Final report

Rapiscan Multispectral Continuous CT Scanner - development and evaluation of the benefits and application of continuous MEXA CT systems

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Abstract

The use of dual-energy X-ray Absorption (DEXA) imaging in the red meat industry is well known both as a method for carcase composition (lean, fat and bone %) and as a sensor to drive automation systems. Rapiscan and MLA engaged in this project to develop and evaluate the applications and benefits of the multi energy (MEXA) continuous computed tomography (CT) for the Australian red meat industry. This represents a large, strategic program that draws on Rapiscan's experience in aviation security to deliver high quality objective measurement at high throughout and high reliability.

This project is an extension of an original project that set out to develop an imaging system using Multi-Energy X-ray Absorption computed tomography (CT) as well as a Multi Energy X-ray Absorption (MEXA) dual view transmission imaging system that was previously successfully delivered. The hypothesis being that MEXA should deliver more accurate quantitative imaging than a DEXA image and so should be beneficial to the red meat industry. The resulting MEXA CT system was designed and manufactured within the course of the program. The MEXA CT system was not deployed in studies relevant to the red meat industry because the technology used to build it was found to be insufficiently robust to allow transport and operational installation. Much technology was developed during this project and many lessons have been learnt. Rapiscan is utilising the learnings and technology matured in this programme to build a Dual Energy stationary gantry CT system which, on completion will be made available to MLA for data collection and subsequent production articles will be offered to MLA for analysis. The Dual Energy CT system in development will address the robustness issues observed which have limited the ability to collect data and transport the system described here.

Executive summary

Background

MEXA Continuous CT systems are seen to be the next generation of livestock and carcass processing objective measurement solutions such that a successful development in this area will likely underpin structural geometry and composition measurement for the Australian red meat industry for the next 50+ years.

This program set out to determine the utility of Multi-Energy X-ray Absorption (MEXA) imaging in 3D in the red meat industry for the purposes of improving accuracy of objective measurement, driving automation systems and increasing the yield of high value product. This program was designed to drive technical development but aimed to deliver significant commercial benefit should the results deliver technology that could enhance the performance, yield and profitability of commercial X-ray imaging for the red meat industry. While this project has not been fully successful it has given Rapiscan Systems enough confidence to carry on and build pre-production systems that should be able to achieve many of the original goals of MEXA CT, albeit initially using Dual Energy rather than Multi Energy CT imaging.

Objectives

- Develop and manufacture a MEXA CT scanner using concepts derived from the airport security sector.
- Evaluate the MEXA CT system for potential to support objective measurement and automation programs in the red meat industry.

RTT6040-ME

Methodology

The MEXA CT scanning system was designed starting with a physics-based analysis, going through detailed design and simulation before starting prototype manufacture. To expedite the development of a scanning system the system was first populated with single energy sensors to enable the system to be commissioned and various subsystems tested and 3D images to be acquired. In parallel, a multi-energy sensor ring was developed with a view to integrating and completing the 3D MEXA CT system to allow data collection and, ultimately delivery of the system.

Additionally, this project exploited parallel outcomes from MDC-funded programs to upgrade Rapiscan's Aviation Security:

- RTT110 hold baggage CT product for continuous carcass scanning, and
- 6040DV checked baggage for multispectral offal scanning, including multi-energy x-ray (MEXA) detection.

RTT110

6040DV-ME

These hardware upgrades were supported by successful software and AI algorithm programs for value optimisation in the red meat industry, including:

- meat grading, structure and health, and
- sortation by organ type, defect and disease-state.

Results/key findings

While proving many of the core design goals were sound and achieved, unfortunately, one of the core components, the RTT x-ray tube proved to be impossible to build and then operate at full specified performance levels. It also proved to be fragile to the point where it was not possible to replace the single energy sensor ring initially installed with the multi-energy sensor ring without risking the catastrophic failure of the x-ray tube. The outcome is unsatisfactory in that the overall system could not be delivered to MLA and their partners at Murdoch University for analysis. However, Rapiscan proposes to use the core outcomes to inform production ready stationary gantry CT systems that are able to discriminate both density and effective atomic number.

Benefits to industry

Automated inspection provides three main benefits to the red meat industry:

1. Improves economic efficiency, automation improves production throughput and provides higher returns with less waste through improved accuracy of fabrication,
2. Addresses labour shortfalls in manual handling and health inspection at meat processing plants, and
3. Provides surveillance of diseases and rapid feedback on animal health to producers.

Future research and recommendations

1. Rapiscan is working towards developing scanners that will be able to meet MLA's future requirements using Rapiscan internal R&D funding; Rapiscan intends to reengage MLA when this technology becomes available.
2. Application of Artificial Intelligence algorithms for enhanced meat grading, structural geometry and health assessment outcomes.
3. Use large datasets to validate and strengthen the detection algorithms, and
4. Develop an automated workflow for analysis, detection, and sortation of meat products.

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1. Background

1.1 Use of X-Ray in the Red Meat Industry

Today in the red meat industry globally, there is widespread adoption of X-ray for basic materials analysis, particularly in chemical lean composition measurement for mixed trim. There is gradual adoption of X-ray imaging for carcass and primal imaging at entry to the boning room, for example. There are some research studies on the use of X-ray CT for calibration of DEXA systems and to explore the potential for CT as an in-line tool to optimise red meat production in the future.

1.1.1 Chemical Lean

Several vendors manufacture basic X-ray systems for automatic analysis of chemical lean of mixed trim. These systems use line-scan X-ray with dual-energy X-ray sensors to generate basic images of mixed trim. Through analysis of the dual-energy sensor signals, recognising that fat and lean have different chemical composition and hence different X-ray absorption characteristics, it is possible to generally classify the percentage lean in the product. The accuracy of the measurement is a few percent when trays are loaded correctly.

1.1.2 DEXA

Dual Energy X-ray Absorption (DEXA) systems have been produced to make higher quality 2D X-ray images of carcasses and primals when conveyed through the scanning system. Here, there is significant contrast between bone, soft tissue and air. DEXA systems are used as the input to automated cutting systems where it is important to know the precise location of bony features, such as a rib or specific vertebra, relative to the soft tissue in order to cut in the correct location. These systems tend to be large, consuming valuable real-estate in the abattoir and are quite expensive too. With appropriate algorithms, DEXA can also accurately describe carcase composition as lean, fat & bone percentage.

1.1.3 X-Ray Computed Tomography

X-ray computed tomography (CT) generates high quality 3D images of tissue with good contrast between fat, lean, bone and air. Given the high spatial resolution of these images, it is possible to make accurate measurement of both spatial features, such as the boundary between regions of fat and lean, as well as quantitative measurement of values such as fat-lean ratio within a muscle. CT scanners in the red meat industry today are medical systems that are used for R&D and calibration purposes. They are used in an off-line laboratory setting to answer scientific questions as well as to perform calibration of DEXA and other yield prediction systems. There are still very few X-ray CT scanners dedicated to the red meat industry in Australia and Internationally.

1.2 Objective Measurement for the Red Meat Industry

Objective measurement describes the process of characterising red meat product based on accurate, repeatable, automated measurements rather than on subjective or indirect measurements such as palpation, fat thickness, colour, and so on.

Research programs in DEXA and X-ray CT show promise in generating objective data, such as percentage of fat within a muscle, muscle density and volume, fat thickness and so on. Although still at an early stage, there is sufficient confidence in the results that can be obtained to pursue further work to (1) generate scanning instruments that can provide objective data routinely in the abattoir setting and (2) construct automated algorithms that translate the objective measurement data into useful business metrics such as eating quality indices.

1.3 Transferring Aviation Security Technology to the Red Meat Industry

For many years, X-ray CT has been used in the aviation and logistics industries to scan bags, parcels and mail travelling across international borders. Automated detection algorithms are deployed to find a range of materials from explosive materials to biosecurity risk items. In contrast to medical CT scanners which are designed to scan a single patient at a time, aviation and logistics CT scanners are design for continuous operation 24 hours per day in high reliability environments. Therefore, this is a natural place to look for CT scanners to work within the red meat industry.

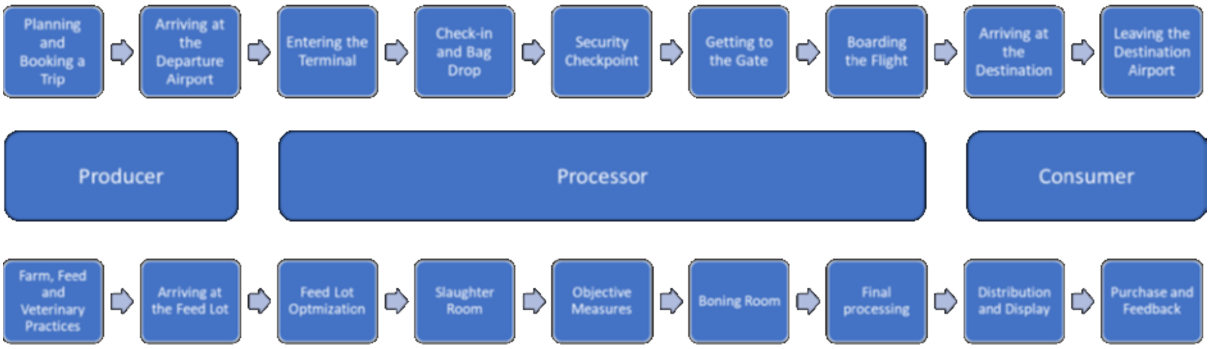

Figure 1: Parallels between the aviation industry and the red meat industry.

In many ways, there are significant parallels between the processes that are followed in the aviation industry and those that are common within the red meat industry (Fig. 1). Here the passenger and a carcass both progress somewhat linearly through a process, the passenger moving from booking to the airport and to the aircraft and the animal from producer to processor to consumer.

There are significant differences between a medical CT scanner and an aviation certified CT scanner that derive from the different use cases. The radiation dose delivered by a medical CT scanner is much higher than that used in aviation scanners, and this results in a higher image quality for the medical CT scanners. The open question is therefore whether the operationally efficient aviation scanner with its consequently lower image quality can provide a viable solution for process line imaging and objective measurement within the red meat industry.

2 Objectives

Automated inspection is a viable solution to ensuring food quality assessment is precise, non-contact, and economically efficient. This is because automated inspection reduces the need for labour and training of personnel, the inherent variability among assessors, and may reduce potential contamination. In addition, the automated inspection can reduce processing times and even achieve real-time output.

This research and development program was established to determine whether Multi-Energy X-ray CT (MEXA-CT) achieve a level of performance in the red meat industry to deliver accurate objective measurement in the production line setting.

Delivering this objective required a large and technologically complex program with considerable risk profile. Despite the risks, we chose to undertake this program due to the significant potential benefit to both the red meat industry, and the aviation and logistics industry, should the hypotheses tested achieve positive outcomes.

2.1 MEXA CT

At the start of the program, Rapiscan Systems and MLA agreed to design and build a MEXA CT scanner with tunnel size of 60cm (W) x 40cm (H). This tunnel size is capable of scanning whole lamb carcasses and many beef primals.

Figure 2: MEXA CT scanner, 6040RTT-ME, developed under this program.

The prototype scanner was constructed by a multi-disciplinary team of scientists and engineers within Rapiscan Systems. After initial mechanical-electrical build and validation in Singapore (Fig. 2), the unit underwent integration in the Rapiscan Systems UK manufacturing facility where the complex X-ray source was manufactured using parts from across Europe and the USA. The system was initially integrated using single-energy x-ray sensors to demonstrate the capability of imaging and enable analysis of tune performance.

A multi-energy sensor array was developed by the Rapiscan sensor team in California, USA. The plan was to install the multi-energy sensor ring and continue image and analysis optimisation. However, the fragility of the x-ray tube meant it was not possible to install the multi-energy sensor ring without risk of damaging the fragile x-ray tube.

2.2 AI Assisted Automated Inspection

Machine and deep learning models have been proven effective for computer vision and pattern recognition tasks. Automated inspection, using deep learning classifications, is a viable solution to the challenges of improving economic efficiency and reducing the risk of human infection. Also, in general, deep learning exhibits better performance for screening tasks. To develop deep learning-based classifications for red meat, the analysis assumes that an abnormal image is caused by abnormal elements, i.e., anomaly, which would not appear in a normal image. Since deep learning networks are trained using a loss function to produce the result as expected, the loss function is determined according to the assumption that abnormal images, of unhealthy meat, contain tissues not found in normal images of healthy meat.

3 Methodology

Aviation security CT requires:

- Conducting an unlimited number of consecutive scans, and
- Image reconstruction occurring in real-time along with detection algorithms so results can be delivered as soon as the scan is completed.

The need for high reliability, high throughput, real-time 3D X-ray imaging match the requirements of the meat processors, and rules out medical CT as used in red meat research.

3.1 RTT6040 MEXA Build

3.1.1 System Design

The 6040RTT-ME was designed as an aviation security fixed-source 3D CT imaging product for regulated cabin baggage screening using high performance multi-energy sensors. It has a 600mm (W) x 400mm (H) tunnel size suitable for scanning whole lamb and some beef primals. Carcasses are placed in plastic tubs during scanning to avoid contamination. At a 300mm/s conveyor speed a lamb can be scanned in approximately 5 seconds. The 6040RTT-ME represents the next generation meat grading product during the program (Fig. 3).

Figure 3: ID drawing of RTT6040 CT scanner

3.2 Software

3.2.1 ScanOS Software

A further major development effort was undertaken during this program to create a single open architecture, open standards, software platform that would work identically for both 2D and 3D image inspection with the same system control, cyber security and other capabilities. This simplifies overall software development tasks – once the platform is in place – and it then becomes easy for users to switch from 2D to 3D system operation without the need for retraining.

The new software platform is now released by Rapiscan Systems as ScanOS. ScanOS incudes artificial intelligence, business intelligence and cyber security tools alongside the core imaging pipelines.

ScanOS is a modular, containerised, software application that is designed using modern software techniques to scale without modification as user demands require.

The core ScanOS (Version 6.2) platform software components, the underlying real-time algorithm run-time framework, and a 3D user interface for the RTT110 are delivered. Algorithm dashboards were developed for review of algorithm detection performance information. The ScanOS platform runs as black box, improves CT volume rendering time, and adds cloud support and a variety file format features to real-time imaging in (2D and) 3D.

The ScanOS platform incorporates:

- High bandwidth USB-based Data Acquisition
- Imaging pipeline providing real-time, optimised, transfer of data from the hardware together with real-time image analysis algorithms.
- Xray system control
- Scanned image rendering and display
- Reporting, Dashboard and Business Intelligence, and
- A containerised runtime environment in the X-ray system computer. The three containers can be individually updated, deployed and launched virtually:
    - Data IO and image pipeline,
    - UI with render, and
    - machine control link module.

Figures 4-6 shows images of ScanOS in operational settings.

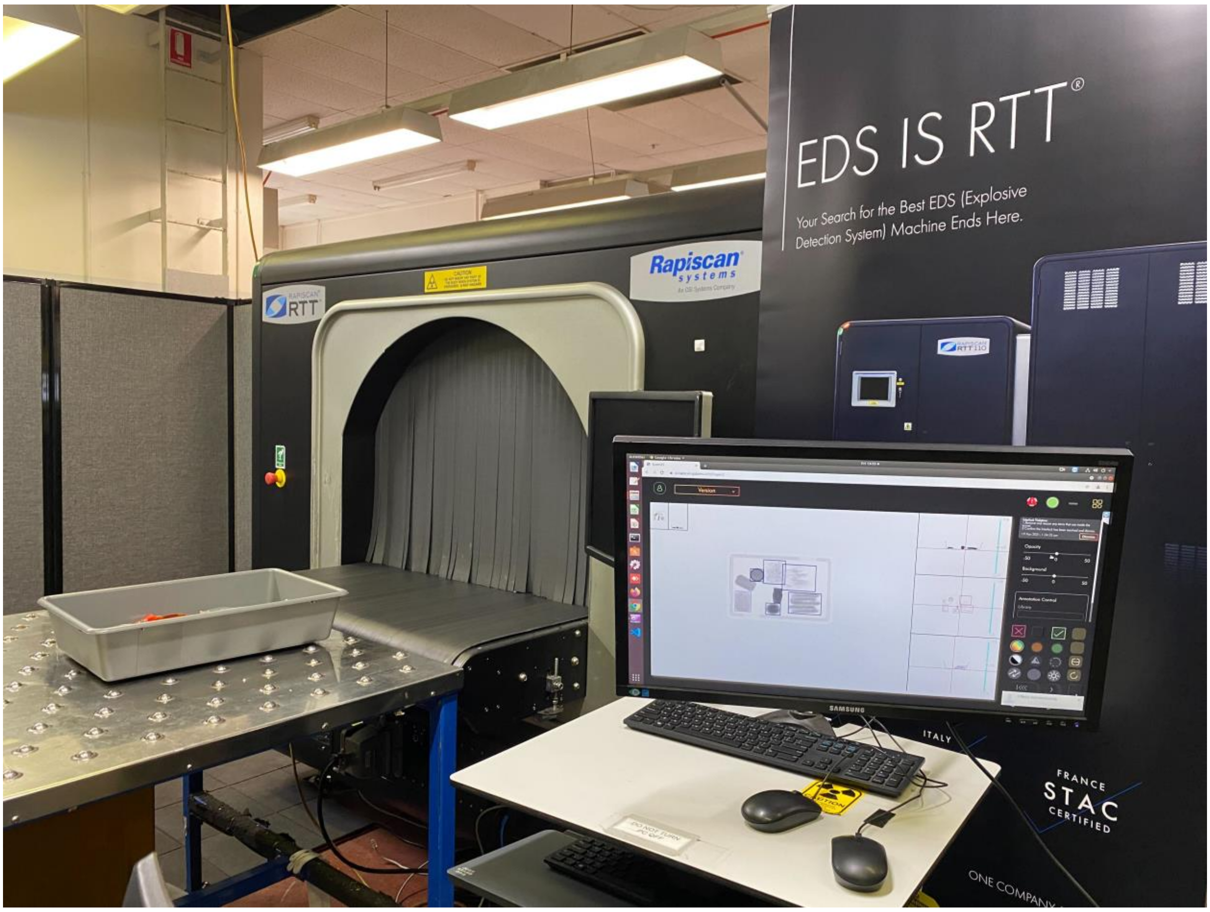

Figure 4: Photo of the Australian Government Biosecurity test station operating the ScanOS software incorporating Biosecurity detection algorithms on the RTT110.

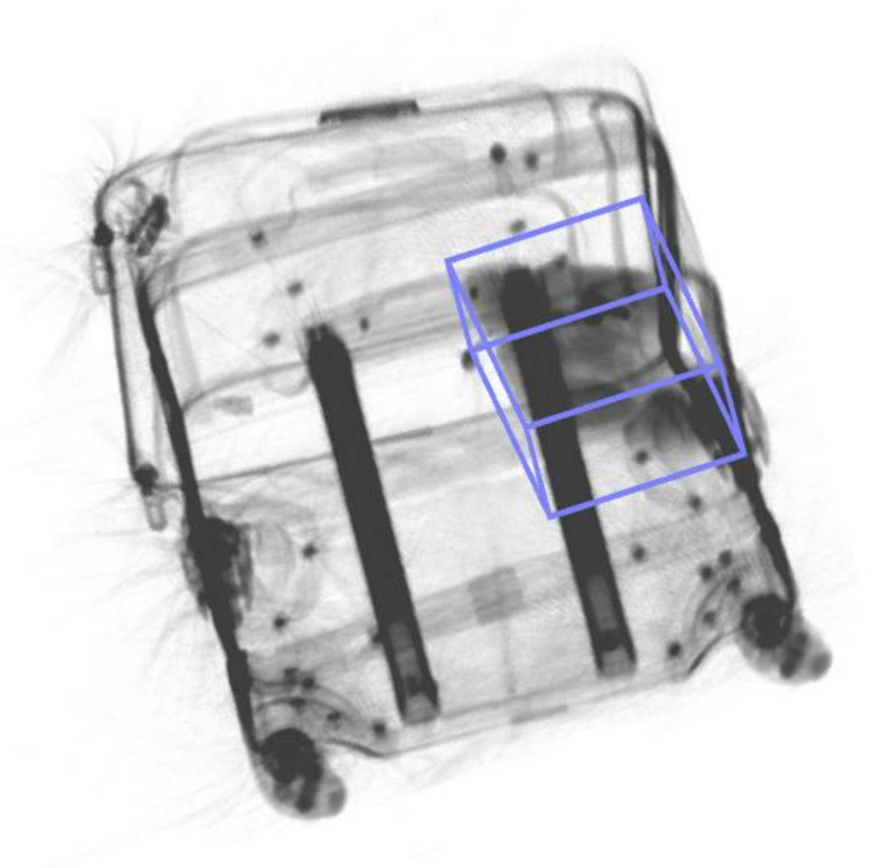

Figure 5: Detection algorithm display for meat found in a passenger bag.

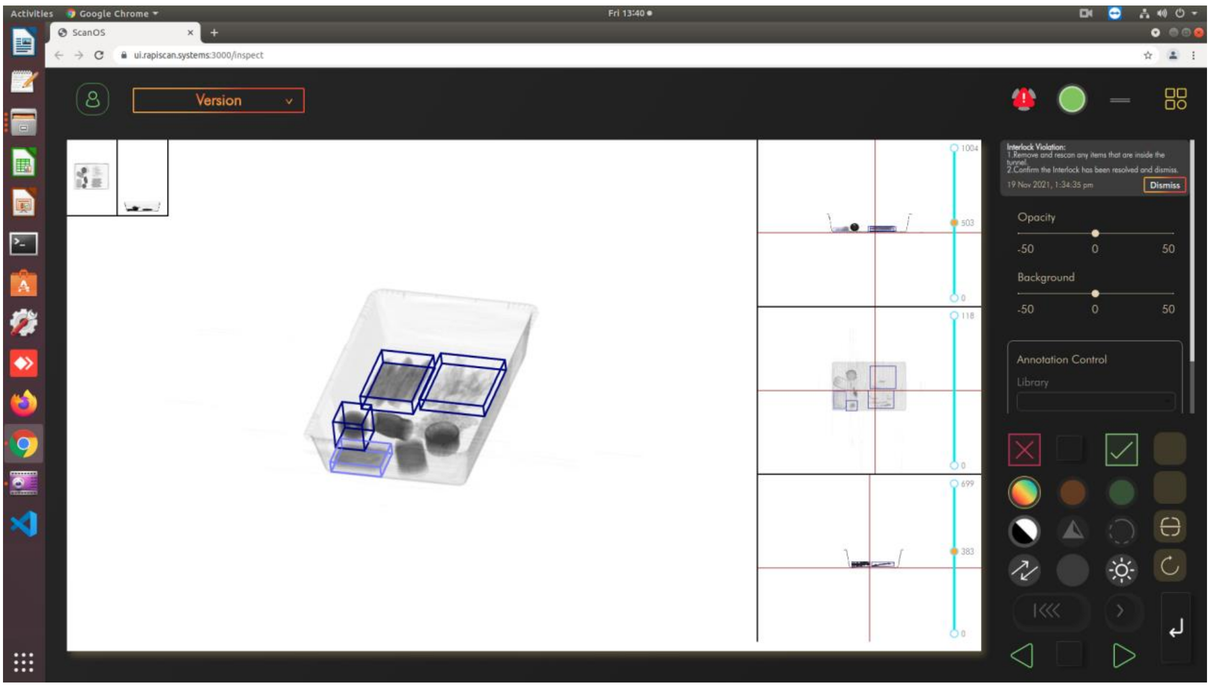

Figure 6: ScanOS User Interface screen shot.

3.2.2 Artificial Intelligence Algorithms

ScanOS supports a real-time algorithm platform for both 2D and 3D image data. Both machine learning and deep learning methods are supported.

The machine learning algorithm platform follows the approach of segmentation followed by feature extraction and then classification. Each segmented blob is assigned a material class following feature extraction (e.g. fat, lean, bone) and this data is then fed into a final stage classifier to build up an overall decision (e.g. fat thickness, marble score, etc.).

Rapiscan has ongoing development programs with the Australian and New Zealand governments to develop automated algorithms for detection of biosecurity risk items contained in passenger luggage or mail parcels. Through these programs, we are developing machine learning and artificial intelligence-based algorithms to detect items such as fruits, meat, fish, vegetable, and plant materials from reconstructed volumetric x-ray CT data, obtained from Rapiscan RTT110 systems deployed at airport and mail gateway locations in Australia and New Zealand.

Results on biosecurity data using deep learning models have demonstrated significant improvement in detection and false alarm rate performance. Biosecurity Algorithm Release 6.0, released and deployed in June 2023, can detect fruit, meat, fish and vegetable and plant materials with a high probability, and balanced with a controlled false alarm rate. The algorithm can detect meat items, including processed meat products such as sausages and dried meat, with a probability of 85%, achieved at a low false alarm rate of 7.7%. A full summary of the algorithm's performance is shown below. The feature extraction techniques developed through the Biosecurity Program are applied directly to the image analysis of reconstructed CT data of beef and lamb carcasses and used in automatic grading and anomaly detection.

Tables 1 and 2 (below) display 2D and 3D performance results with Biosecurity meat detection algorithms. From March 2022, 2D dual energy meat detection algorithms achieved:

- 94.2% probability of detection,
- 22.2% false alarm rate,

which is

- 95.7% Precision,
- 94.2% Recall,
- 94.9% F1, and
- 82.7% Accuracy.

Type	Number of scans
sausages	447
pork meat	317
salami	309
Other meat	228
jerky	185
Sticks	161
beef meat	65
Mixed	56
animal food	45
hotdogs	36
chicken meat	7

Table 1: Number of scans and the types of meat items.

From May 2023, 3D single energy CT (RTT110 Biosecurity 7.0) meat detection algorithms achieved:

Bio-algo	Fruit P_D (N)	Meat P_D (N)	Fish P_D (N)	Vegetable P_D (N)	Plant Materials P_D (N)	P_{FA} (N)
7.0	94% (1,488)	88% (2,446)	79% (314)	81% (603)	90% (168)	12% (4,450)

Table 2: The performance of Biosecurity algorithm 7.0.

4 Results

4.1 RTT6040-ME

This scanner has a tunnel size of 600mm (W) x 400mm (H) and thus is suited to scanning whole lamb and beef primals. The conveyor is designed to run at 0.3m/s as standard with demonstration in this report at 0.5m/s scanning speed too.

The system is operational and able to generate image data routinely.

4.1.1 System Build

A first MEXA CT system was manufactured and operated at reduced power in the Rapiscan Systems UK facility. A second MEXA CT system was manufactured and assembled in our Singapore facility (Fig. 7). This unit is light in weight compared to other CT systems and is sufficiently compact to fit through a standard doorway.

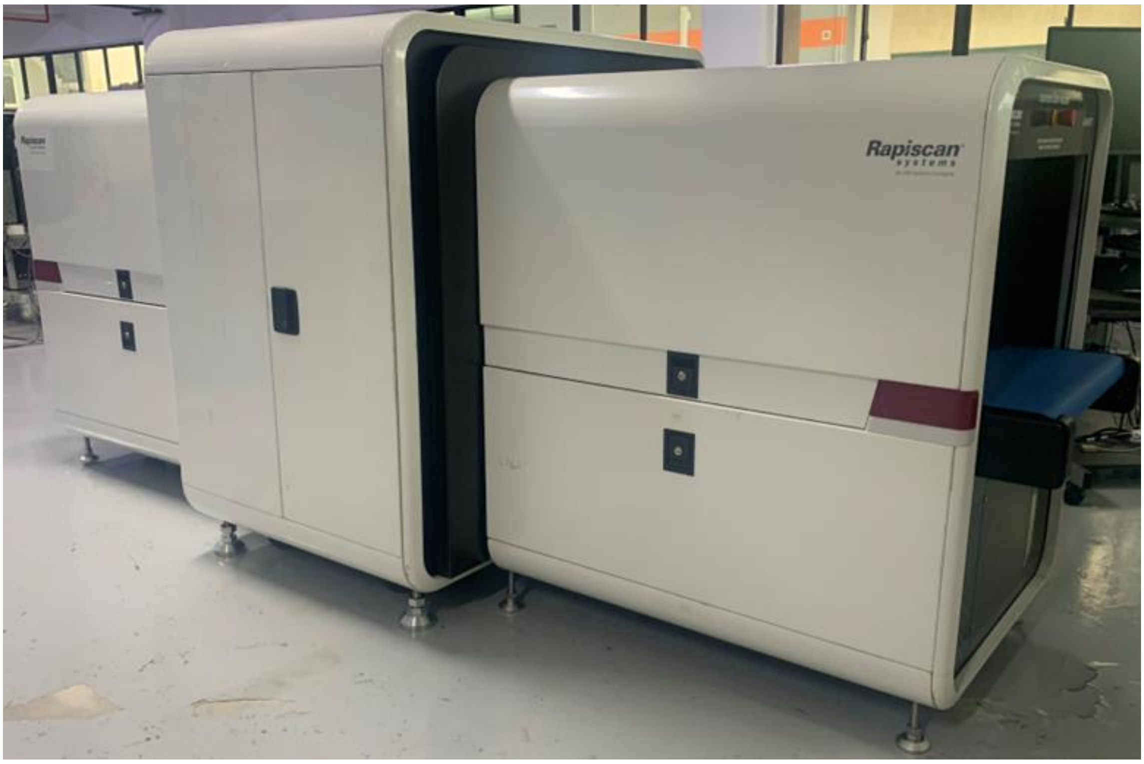

Figure 7: Photograph of the as-built MEXA CT system

Currently, the covers (Fig. 8) and conveyor are not designed for food industry applications and so are fabricated using painted steel. However, the design has been modularised in such a way that a future conversion to food industry compatible covers is manageable.

Figure 8: Photograph of the MEXA CT system with its covers open for servicing,

The system is 3200mm long (Fig. 9), comprising four internal 800mm long conveyor sections. Lead-rubber curtains are used to reduce radiation dose at the covers and ends of the tunnel to meet international radiation safety standards. On construction, issues were noted with the x-ray shielding which would require extensive patching in the short term and re-design in the long term. To operate the system, even at reduced power, the unit operated in an interlocked x-ray shielded room. The focus was on the operation of the system and imaging rather than on trying to optimise the shielding for operation, which could be addressed at a later date.

The system was designed in three sections: a central imaging section, an entrance conveyor section and an exit conveyor section (Fig. 10). Total system weight is just under 1600kg with the central section being heaviest at ~610kg, the entrance section at ~380kg and the exit section ~450kg. Each section was designed to be less than 950mm wide to allow access through a standard doorway. Figure 11 shows the RTT6040 installed at Rapiscan Singapore.

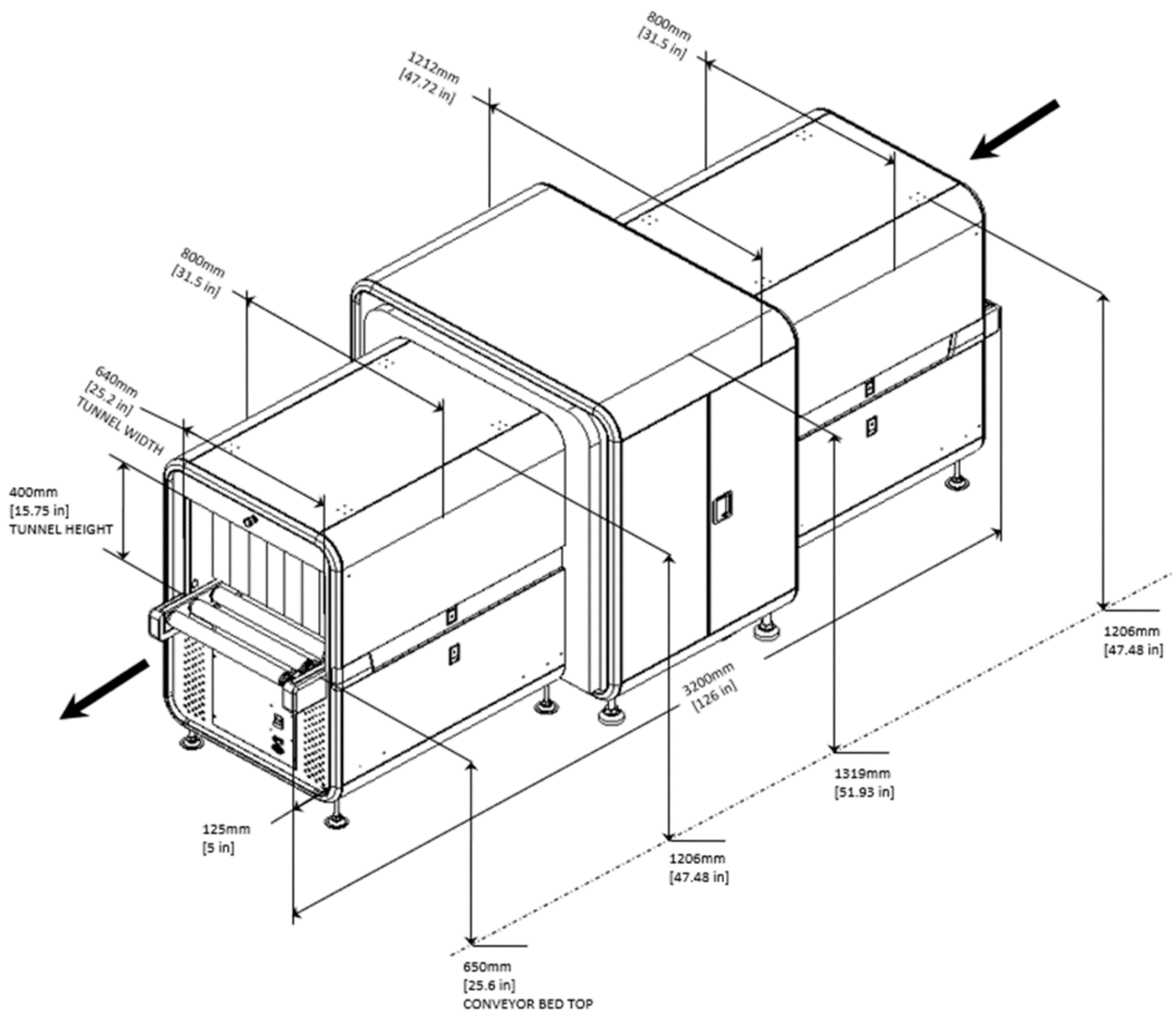

Figure 9: Dimensions of the MEXA CT system.

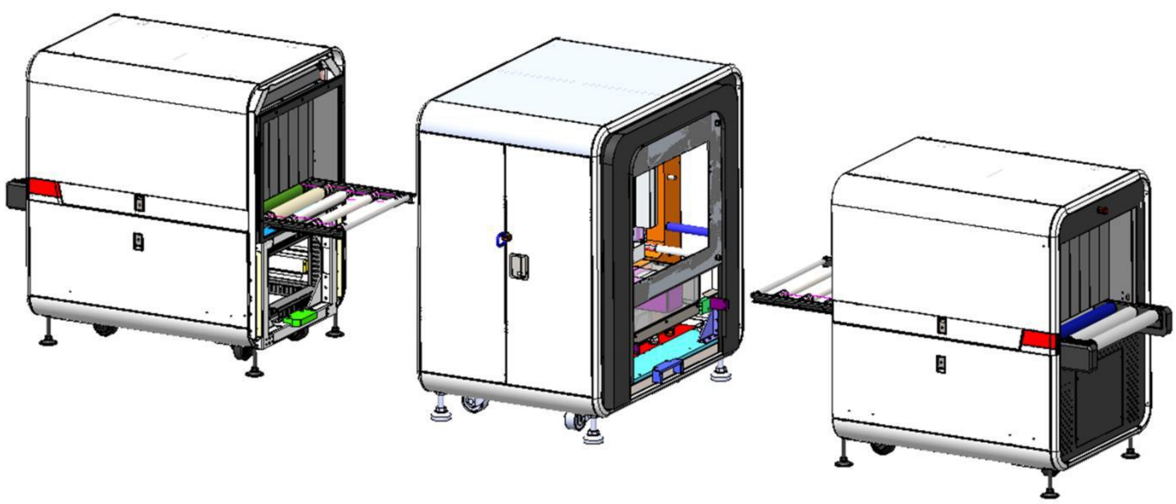

Figure 10: Modular design facilitates system shipping and installation.

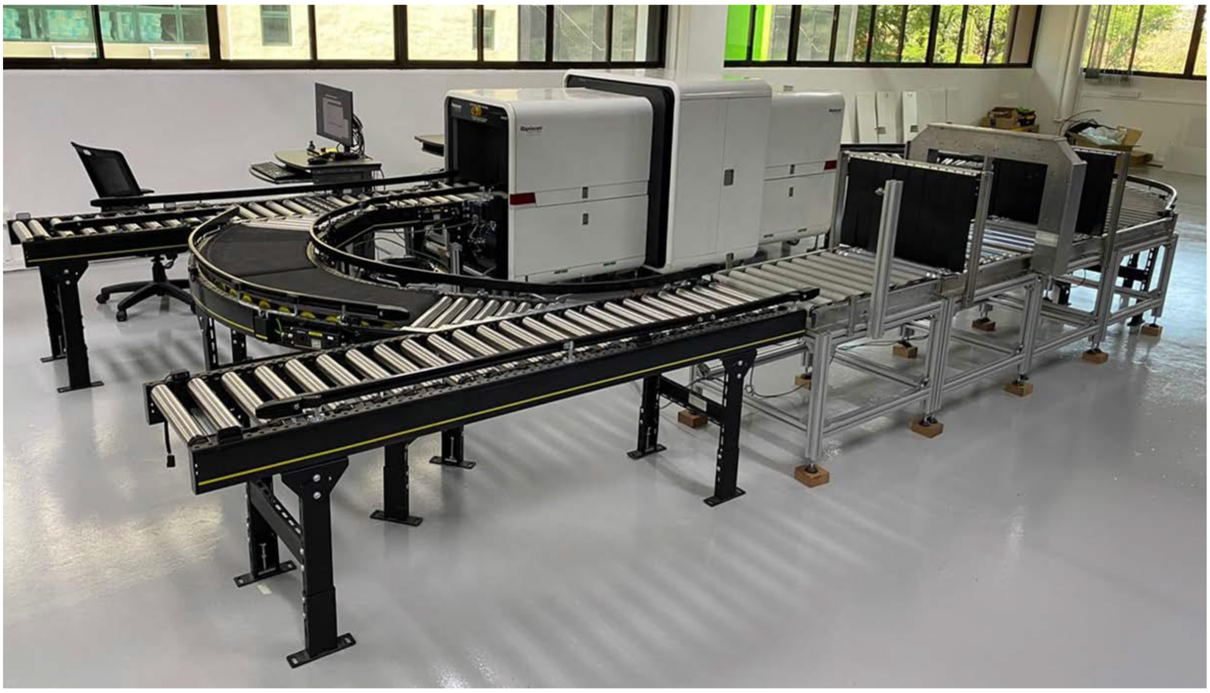

Figure 11: Prototype 6040RTT-ME in the Singapore R&D laboratory undergoing mechanical/electrical integration.

4.1.2 Xray Tube Build

Many new design features and fabrication techniques were incorporated into the RTT6040 CT tube design compared to the RTT110 scanner. These new features and methods were designed with the aim of improving the performance and stability of the CT tube as a system, both from a physics and mechanical standpoint, while aiming reduce the production cost. New technology comes at a risk of anticipated and unanticipated delays in design, fabrication, and integration. The development of the tube took much longer and cost Rapiscan far more than anticipated and, in the end, did not result in an effective and robust design.

Unfortunately, the tube could not be operated at the design specified voltage of 160kV and 5 mA. Lessons have been learnt and the development of RTT tube technology remains a core Rapiscan competence, future systems are in development that will be operable at the full tube voltage and x-ray beam current specified.

4.1.3 ME Sensor

Central to the design of a MEXA CT system is its X-ray sensor array. For a MEXA system, a pixelated photon counting, energy resolving, sensor is required with high data bandwidth to extract the data and pass it to the image reconstruction pipeline.

The CT multi-energy detector module consists of a printed circuit board (PCB), electrical components soldered onto the PCB to create a printed circuit board assembly (PCBA), and a detector crystal (CdTe or CdZnTe) assembled onto the PCBA (Fig. 17). Figures 18-21 display the build of the PCBA array for testing, example image output and consequent installation in the tube shielding module.

The image reconstruction pipeline has been optimised to run in real-time with conveyor belt speeds of both 0.3m/s and 0.5m/s (Fig. 12). This image data shows a cross section through a plastic cylinder of diameter approximately 50mm within a plastic Pelican Case. The hinge and clip details in the case are visible clearly. Reconstructed voxel dimension is approximately 0.8mm in each dimension.

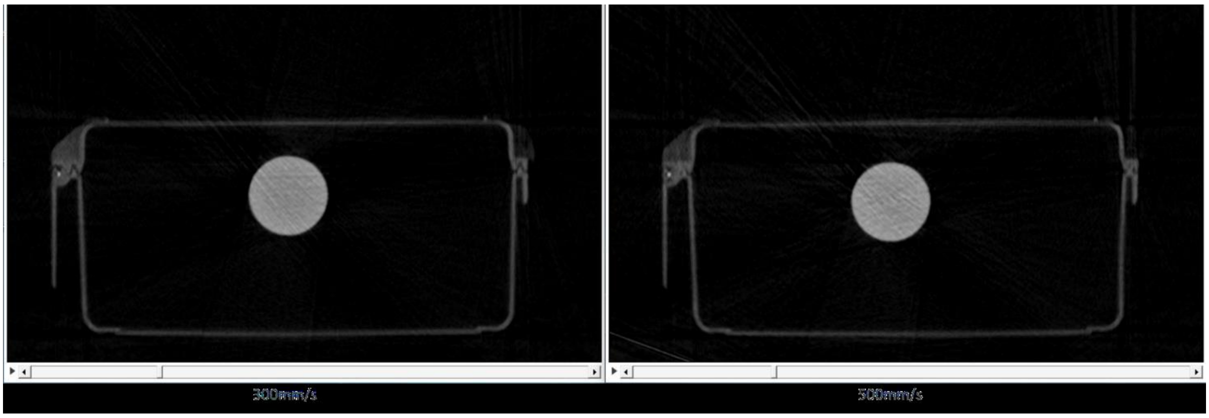

Figure 12: Reconstructed image data from the MEXA CT system using a single energy channel.

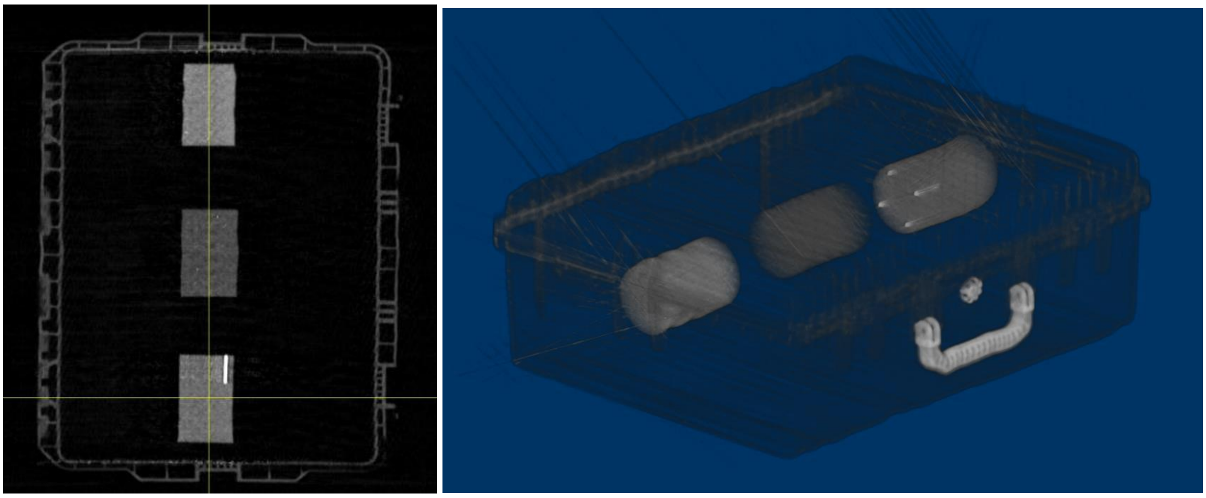

Figure 13: Orthogonal plane and 3D rendered views of test case from the MEXA CT system using a single energy channel.

Figure 13 was reconstructed using a single energy channel. However, the reconstruction algorithm has been written to accept up to four energy channels for use with single energy, dual-energy and multi-energy detectors. The first part of the reconstruction algorithm decomposes the input energy data into Photoelectric and Compton projection data. This creates two projection data sets: Compton and Photoelectric. The two data sets are reconstructed separately and then combined at the final stage to create an Intensity image, a Density image and a Z-effective image.

The intensity image is used to render the best image to the screen. The Density image and Z-Effective image are then used to colour the intensity image based on the two quantitative values. When this data is reconstructed using the MEXA reconstruction algorithm, quantitative results for the density and Z-effective of each material are reconstructed for every voxel in the image independently (Fig. 14). Taken together, these results show that MEXA CT can reconstruct accurate image data at high spatial resolution and with good quantitative accuracy.

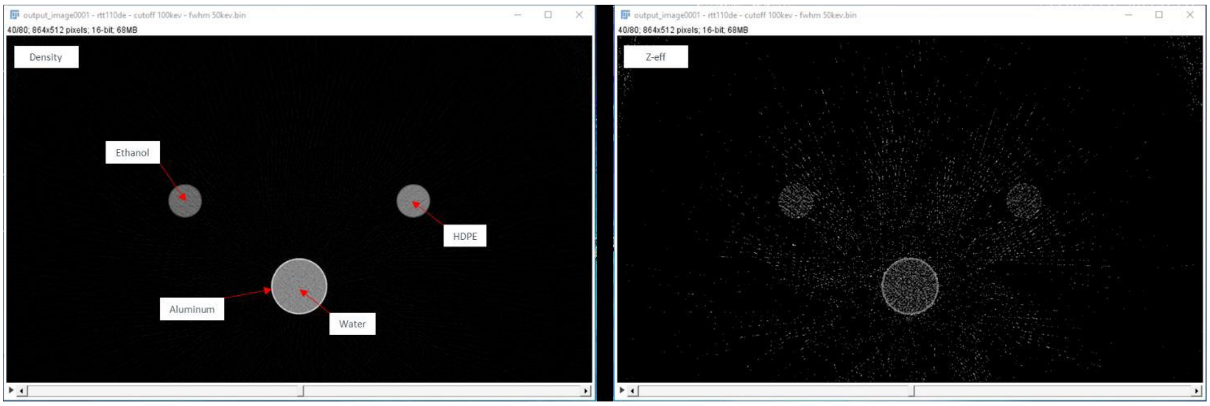

Figure 14: Reconstructed MEXA image volume. Left: Density. Right: Z-effective.

4.1.4 Image Reconstruction

The 6040RTT-ME has two unique features:

- A rectangular cross section geometry, and
- Multi-energy sensing.

A new image reconstruction algorithm was developed for both these requirements. An advanced multi-energy scatter correction algorithm has been developed. This correction performs an accurate first-order simulation of the scatter signal based on an initial uncorrected reconstructed image. This estimated scatter signal is then subtracted from the measured projection data and reconstructed to form a scatter-corrected image. Results with simulated data have demonstrated significant improvement in the quantitative accuracy of reconstructed density and Z-effective values. Unfortunately, the algorithm has proven to be too computationally costly for use in the real-time image processing pipeline.

4.2 RTT110 Carcass Scanning

The RTT6040-ME was designed to scanning whole lamb carcasses and many beef primals. In support of this scanning outcome methodologies were developed for:

1. Fat/Lean/Bone volume structure and content measurement, and
2. Optimised fixture material and design for carcass mounting,

These measurements were made using a modified Rapiscan RTT110 scanner. This works showed the viability and readiness of CT red meat scanning to the small format RTT6040-ME.

4.2.1 Scanning

Several rounds of single and multiple day scanning were performed, including:

- 15 beef loin and rib sections in December 2020,
- 30 lamb carcasses, each in three sections (fore, rib and hind) in February 2021,
- 6 beef sides cut into smaller sections (shoulder, butt, loin, brisket, etc.) in March 2021
- Boxed beef sections in January 2022,
- Boxed beef sections in April 2022, and
- 3 beef sides in May 2022.

Each round advanced the presented capability from real-time, legacy Aviation Security capture (448 emitter, 0.5m/s) to meat algorithm capture:

- real-time,
- 0.25m/s,
- at 200mm separation, and
- up to 2.7m scan length.

Additionally, a range of materials for section holding clamps and supporting mechanisms were tested. These included acetyl, aluminum and metals - titanium, iron and copper.

Shrouding plastic sheets, for contamination avoidance, were also tested. Figures 15-19 display images from these rounds of carcass scanning.

Figure 15: A beef section mounted in an Acetyl holder.

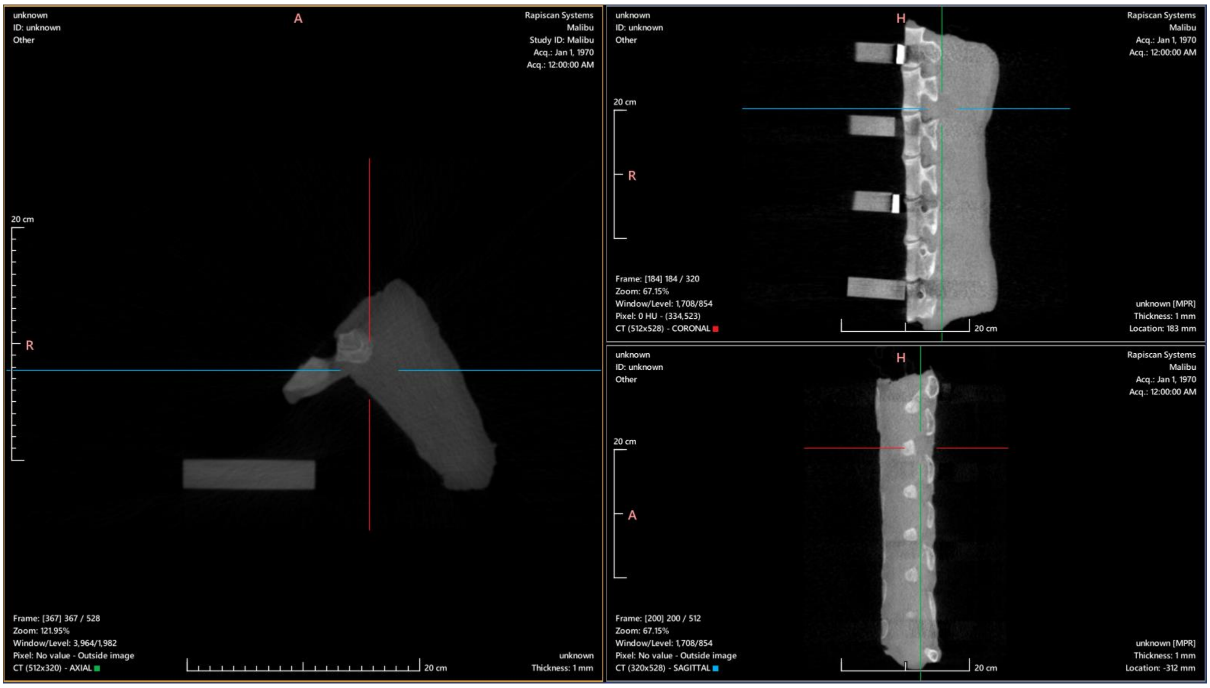

Figure 16: Planar slices from the beef scan showing holder.

Figure 17: RTT110 installation for carcass scanning.

Figure 18: A lamb section ready for scan.

Figure 19: A beef side being cut for scanning.

4.2.2 Fat/Lean/Bone Volume Structure

The CT orthogonal views (Axial, Coronal and Sagittal) in Fig. 20 show the volumetric structure of a beef loin captured in March 2021. Figure 21 displays an example 2D projection from the captured 3D scan. These images display sufficient content for automated cutting based on bone identification and positioning.

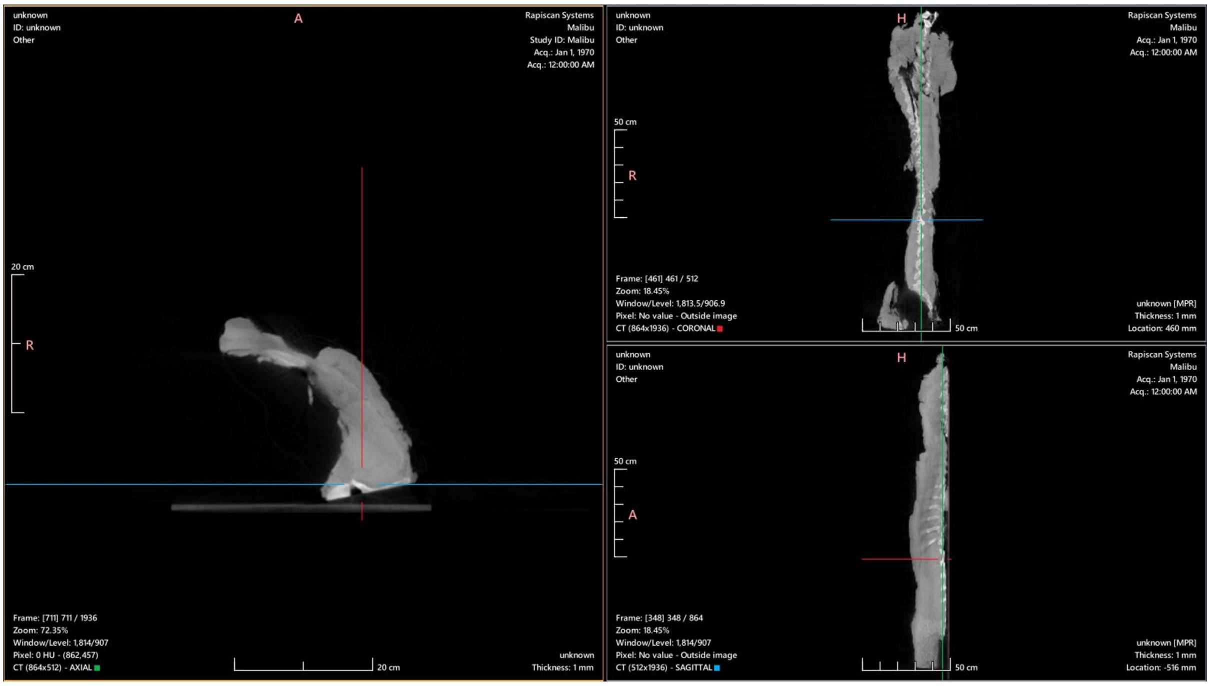

Figure 20: Orthogonal slices from a beef side scan.

Figure 21: A 2D projected image from the 3D scan of a beef leg. The projection displays the bone, lean and fat distribution in different shades of grey.

4.2.3 Fat/Lean/Bone Volume Content

Simple, per slice histogram segmentation of the CT volume made Fat/Lean/Bone percentage analysis is possible. Figures 22-25 and Table 3 illustrate how the analysis is performed with example outcomes. Using knowledge of the voxel dimensions, this could be presented as actual volumes. Such objective and automated meat quality and meat volume measures could be enablers for the optimisation of carcass value.

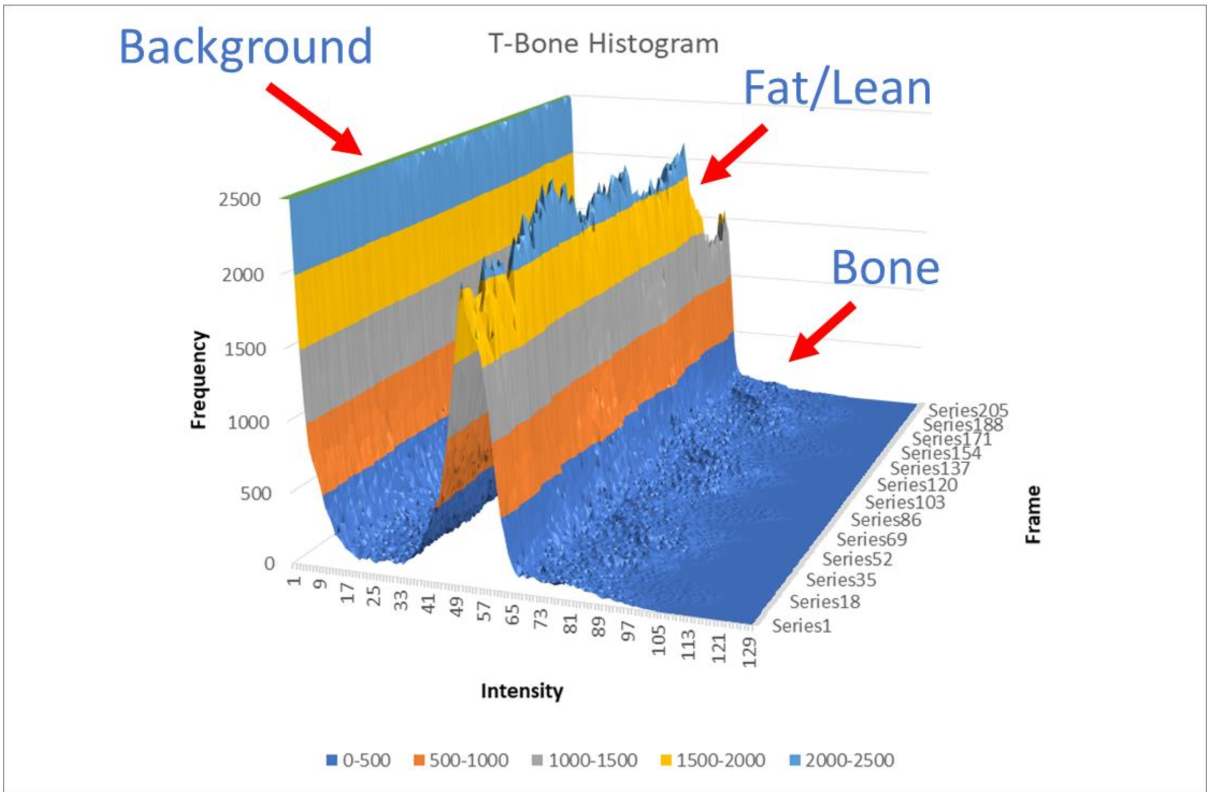

Figure 22: A 3D plot of the per slice intensity histograms for a T-Bone section.

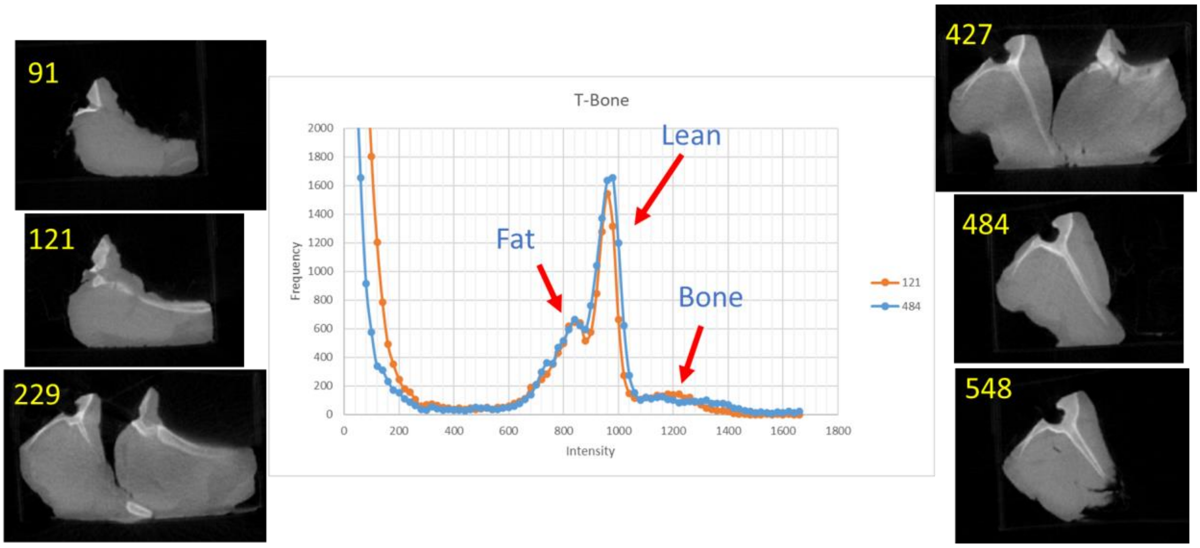

Figure 23: Individual slices from the T-Bone scan and example histograms illustrating the ability to separate fat, lean and bone.

Table 3: Volumetric and percentage composition from the T-Bone section.

Slice	91	121	229	427	484	548
Total (mm^2)	10198	13328	29503	32240	15655	12841
Fat	3782	4958	7823	10005	5108	3741
Lean	5994	6866	18428	18286	8806	7250
Bone	422	1504	3252	3949	1741	1850
Composition						
Fat	37.1%	37.2%	26.5%	31.0%	32.6%	29.1%
Lean	58.8%	51.5%	62.5%	56.7%	56.3%	56.5%
Bone	4.1%	11.3%	11.0%	12.2%	11.1%	14.4%

The statistics for the entire T-Bone section are:

- Total Volume 12,020 cm^3,
- Fat Volume 6,120 cm^3, i.e. 51%,
- Lean Volume 4,870 cm^3, i.e. 41%, and
- Bone 1,030 cm^3, i.e. 8%.

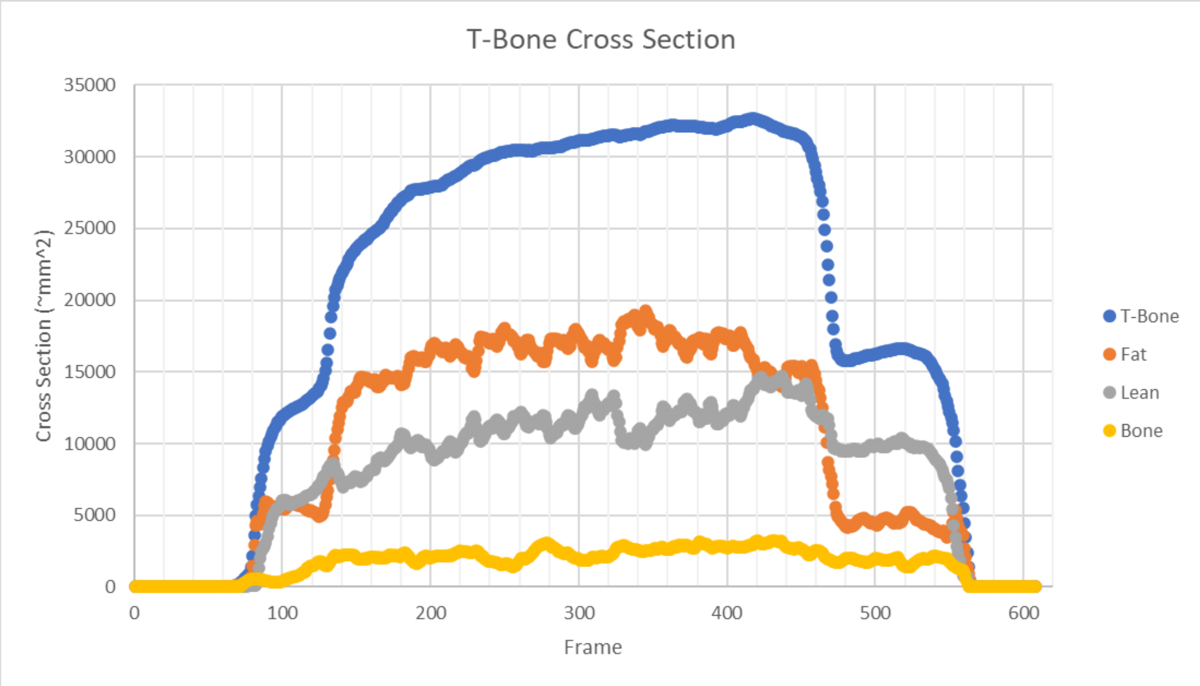

Figure 24: Cross-section profile of the T-Bone section.

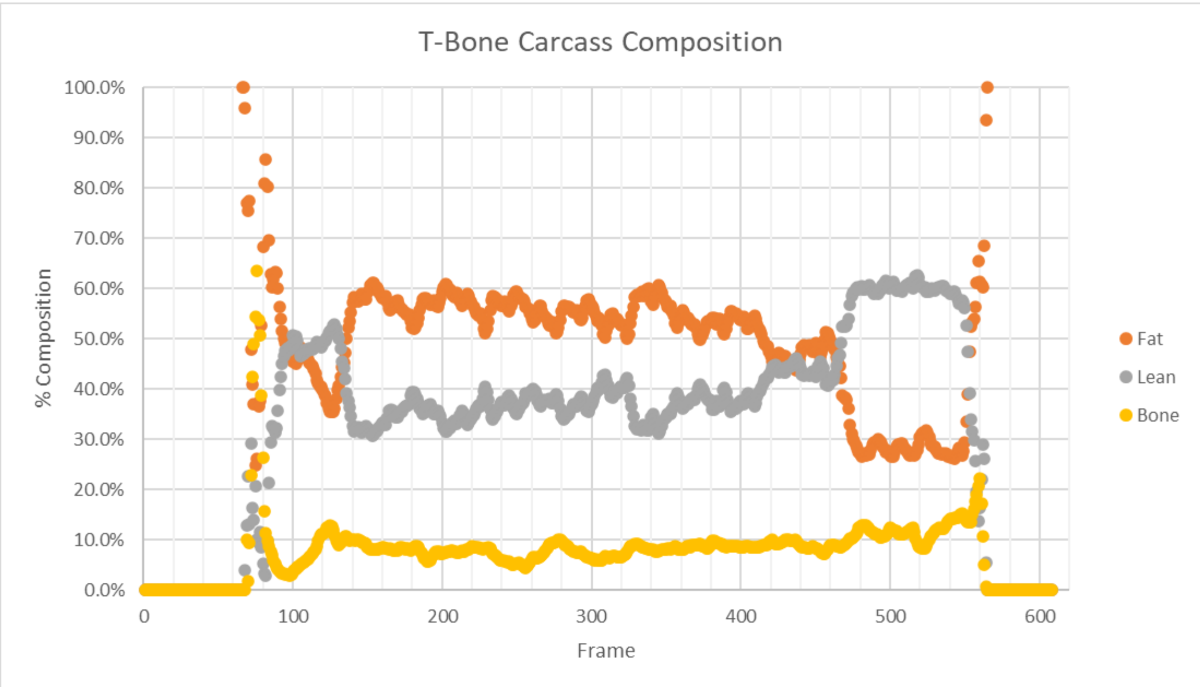

Figure 25: Percentage composition profile of the T-Bone section.

4.2.4 Material in beam

The slice image (Fig. 26) shows a beef section held in an Acetyl clamp with a small Titanium jaw tip (for durability). Image saturation and many streaking artefacts emanating from the highly attenuating Titanium tip make this material of limited value for meaningful scanning.

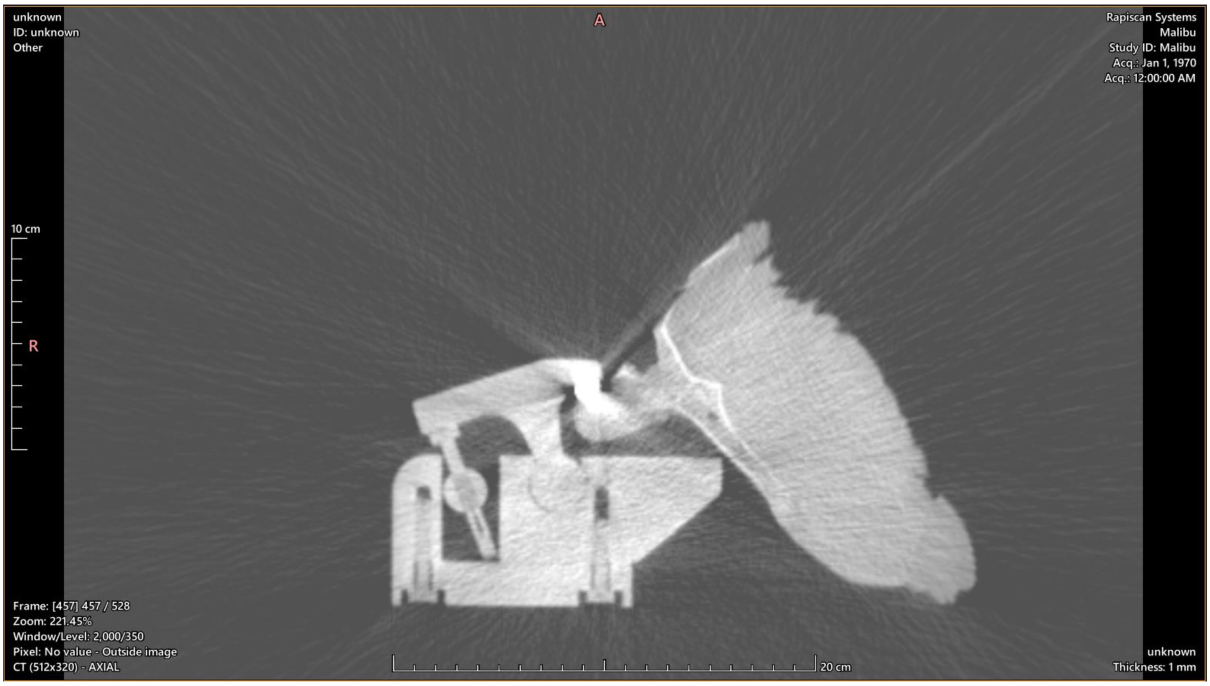

Figure 26: A slice from the scan of a T-Bone section held in Acetyl clamp with a Titanium tip on the clamp jaw.

To limit mess and potential contamination, e.g. when scanning diseased pieces, the meat may be contained on a support and wrapped in a plastic sheath. This slice image (Fig. 27) shows the thin plastic sheet and thicker plastic supporting mat. These two thin items display limited impact on image quality.

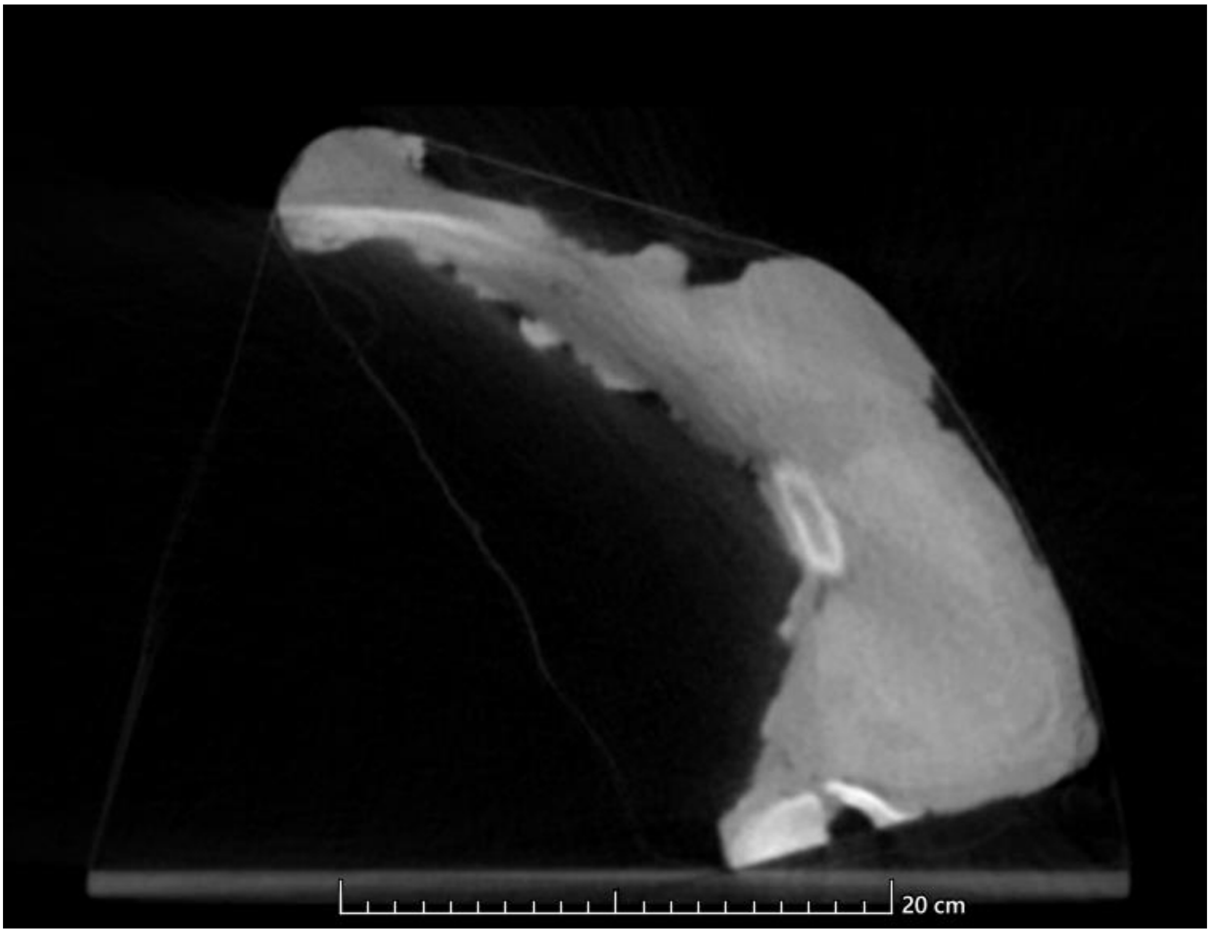

Figure 27: A slice from the scan of a beef side wrapped in a thin plastic sheet and riding on a plastic mat to avoid contamination to the inside of the RTT110 tunnel.

4.3 Artificial Intelligence in Offal Sortation

Another outcome from the RTT6040-ME program was the application of real-time, deep-learning Artificial Intelligence algorithms to automate and quantify product analyses. This work used beef and sheepmeat and offal as the product and was conducted on a linear 6040DV-MEXA (and multispectral) scanner. Detection outcomes from this work included:

- organ differentiation,
- defect and disease state measurement, and
- meat product provenance.

In each case, the accuracy of the processing was above 85%. Of relevance to this project, the algorithms developed worked automatically either 'flagging' organs with defects after classification or showing an image with coloured regions where the anomaly is detected, which could assist health inspectors focus further inspection. These MEXA-2D algorithms will be applied to MEXA-CT red meat scanning when available.

4.3.1 Organs and Handling

Normal and abnormal organs were acquired from abattoirs, scanned by the multi-sensor system, and then histopathological inspection performed by expert veterinarians. Organs that were considered abnormal (diseased or sick) at veterinary inspection in the abattoir were collected and then confirmed by histopathological inspection at the Veterinary teaching Hospital of The University of Sydney. Data collected was then used to develop various algorithms for the automatic detection of abnormal organs using various machine learning and deep learning algorithms, both supervised and unsupervised. Automatic identification of defects in both beef and sheep organs using hyperspectral imaging showed up to 92% accuracy.

For this study, 126 organs were collected as follows:

- 95 livers, 43 healthy and 52 unhealthy,
- 17 kidneys, 13 healthy and 4 unhealthy at abattoir but then deemed healthy at post-mortem inspection, and
- 14 lungs, 12 healthy and 2 unhealthy but only 1 was confirmed unhealthy during post-mortem inspection.

Livers were the most affected organs and therefore provided the strongest dataset for algorithm development. However, all organs were scanned but it was not possible to develop detection algorithms with such as low number of organs for kidneys and lungs.

The organs were scanned with the 6040DV multi-sensory platform at the University of Sydney Camden campus. The organs were examined grossly and, subsequently, histologically by veterinary pathologists at the University of Sydney Veterinary Teaching Hospital at Camden to confirm abnormalities. Indicative of the flexibility of the multi-sensory system, the last three days of organ imaging were performed virtually from Melbourne supporting the onsite handling of the organs.

4.3.2 Detection Algorithm Development

The detection algorithm development includes:

- data pre-processing,
- a deep learning network, and
- loss functions.

4.3.2.1 Data Pre-Processing

Deep learning models are often sensitive to the dataset distribution, and data variations or redundancy which may lead to performance decline of a deep learning model. To alleviate the negative impacts of distractive or redundant information from visible HS images, pre-processing operations (as illustrated in Fig. 28) were performed, including:

1. manual removal of irrelevant regions and selection of regions of interest (ROI),
2. band filtering,
3. value normalization, and
4. split of training and test datasets.

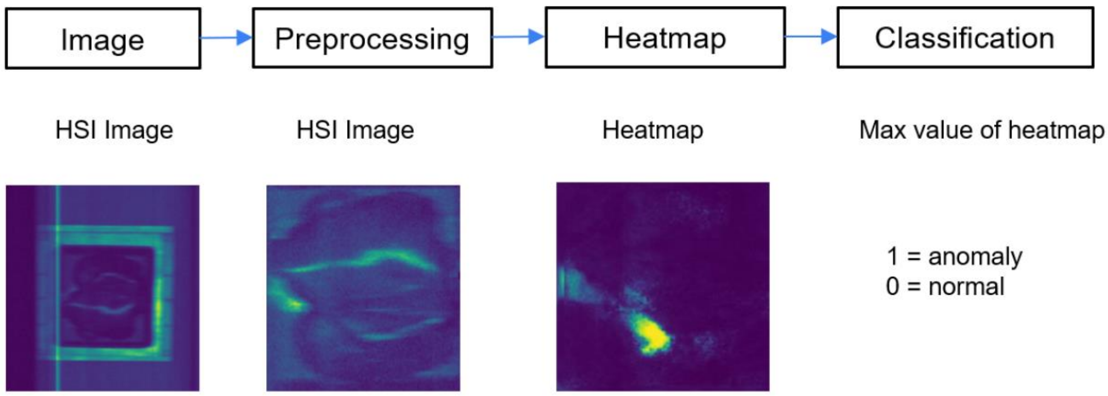

Figure 28: Algorithm development: The collected images are pre-processed and fed into a deep learning network, the output of which is a defect probability heat map of the images. The maximum value of the heat map is used to determine if the image contains defects, and the heat map can also be used as a localisation of the defects.

4.3.2.2 Deep Learning Network

The deep learning network is responsible for converting the pre-processed data into a defect probability heat map, the task's output. The deep learning model receives hyperspectral images of beef livers and outputs the probability of image pixels being a disease as a heat map (Fig. 29). The maximum value in the heat map determines the screening of an image as diseased or normal.

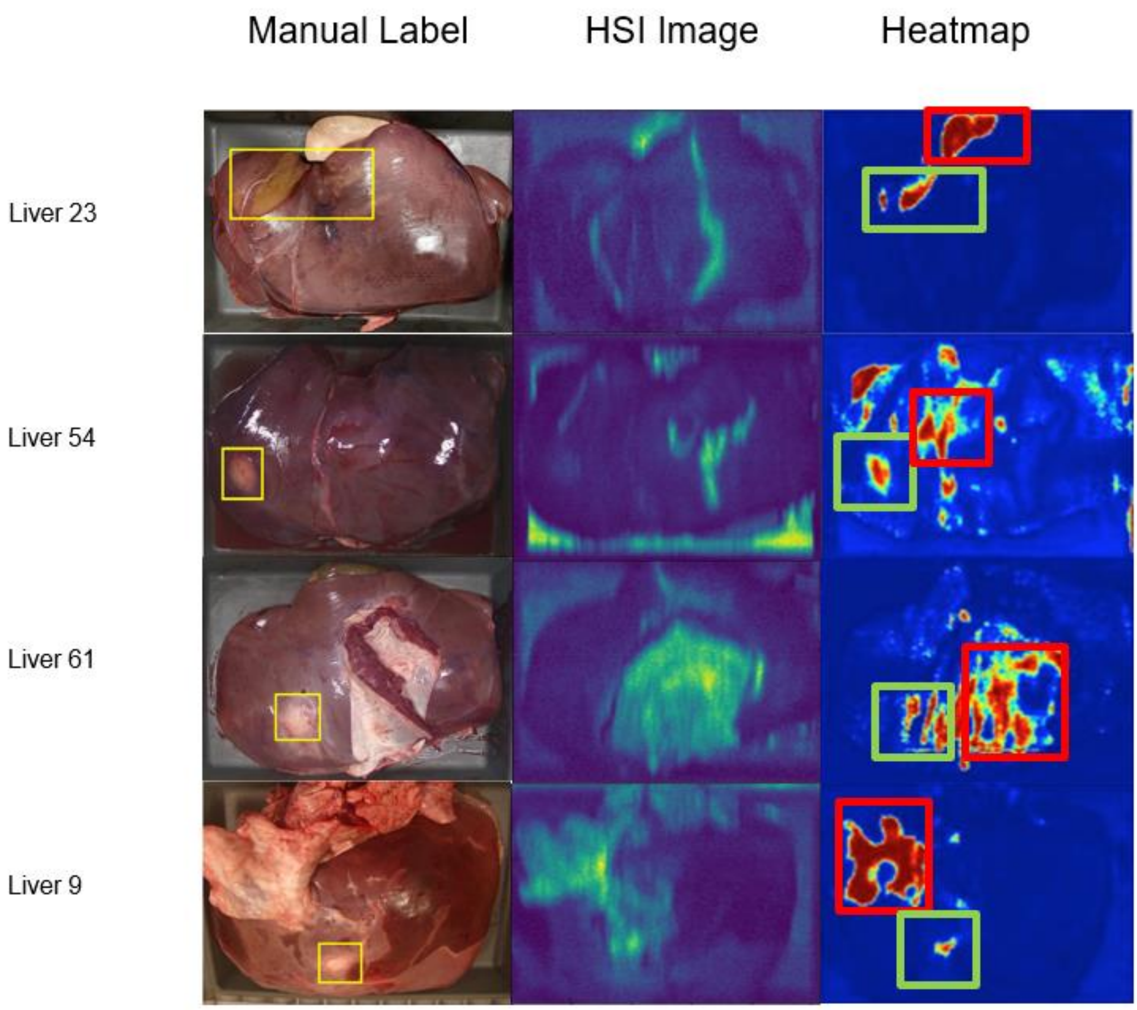

Figure 29: Results visualisation of beef liver with anomalies using deep learning algorithms.

4.3.2.3 The Loss Function

The loss function is how the deep learning network is trained to produce the result as expected and is determined according to the hypothesis that diseased beef liver contains tissues not found in healthy beef livers. The network must predict each pixel for a given image and display the results as a heat map. The higher the heat map value, the higher the probability that a feature in the image is anomalous (0 for the normal, 1 for the anomaly). Although the location of the abnormality in the disease image is unknown, the abnormal tissue in the abnormal image should be the maximum in the image, as assumed above.

Table 4: Model metrics on the test (validation) set of diseased and healthy liver samples (1/3 of the 95 liver dataset).

Metric on Test Set	
Accuracy	0.92
Precision	0.88
Sensitivity	0.93
Specificity	0.84

In addition to the binary automated classification of abnormal and normal, as illustrated in Figure 29, our method can also generate heatmaps for anomaly detection. The anomaly locations generated entirely automatically. Moreover, the network generates meaningful results compared to manual segmentation (Table 4). For example, the network could detect the tumour location. In Livers 54, 61, and 9, the tumour location is displayed as high contrast in the heat map (shown as green box in heatmap). However, the network also finds other anomalies (shown as red boxes in the heatmap). These anomalies do not appear in any of the normal images but in the anomalous images. According to our hypothesis, they are also anomalies. Therefore, our discriminator also identifies them as anomalous tissues.

5 Conclusion

The MEXA CT system operated at the Rapiscan Systems UK facility, albeit at lower voltage and with only a single energy detector array. It was viewed by Daryl Heidke of MLA. The operating tube voltage (100kV) is lower than the planned value which limits the penetrating power of the system. A long-term remediation program would be needed to increase tube voltage up to 160kV but this was beyond the scope of the P.PSH.0886 project in terms of both time and budget. Instead, Rapiscan has taken enough confidence to continue the development of energy discriminating solid state CT. This technology will result in a new unit that is currently in design and is expected to be commissioned in the early part of calendar-year 2024. The new design has taken many of the lessons learned from the RTT6040 program and incorporated them in the design for future products. Rapiscan will continue to engage MLA and plans to future develop the X-ray sensors.

The MEXA CT image reconstruction pipeline is able to operate at full speed but software integration does not yet allow seamless data collection from the MEXA CT scanning system.

Further software integration work would have been required to complete the link between data acquisition, image reconstruction and image visualisation, although the program is now closed.

No attempts have been made to image meat products with this system.

5.1 Key findings

This equipment development program has delivered SEXA CT X-ray capability, albeit operating off-line and not able scan and present images in real-time.

- MEXA X-ray transmission imaging is a brand-new field with little experience accumulated to date. Over the coming years, our experience will grow and the delivered systems will be optimised. When this happens, the true potential for MEXA compared to DEXA imaging will become clear.
- Static gantry CT has been proven in the aviation industry over many years and its introduction to the red meat industry will unfold over the coming years.
- Static gantry MEXA CT is a unique program that is being developed exclusively through this MDC program. We are very close to determining whether energy resolving high speed CT will play a valuable role in the red meat industry.

5.2 Benefits to industry

At this stage, it is hard to gauge the potential benefit to industry from MEXA products compared to standard CT and DEXA transmission systems. However, this program has established the technology platform on which colleagues in veterinary and meat science can move forward in partnership with industry to find those use cases where these advanced technologies will play a key role.

At the start of this program, the outcome focus was on automation and objective measurement. Today, there are likely to be many applications in quality assurance which together may come to dominate the role for X-ray, DEXA and MEXA systems in the red meat industry.

It is possible that X-ray guided automation systems will move from the kill floor to the boning room where they can be made in a compact way to substitute for skilled labour where shortages are acute.

In the coming year, as the technology matures to commercial first articles from R&D prototypes, it will be important to get systems into the hands of potential users in the red meat industry. At the same time, a new network of AI developers could be introduced to take the rich data set from MEXA CT systems and exploit this for commercial gain in the red meat industry.

What is clear is that more automation is likely to be required in the red meat industry over coming years to achieve meat sustainability and other targets. It is very likely that X-ray imaging will play a role in supporting these developments, although the precise way in which these solutions will be delivered is not clear today.

6 Future research and recommendations

For the MEXA CT program, the following R&D strategy is recommended:

- Continue to refine the RTT technology to deliver the most reliable, highest performing systems possible.
- Work with scientific and commercial partners to exploit the use of DEXA or MEXA CT in different application areas including automation and quality control processes. Evaluate the potential for objective measurement of eating quality and other metrics.
- Develop a network of AI partners who can add value to commercial processes by using image data to achieve commercially valuable outcomes.
- Rapiscan plans to continue to engage with MLA on development of solid-state CT products. When available Rapiscan will endeavor to get meat images into the hands of MLA’s development teams and research partners for analysis.
- Rapiscan will look to determine on what basis some of the earlier examples of new scanners can be provided to MLA and their partners for analysis.