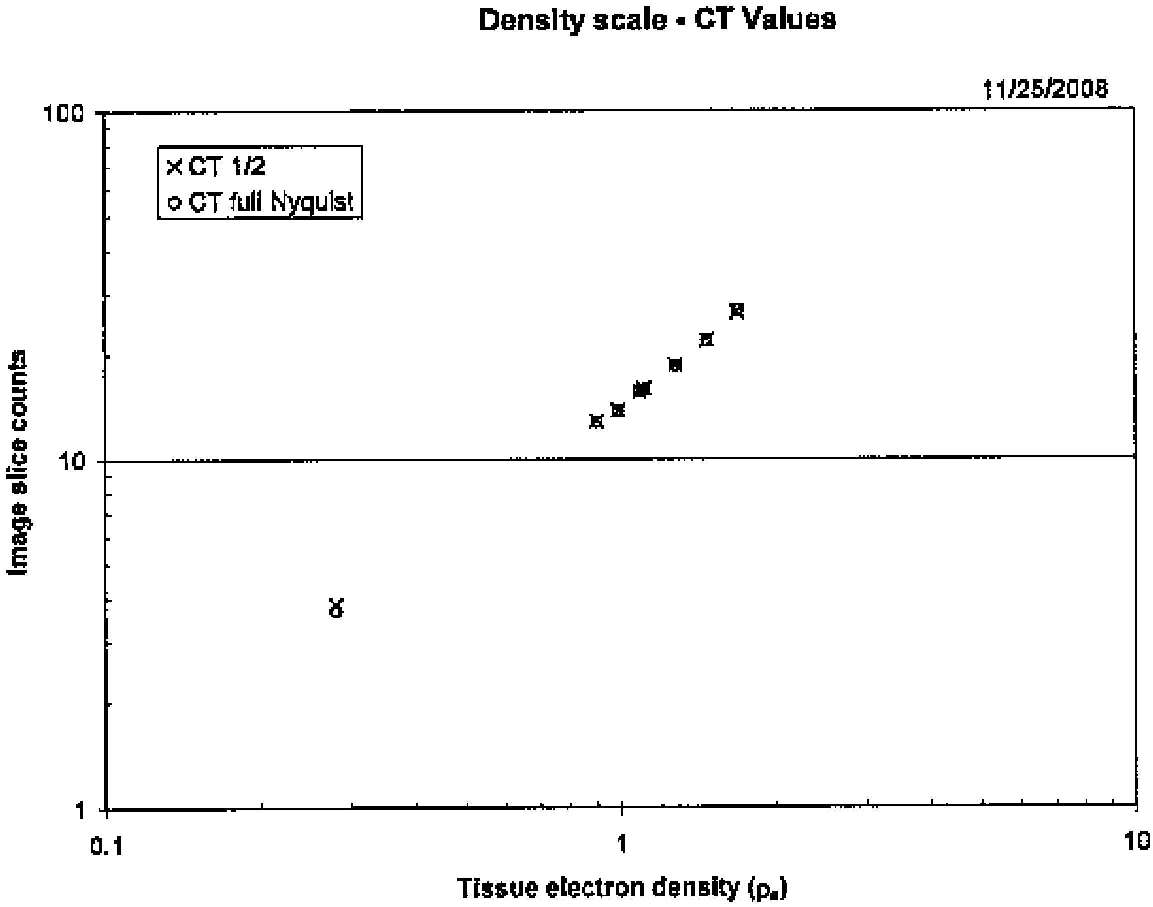

Figure 9. Density gauge CT values

Figure 9 shows CT values from processed volume reconstruction of the density gauge scan. The density gauges) scanned are shown in Figure 10. CT values of the density gauges scaled to Hounstield units are shown in Figure 11. The density signal level in CT and Hounsfield units is plotted for both full and half Nyquist sampling. The results are nearly identical indicating no degradation in density statistics from V2 Nyquist reduced sample rate.

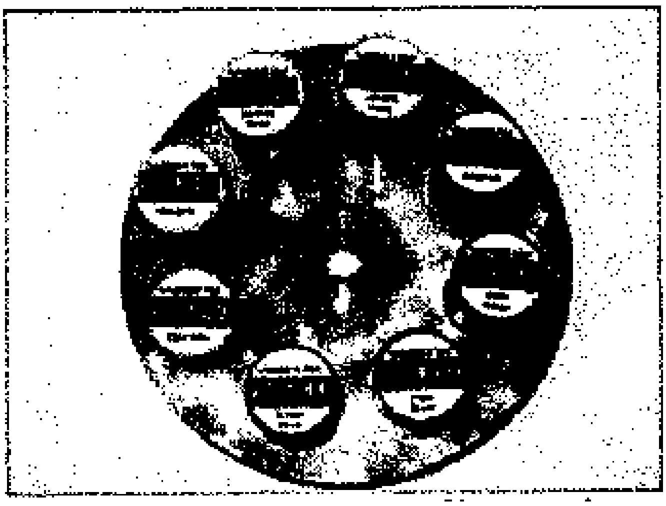

Figure 10. Density gauges of human tissue scanned for CT calibration

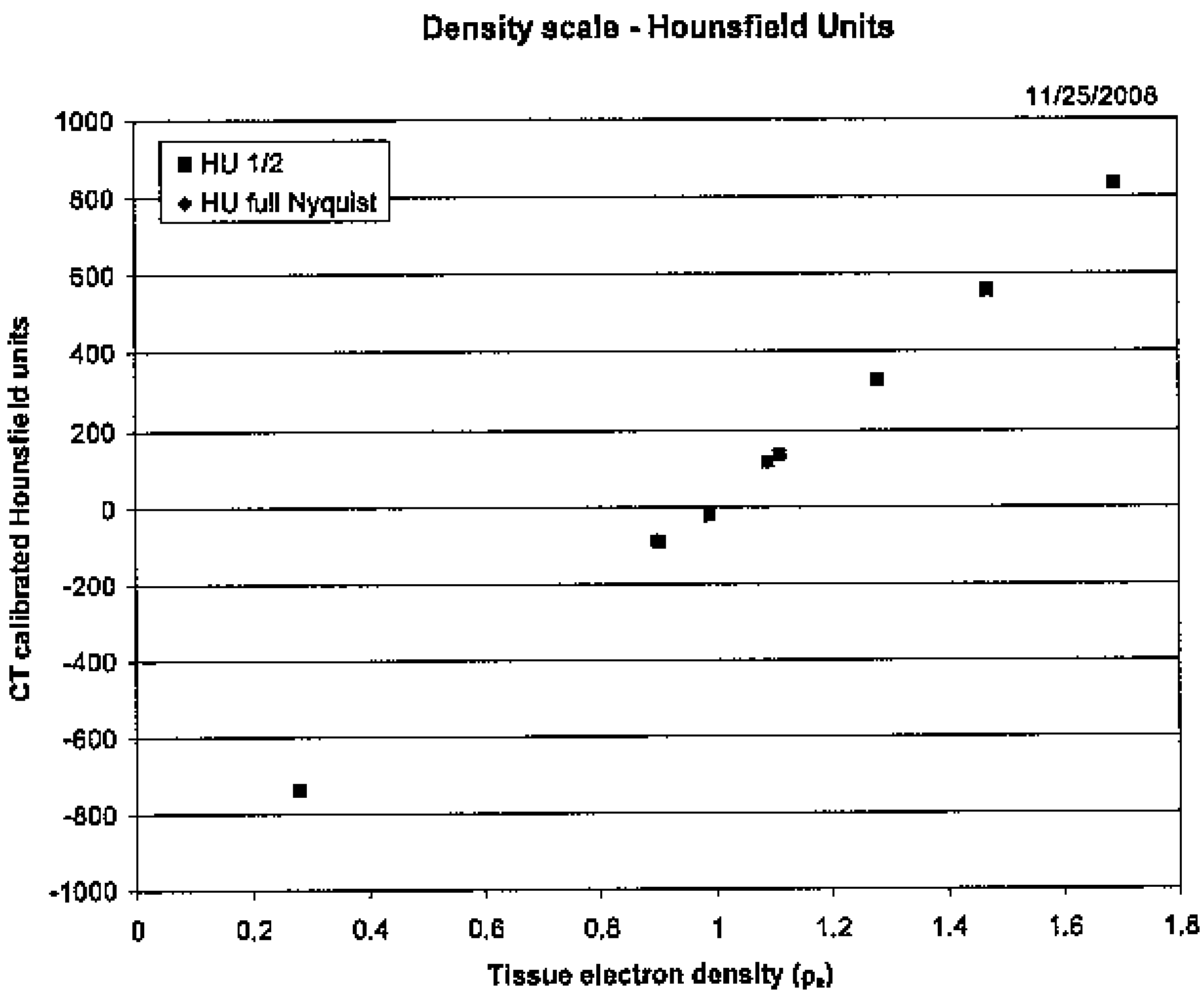

Figure 11. Density gauge CT values converted to Hounsfield units

5 Statistical evaluation

5.1 Vision program

The Vision program is designed for volume visualization in industrial uses. It is built for flexibility due to the wide range of industrial components where no two parts look alike. We are using a 'beta' version of the Vision program for the beef statistical proof of principle; components of the program are still being built.

Due to the flexibility of the Vision program and variability of meat size and shape, precise control of evaluation conditions is not built in. The current Vision program provides a sample of the statistical evaluation but is not set up for automated processing.

5.2 Centre cut profiling

In reviewing cross section profiles through beef samples, roll off toward the outer edge is evident. This edge affect is evident near the meat to air boundary. Full cross section results in sloping towards the edge, figure 9. Windowed centre cut cross sections results in flat profiling, Figure 10, with the edges cropped.

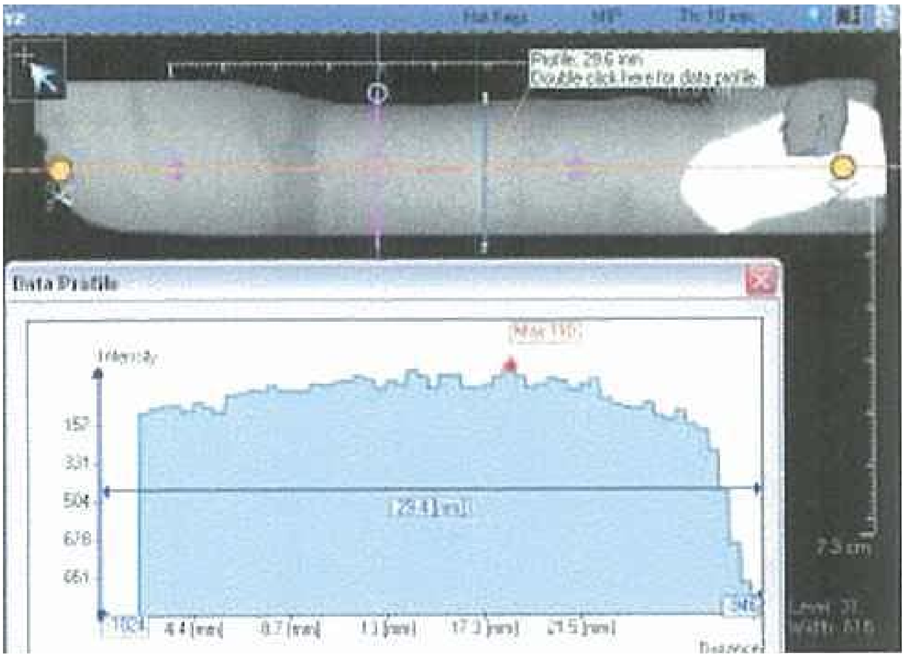

Figure 12. Full volume sloped profile

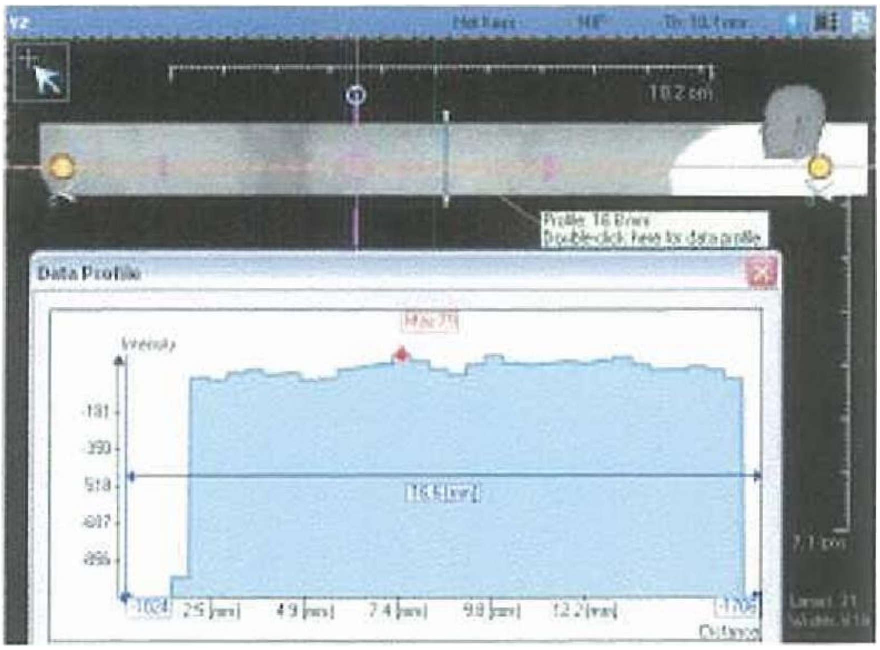

Figure 13. Centre cut flat profile.

A migrating material flattening algorithm applied to the data set would provide great improvement in statistical component detection accuracy over the full volume. The profile in figure 6 indicates the sharp transitions between fat to meat and bone. The sharp material change transitions can be distinguished from the slopping edge affects to retain sharp edges while flattening gradual transitions.

5.3 Statistical volume creation

In this proof of principal test series the edges of the reconstructed volume were cropped in volume statistical computations to avoid the roll off edge affect blurring or statistical results.

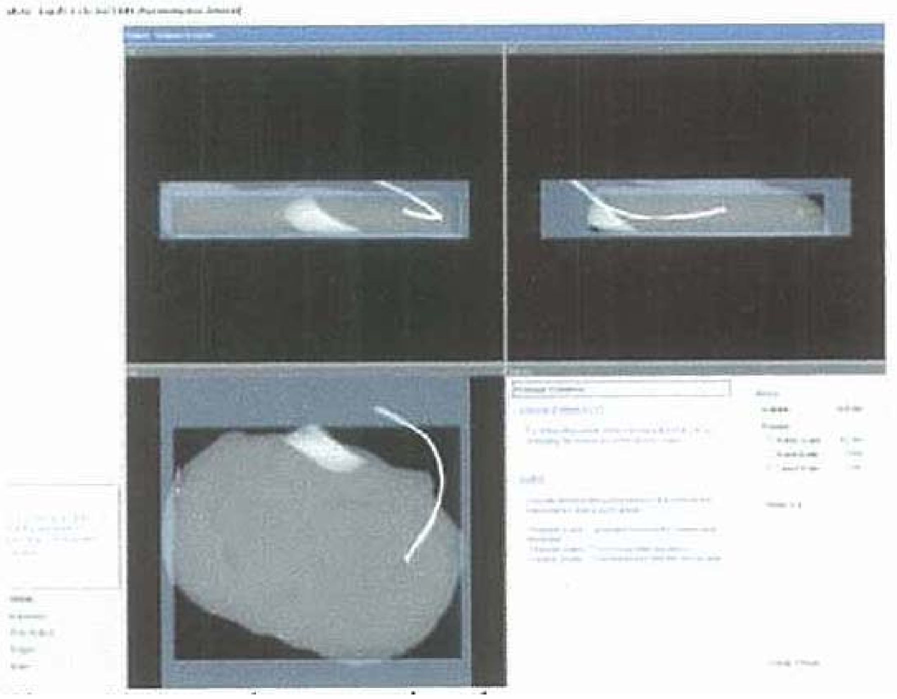
Figure 14. Cropped reconstruction edges

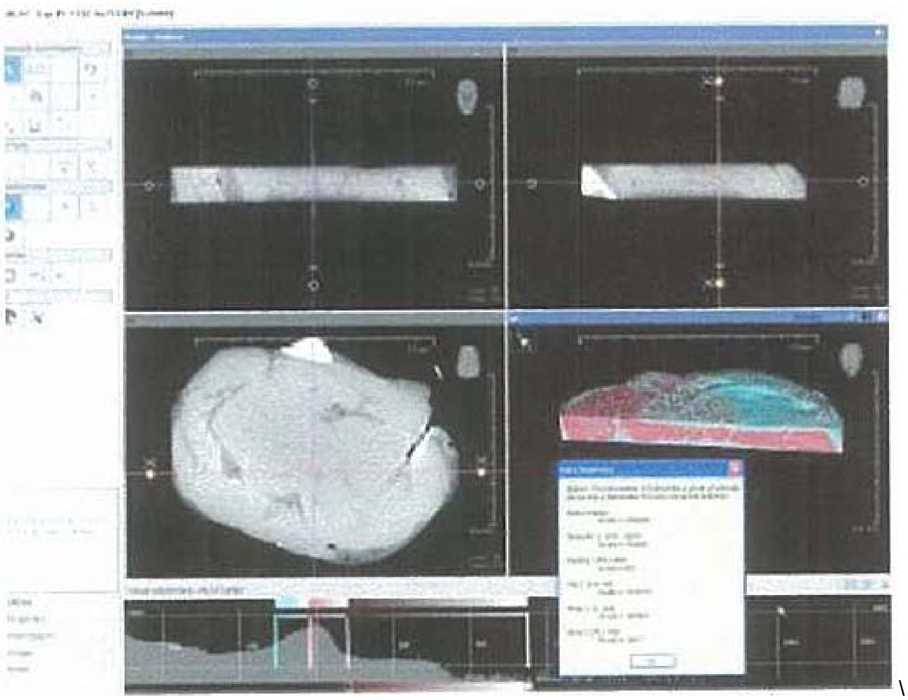

Figure 15. Resulting volume and cross sections with statistics

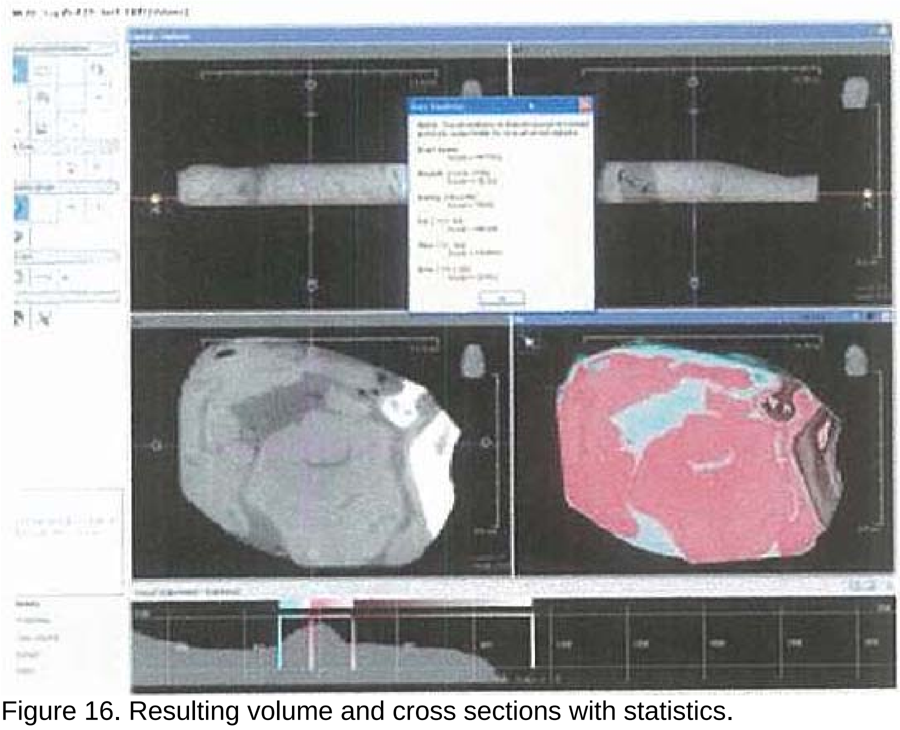

Figure 16. Resulting volume and cross sections with statistics.

6 Experimental results

Table 1 shows the measurement categories recorded for each beef sample. Subsequent experiment summaries in general indicate only the percentage result of each category.

6.1 Experiment #1- Same cut different animal

Experiment #1: 10 samples from different animals, all at 5°C.
Steaks oriented vertically in container due to size. This resulted in a larger object mask window requiring more scatter correction. Scatter correction of 18 was applied to this data set. Similar statistical results were achievable in vertical or horizontal orientation.

Table I. Experiment #1 categories recorded

		Surface Area Pixilated (count)	Surface Area %	Weight (g)	Weight %	CT Statistics (voxels)	CT %	CT Density Range	CT Density Range
	date							Low Limit	High Limit
Exp#1 B#1	8/18/2008								
Fat		487	40.0	248.1	38.9	9,793,534	38.1	-194	114
Meat		731	60.0	389.8	61.1	15,926,086	61.9	118	363
Bone		o	0.0	0	0.0	17,255	0.1	397	733
total		1,218	100.0	638	100.0	25,736.875	100.0		

During the evaluation of experiment #1 initial density ranges were reviewed in CT units. CT unit ranges were found to shift around in the Vision program as it displays intensity in an HU scale. When this was discovered HU scaling during reconstruction processing was initiated. HU scaling stabilized the density ranges in Vision. The HU calibration process was not established until experiment #1 beef sample #10. The HU calibration was post-process applied to experiment #1 beef #1 to 9. This resulted in some variations in the scaling of experiment 41 to #4 before the calibration stabilized. The early meat samples were recorded some days before the later meat samples in experiment #1. It is determined to be a key process to perform HU calibration the time period of the data scan for stable results

	Surface %	Weight %	CT %		CT density Hounsfield units	
					low limit	high limit
Exit #1 B#1					**HU Vertical Cal3**	
Fat	40.0	38.9	38.1		-194	114
Meat	60.0	61.1	61.9		118	363
Bone	0.0	0.0	0.1		397	733
total	100.0	100.0	100.0			
Exp #1 B#2						
Fat	37.6	34.6	38.6		**HU Vertical Cal2**	
Meat	58.3	58.9	57.8		-378	-198
Bone	4.1	6.5	3.6		-194	-36
total	100.0	100.0	100.0		-33	905
Exp #1 B#3					**HU Vertical Call**	
Fat	38.9	37.2	20.5		-284	-104
Meat	59.2	61.1	78.4		-101	57
Bone	1.9	1.8	1.1		60	998
total	100.0	100.0	100.0			
Exp #1 B#4					**HU Cal Horizontal**	
Fat	46.6	37.6	37.0		62	479
Meat	46.6	57.9	61.4		485	801
Bone	6.8	4.5	1.6		803	1530
total	100.0	100.0	100.0			
Exp #1 B#5					**HU Vertical Cal1**	
Fat	28.3	21.3	35.8			
Meet	62.4	60.7	54.0			
Bone	9.3	18.0	10.3			
total	100.0	100.0	100.0			
Exp #1 B#6					**HU Vertical Call**	
Fat	40.3	33.8	21.0			
Meat	52.4	60.3	76.7			
Bone	7.3	5.9	2.3			
total	100.0	100.0	100.0			
Exp #1 B#7					**HU Vertical Cal1**	
Fat	35.8	43.8	26.7			
Meat	63.5	55.4	72.6			
Bone	0.7	0.8	0.7			
total	100.0	100.0	100.0			

Exp #1 B#8					**HU Vertical Call**	
Fat	42.4	39.9	45.1			
Meat	54.2	58.5	53.9			
Bone	3.4	1.6	0.9			
total	100.0	100.0	100.0			
Exp #1 B#9					**HU Vertical Call**	
Fat	24.7	28.8	27.0			
Meat	68.5	59.4	66.2			
Bone	6.7	11.9	6.8			
total	100.0	100.0	100,0			
Exp #1 B#10					**HU Vertical Call**	
Fat	35.7	32.7	33.7			
Meat	56.7	56.6	60.6			
Bone	7.7	10.6	5.7			
total	100.0	100.0	100.0			
Exp #1 B#11l					**HU Vertical Call**	
Fat	28.1	31.6	31.6			
Meat	63.6	58.1	81.9			
Bone	8.4	12.3	6.5			
total	100.0	100.0	100.0			
Exp#1 B#12					**HU Vertical Call**	
Fat	34.1	36.9	25.4			
Meat	61.6	58.0	72.8		'piece too long for detector	
Bone	4.3	6.0	1.8		Missing some portion of meat	
total	100.0	100.0	100.0			

At this point each measurement method is prone to error on the entire volume but reasonable tracking trends arc identifiable.
During the course of experiment 41 additional data sampling checks on statistical results shown in Table 3 and a scan to scan same beef result in Table 4. Both show stability.

Table 3. Resolution of statistical sampling, Low resolution statistics show same results

Exp #1 B#11	hi mem res (Voxels)		HU Cal1		low mem res (Voxels)		HU Cal1	
Fat	7,792,897	31.6	-284	-104	974,149	31.6	-284	-104
Meat	15,259,994	61.9	-101	57	1,906,862	61.9	-101	57
Bone	1,610,592	6.5	60	998	201,414	6.5	60	998
total	24,663,283	100.0			3,082,425	100.0		

Table 4. Scan A vs. Scan B statistics.

Exp#1 B#10	Scan A (Voxels)	CT % (low resolution)	HU **Cal1**		Scan B **(Voxels)**	CT % (hi resolution)	HU Cal1	
Fat	8,239,156	33.7	-284	-104	1,012,526	33.2	-284	-104
Meat	14,826,288	60.6	-101	57	1,865,704	61.1	-101	57
Bone	1,392,497	5.7	60	998	175,196	5.7	60	998
total	24,457,941	100.0			3,053,426	100.0		

6.2 Experiment #2 - Variable cut same animal

Experiment #2: Variable cut, same animal, 0°C. Results are stable with constant HU cal

	ending temp	Surface Area %	Weight %	CT %	CT Density Range	CT Density Range
Grain				Hu 71.4	Low Limit	High Limit
Exp #2 B#1	**6° C**	**Rib eye**		**Horizontal**	**HU Cal Exp4**	
Fat		24.7%	23.3%	36.0%	-214	-34
Meat		57.6%	56.9%	55.3%	-31	165
Bone		17.7%	19.8%	8.7%	170	1108
total		100.0%	100.0%	100.0%		
Exp #2 B#2	1°C	**Rib eye**			HU Cal **Exp4**	
Fat		31.2%	42.6%	41.8%		
Meat		47.4%	43.3%	51.6%		
Bone		21.4%	14.1%	8.6%		
total		100.0%	100.0%	100.0%		
Exp #2 B#3	**0° C**	**RIP eye**			**HU Cal Exp4**	
Fat		27.1%	38.2%	31.0%		
Meal		55.0%	52.6%	64.9%		
Bona		17.9%	9.2%	4.1%		
total		100.0%	100.0%	100.0%		
Exp#2 B#4	**1**° C	**T Bone**			**HU Cal Exp4**	
Fat		28.2%	27.8%	31.8%		
Meat		65.6%	61.2%	63.9%		
Bone		6.2%	11.1%	4.3%		
Total		100.0%	100.0%	100.0%		
Exp #2 B#5	0° C	**T Bone**			**HU Cal Exp4**	
Fat		37.5%	23.5%	40.8%		
Meat		48.5%	57.7%	51.3%		
Bone		13.9%	18.9%	7.9%		
Total		100.0%	100.0%	100.0%		
Exp #2 B#6	**2° C**	**T Bone**			**HU Cal Exp4**	
Fat		28.2%	20.8%	30.9%		
Meat		64.2%	59.6%	61.0%		
Bone		9.6%	19.5%	8.1%		
Total		100.0%	100.0%	100.0%		

6.3 Experiment #3 - Age

Experiment #3: Variable Age.

Not performed

6.4 Experiment #4 - Grain vs. Grass

Experiment 44: Grain vs. Grass shows stable statistical results in density range statistics throughout the experiment. Centre section cut on meat samples required a slight shift in the fat to meat boundary density ranges due to less edge area being used. Grass fed beef shows significantly leaner by all measures.

Exp #4	starting temp	Surface Area 56	Weight %	CT %
				Centre section
Grain				**HU** Cal Exp4
Exp #4 8#1	0° C			
Fat		34.6	31.1	29.0
Meat		61.6	52.2	60.5
Bone		3.8	16.7	10.6
total		100.0	100.0	100.0
Exp #5-1 B#2	0° C			
Fat		33.5	28.6	34.5
Meat		56.7	50.3	56.6
Bone		9.8	21.1	8.9
total		100.0	100.0	100.0
Exp #4 B#3	-1°C			
Fat		32.6	40.4	32.0
Meat		64.5	58.6	67.8
Bone		2.9	1.0	0.2
total		100.0	1110.0	100.0
Exp #4 B#4	0°C			
Fat		24.1	33.8	33.8
Meat		70.8	64.1	65.4
Bone		5.2	2.2	0.8
total		100.0	100.D	100.0
Grass				
Exp #4 B#5	0° C			
Fat		23.1	18.0	25.3
Meat		76.9	82.0	74.7
Bone		0.0	0.0	0.0
Total		100.0	100.0	100.0

Exp #4 B#6	0° C			
Fat		11.4	19.7	13.5
Meat		88.6	80.3	86.5
Bone		0.0	0.0	0.0
Total		100.0	100.0	100.0
Exp #4 B#7	0° C			
Fat		16.4	9.9	20.6
Meat		83.6	90.1	79.4
Bone		0.0	0.0	0.0
Total		100.0	100.0	100.0
Exp #4 B#8	0° C			
Fat		25.4	15.5	19.9
Meat		74.6	84.5	80.1
Bone		0.0	0.0	0.0
Total		100.0	100.0	100.0

6.5 Experiment #5 - Temperature

Experiment #5 Temperature shift on beef samples. This experiment results in fairly stable CT statistics on the same piece of meat at different temperatures with a shift in HU fat to meat boundary for the different temperature ranges. CT results are very comparable but are not identical. This is to be expected with the current evaluation tool available which are not setup to provide identical volume selection from scan to scan. Experiment #4 Grain fed served as the 0°C input on Experiment #5.

CT Temperature		0°C CT %	5°C CT %	10°C CT %	37°C CT %
fat to meat HU boundary		-9	-32	-32	-52

Exp #5	Surface Pixel %	Weight %	0°C CT %	5°C CT %	10°C CT %	37°C CT %
Temperature			Centre section			
Exp #6 B#1						
Fat	34.6	34.6	29.0	29.0	25.6	30.2
Meat	61.6	61.6	60.5	62.1	64.8	61.4
Bone	3.8	3.8	10.6	8.9	9.6	8.4
Total	100.0	100.0	100.0	100.0	100.0	100.0
Exp #5 B#2						
Fat	33.5	33.5	34.5	28.7	29.3	32.3
Meat	56.7	56.7	56.6	63.1	62.0	60.5
Bone	9.8	9.8	8.9	8.2	8.7	7.2
total	100.0	100.0	100.9	100.6	100.0	100.0
Exp #5 B#3						
Fat	32.6	32.6	32.0	35.4	29.0	39.2
Meat	64.5	64.5	67.8	64.3	70.6	60.3
Bone	2.9	2.9	0.2	0.3	0.4	0.5
total	100.0	100.0	100.0	100.0	100.0	100.0
Exp #5 B#4						
Fat	24.1	24.1	33.8	38.3	39.7	37.6
Meat	70.8	70.8	65.4	60.7	59.4	61.5
Bone	5.2	5.2	0.8	1.0	0.9	0.9
total	100.0	100.0	100.0	100.0	100,0	100.0

7 Summary

CT scans of beef are shown to be successful in detection of beef quality rating in ratios of fat, meat, and bone. Current equipment produced usable CT scans in — 6 minutes on steak size samples. Faster scan time can be explored with detector down sampling, detector modification, more efficient X-ray geometry, or a higher flux source. We have demonstrated a basic functional Hounsfield unit calibration which holds stable for each experimental series. Radiographic edge affects of current scan processing can blur meat density statistics if not taken into account.
A modified processing or analysis algorithm to correct edge affects is needed to improve statistics of entire volume. Custom software development is needed to provide consistent processing and automated statistical results.

Once automated analysis tools are available, further studies would be of high interest. Study of beef contrast versus X-ray kV and statistical stability over a range down sampling methods would be of high interest, and comparison of cone beam to spiral CT would help build a good knowledge base.

8 References

[I] RMI electron density CT phantom, Gammex Inc.