Final Report

Imaging Report

Micro-X Red Meat CBCT Scanner Project

Project Code
2021-1208

Prepared by
Peter Cooper

Date Submitted
22/06/23

Published by
AMPC

Date Published
22/06/23

1 Contents

2 Executive Summary

The objective of the project was to identify opportunities for Micro-X’s Cone Beam Computed Tomography (CBCT) solution to be used in a meat processing and packaging application for the Australian Red Meat Industry, and to identify and evaluate possible designs for implementing a solution.

The initial project activity was to review summarised reports provided by AMPC of past CBCT related studies in order to clearly define the required outcomes and to determine what work had already been carried out towards those outcomes. Preliminary design ideas for a CBCT solution were then generated and reviewed with AMPC, and it was determined that a rotating CBCT system deployed along the meat production line would provide the optimal solution. The number of tubes required in this system, as well as the number of shots that would be needed, would be determined as part of an imaging trial that made up the next part of the project timeline.

The imaging trial took meat cuts of varying sizes and thicknesses and scanned them in Micro-X’s CBCT imaging testbench. Whilst not fully representing the ideal image geometry, the aim was to reuse existing equipment in development to assess the feasibility of progressing a representative prototype in next stages, without needing to invest in expensive new technology. Results of this imaging study are given in Section 6.3.

Overall, given the limitations of the existing imaging system and the basic algebraic reconstruction techniques used, which are designed specifically for imaging human heads, the results show that the technology and proposed imaging architecture is feasible and with focused imaging development can generate the desired images.

The final activity of this project phase is to develop a roadmap for a commercially viable solution that will be acceptable for both Micro-X and the Australian red meat processing sector. This report contains a suggested roadmap defining the activities that will need to be carried out in any future project phases. The main components of the roadmap are as follows:

1. Micro-X to carry out activities to optimise the imaging. This will require further scanning and development of the reconstruction algorithms in order to produce scans that are fit for purpose using the minimum number of tubes, shots, and mAs.
2. Micro-X to develop a demonstrable scanner model. This model will be used at the customer site for a supervised test activity.
3. Micro-X to develop a test unit that can be used for a longer-term on-site trial.

3 Introduction

AMPC's 2020-2025 Strategic Plan identified the need for programs to be developed to meet the following needs:

- Increased safety via hands-off meat processing,
- Increase profitability through more accurate processing,
- Acquisition of product information and leverage of data insights,
- Improving staff retention through making tasks more interesting,
- Development of tasks requiring higher skill and intellect, and
- Reduction in the need for high-risk processing operations.

One way to meet at least some of the above goals is to introduce greater automation of the meat processing task. This would require a method of scanning meat carcasses and feeding data to a robotic cutting system. It has been identified that Micro-X's Carbon Nanotube CBCT scanning technology is a strong contender to meet the needs of the scanning component of any future automated system.

The purpose of Phase 1 of the project is therefore to investigate and demonstrate how Micro-X's CBCT technology could be used in such an automated system. An initial high level system design will be proposed and based on this architecture a series of scans will be taken on meat samples of various sizes and thicknesses. The scope of the scanning activity is to verify that Micro-X's CNT technology will be sufficient for the purposes of an automated scanning system and also to assist in determining the optimal number of tubes, scans and the mAs required.

4 Project Objectives

The following project objectives were specified in the research agreement.

4.1 Milestone 1

- Conduct a review of past CBCT work carried out,
- Discuss and agree on focus areas for CBCT scanning work,
- Site visits for Micro-X staff to processing plants.

4.2 Milestone 2

- Draft roadmap of possible Micro-X CBCT applications to focus on,
- Agree sample plan for scanning evaluation,
- Milestone report submitted and approved.

4.3 Milestone 3

- Review of scanning results
- Milestone report and meat purchase complete.

4.4 Milestone 4

- Final scanning results and review

4.5 Milestone 5

- Submit snapshot and final report with future state roadmap.

5 Methodology

The project progressed through the following phases:

5.1 Concept Design

The project commenced with the Concept Design phase, where options for a solution were explored and evaluated. Based on the literature study it was determined that conventional 2D imaging would not meet the needs of the application, and that a 3D scanner using Cone Beam Computed Tomography (CBCT) would be required. It was then determined that the most practical solution would require the tube(s) and detector to be rotated about the sample rather than rotate the sample.

Based on these design decisions the following concept design was generated:

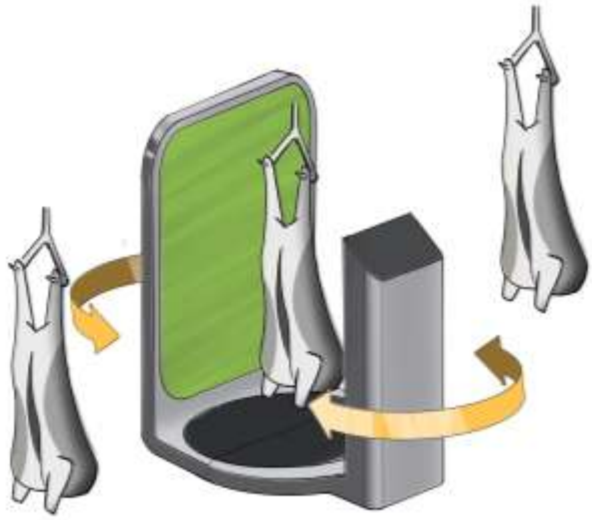


Figure 1 Rotating Scanner Concept

Figure 1 Rotating Scanner Concept shows a conceptual view of a factory-based system for scanning meat carcasses progressing along a production line. Figure 2 Flat Scanning with Multiple Sources shows a similar factory-based system for scanning smaller samples.

Figure 2 Flat Scanning with Multiple Sources

5.2 System Architecture

A preliminary System Architecture was then created as shown in Figure 3 Preliminary System Architecture. The System Architecture defined the functional blocks that would be required in the final system, and their interfaces.

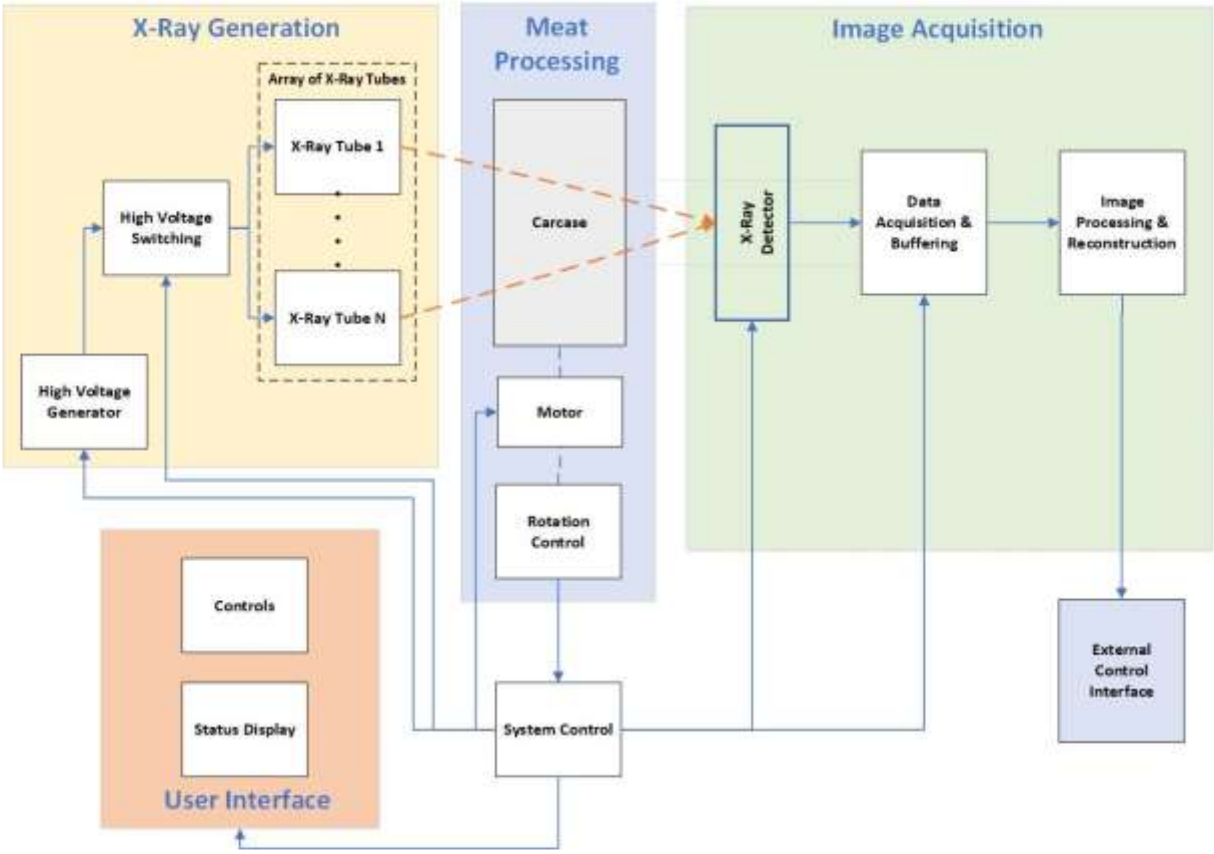


Figure 3 Preliminary System Architecture

5.3 Imaging Requirements

Table 1 below gives an indication of the required tube specifications for meat processing as provided in (Jonathan Cook, 2017) (Andrzej Junkuszew a, 2004) (E A Navajas, 2009) (J. Kongsro a b, 2008) (N Prieto 1, 2010). Note that these studies were carried out with conventional CT rather than Cone Beam CBCT which requires smaller kV, mA and mAs values.

Tube	Required Tube Voltage (kV)	Required Tube Current (mA)	Required mAs
Cutting, Deboning, Trimming and Grading	100-160	100-180	150-170

Finished Product and Health Inspection	100	1-2	10-20

Table 1

Table 2 below gives specifications for current Micro-X tubes. It can be seen that the voltage range for all tubes in the table is consistent with the range required for Cutting, Deboning, Trimming, and Grading, whilst the mAs value given is higher than the current tube range. As noted above, the values given in the table are for conventional CT and therefore will be lower for CBCT. In addition, larger tube powers can be achieved in future tubes if this is required.

Tube	Tube Voltage (kV)	Tube Current (mA)	mAs
Mosaic	40-120	20-90	0.2-80
MBI	160	2	40
MBS	160	8	
Nugget	40-110	40-80	0.2-20

Table 2

5.4 Preliminary Cost Estimates

A preliminary cost estimate for a final system was then created using an estimated Bill of Materials as shown in Figure 4 Bill of Materials. Note that multiple detector choices are included based on required performance. Final selection of the detector and the number of tubes will be based on experimental data and specific customer needs.

Materials	Cost $AUD
X-ray Tube	1,000
Generator	10,000
Detector (high frame rate)	40,000
Detector (standard frame rate)	10,000
Detector (energy sensitive)	100,000
Shielding	5,000
Cabling	1,000
Motion Systems	5,000

Figure 4 Bill of Materials

5.5 Sample Imaging

The final phase of the project was to produce CBCT images of selected meat cuts in order to test the feasibility of the concept outlined in previous phases, as well as to determine the optimal number of tubes and the required dose to produce useful images.

The imaging study seeks to answer the following questions:

- Can we view bone definition in the sampled images?
- To what extent can fat/meat/muscle tissue be distinguished in the images?
- What mAs is required to penetrate the various cuts sampled?
- What artefacts will be produced in the images and what will be necessary to correct them?

5.5.1 Selected Meat Samples

In consultation with AMPC, the meat cuts shown in Table 3 were selected for sample imaging. As shown in the table, the dimensions of the meat varied so as to assess Micro-X's technology against a range of meat types and thicknesses.

Sample ID	Cut	Image	Height/Width/Length (cm)
1	Beef Loin with Chine		21x18x26

1V	Beef Loin with Chine – Vacuum Wrapped		20x17x27
2	Lamb Ribs Unfrenched		8x18x25
2V	Lamb Ribs Unfrenched – Vacuum Wrapped		5x16x22

3	Tomahawk Steak		5x15x35
3V	Tomahawk Steak – Vacuum Wrapped		5x17x36

Table 3 – Meat Samples

5.5.2 Test Rig

The existing Micro-X Vader testbench was used to scan the meat samples listed in Table 3. The Vader testbench consists of a single Micro-X "Nugget" X-Ray tube mounted on a bracket which can be rotated in an arc as shown in Figure 5 - Vader Rotation Diagram. The Vader testbench is capable of operating between 0.2 and 12.5 mAs for 100kV.

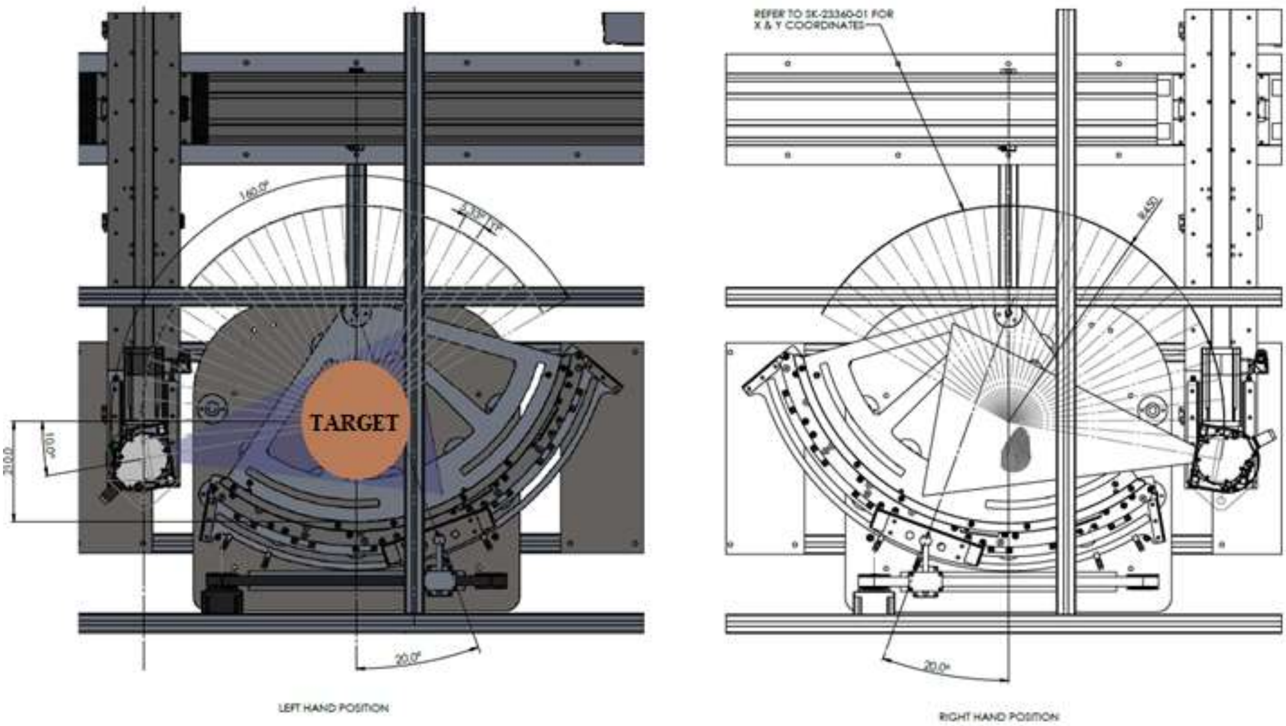


Figure 5 - Vader Rotation Diagram

The Vader testbench allows for both tube and detector to be rotated into different positions [see Figure 6 – Tube and Detector Selectable Positions] and can therefore be used to simulate a variety of tube and detector configurations in the final product.

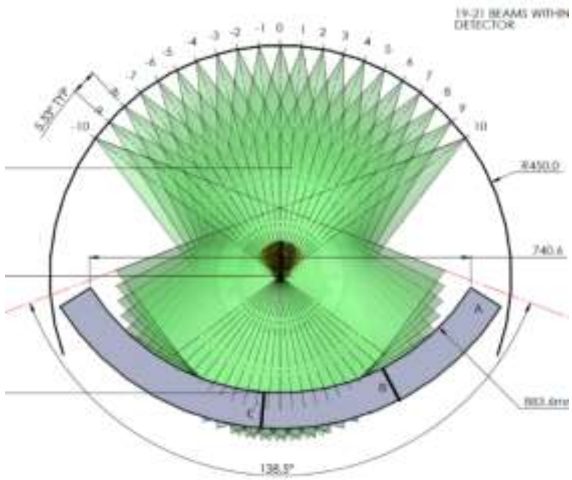


Figure 6 – Tube and Detector Selectable Positions

The testbench was used to scan the cuts of meat shown in Table 3 – Meat Samples. Using the default testbench configuration, 21 shots were taken by moving the X-Ray tube into each of the positions shown at the top of Figure 6 and firing the tube. The detector for these 21 shots was kept in the 0 degrees position marked as position “B” in

Figure 6. This process was then repeated twice with the detector at position “A” and at position “C”, giving 63 shots of the target in total. These shots are then reconstructed into the final CBCT image.

The number of shots and the positioning of the detector is designed to allow maximum coverage of the target and to ensure all angles are imaged. The resulting scans are shown in section 6 Project Outcomes.

The Vader testbench has the following limitations:

- Imaging is done at a low framerate designed for human head medical imaging.
- Reconstruction Software is at a preliminary stage and requires further optimisation to improve image quality.
- Reconstruction Software is designed for stroke (soft tissue) imaging.

5.5.3 Imaging Process

Using the Vader testbench and meat samples listed in Table 3 – Meat Samples, the following sequence of experiments was conducted.

5.5.3.1 Exposure Parameter Investigation

The objective of this experiment was to determine the optimal exposure settings, specifically the milliampere-seconds (mAs) and kilovolt (kV) values that would be needed for the testbench scans. The Micro-X Rover Mobile X-ray cart was positioned 1 metre from the digital detector. A beef loin, the thickest meat sample available, was selected as the subject for this study.

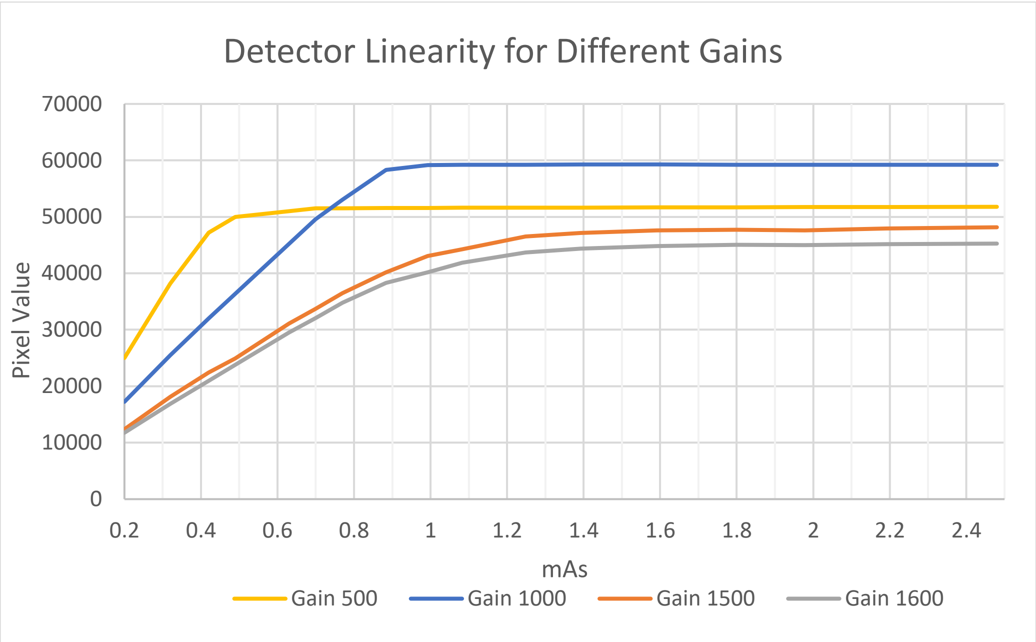
Figure 7: Micro-X Rover Mobile X-ray Cart Set up with Beef Loin

Images were acquired using different combinations of mAs and kV values. The mAs determines the total amount of radiation exposure, while the kV controls the energy of X-ray photons. Multiple exposure settings were tested to evaluate their impact on image quality. Results of this study are given in 6.1.

5.5.3.2 Detector Linearity Investigation

The Vader testbench utilises a curved detector which is optimised for human head CBCT imaging. Prior to using the testbench for scanning meat cuts it was therefore necessary to investigate the response of the imaging system's X-ray curved detector to proposed changes in the X-ray current over time (mAs). The experiment aimed to gather crucial information on how the detector's pixel values would be affected when the mAs settings were modified. Specifically, the experiment sought to identify any nonlinearities or limitations in the detector's response to increasing mAs values.

By measuring the pixel values at different mAs settings, the study aimed to determine if there were any points at which the relationship between mAs and pixel values deviated from linearity. This deviation would indicate that the detector's response was no longer directly proportional to the changes in mAs, thereby highlighting the limitations of the current imaging system detector.



The results of this study are given in 6.2.

5.5.3.3 Meat Scanning

Meat samples were scanned by placing them in the testbench cradle as shown in Figure 8 - Meat Placement below.

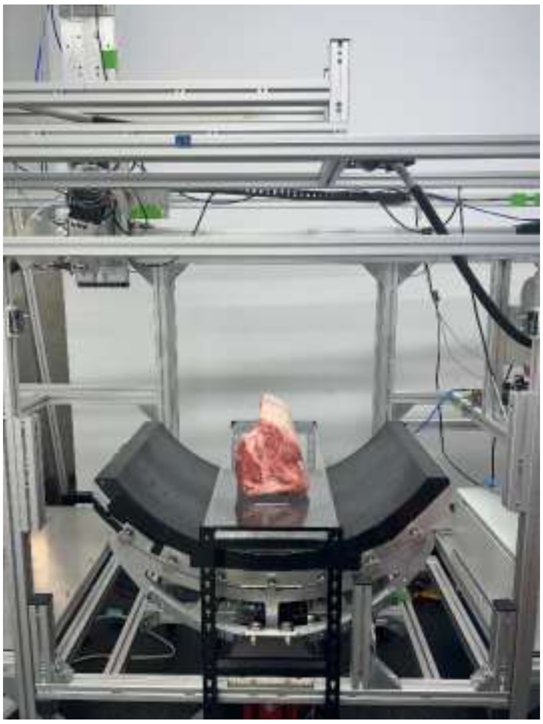


Figure 8 - Meat Placement

The steps for meat sampling were as follows:

1. Calibration.
   Before scanning meat samples, dark images were taken in order to determine the base background noise of the detector. Dark images are taken by capturing data from the detector without any radiation being generated. This information is used in the reconstruction phase to factor out noise from the raw data.

   Once dark images had been taken, blank images were captured by triggering a full scan without a target between the detector and X-ray tube. Blank images are used to evaluation the position of the beam without a target. When the target image has been scanned, the data from the blank images is compared to the beam position with the target present in order to reconstruct the CBCT image.

2. Imaging
   Once calibration was complete, a scan was initiated. During the scan, the X-ray tube rotated and captured an image at each of its 21 preset locations. At the conclusion of the 21 scans the detector was rotated into the -20 degrees position and a further 21 scans were taken. The detector was then rotated into the +20 degrees position and the final 21 scans were captured.

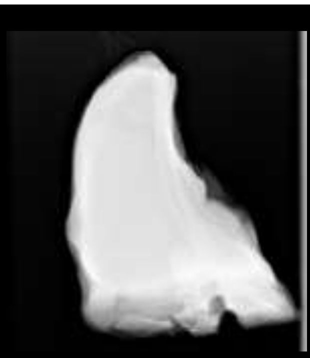
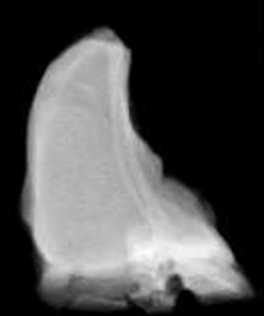
3. Reconstruction
   In the reconstruction phase, the 63 captured images were reconstructed using the Vader testbench reconstruction software.

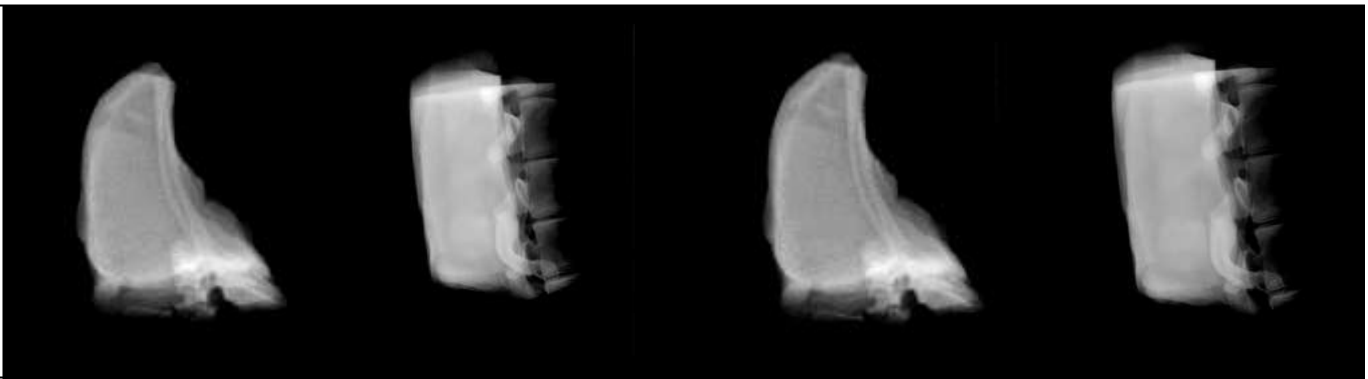
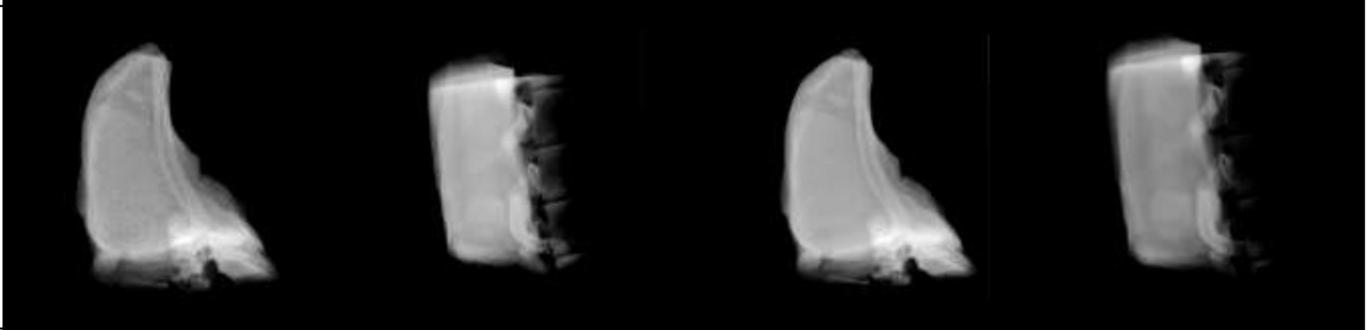
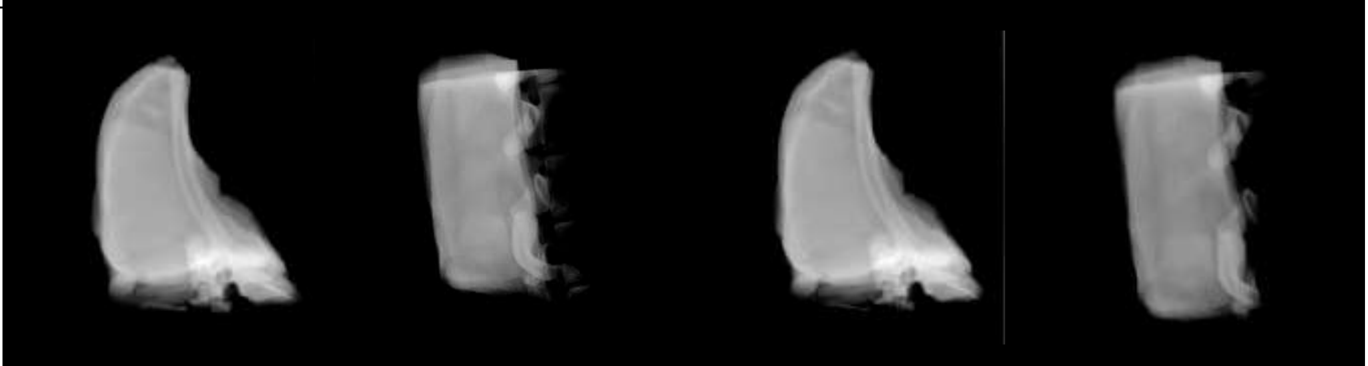
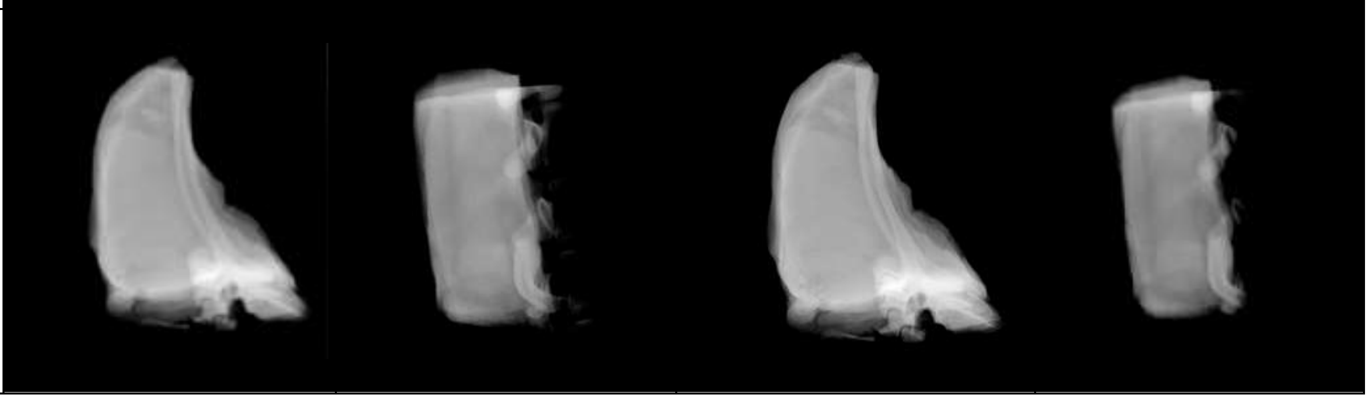
6 Project Outcomes

This section provides the results of the experiments listed in section 5.5.3. Cross sections of the resulting CBCT images are provided. See Appendix 10.1 and Appendix 10.2 for the full cross-sections captured.

6.1 Exposure Parameter Investigation

Table 4 – Exposure Study contains the results of the experiments defined in section 5.5.3.1. The aim of this experiment was to determine the optimal mAs and kV values for scanning the meat samples. The table shows scans of the meat samples listed in Table 3 – Meat Samples at varying mAs and kV levels.

mAs	100kV		110kV	
0.4				
1				
2				
3.2				

4	
5	
6.3	
7.1	
8	

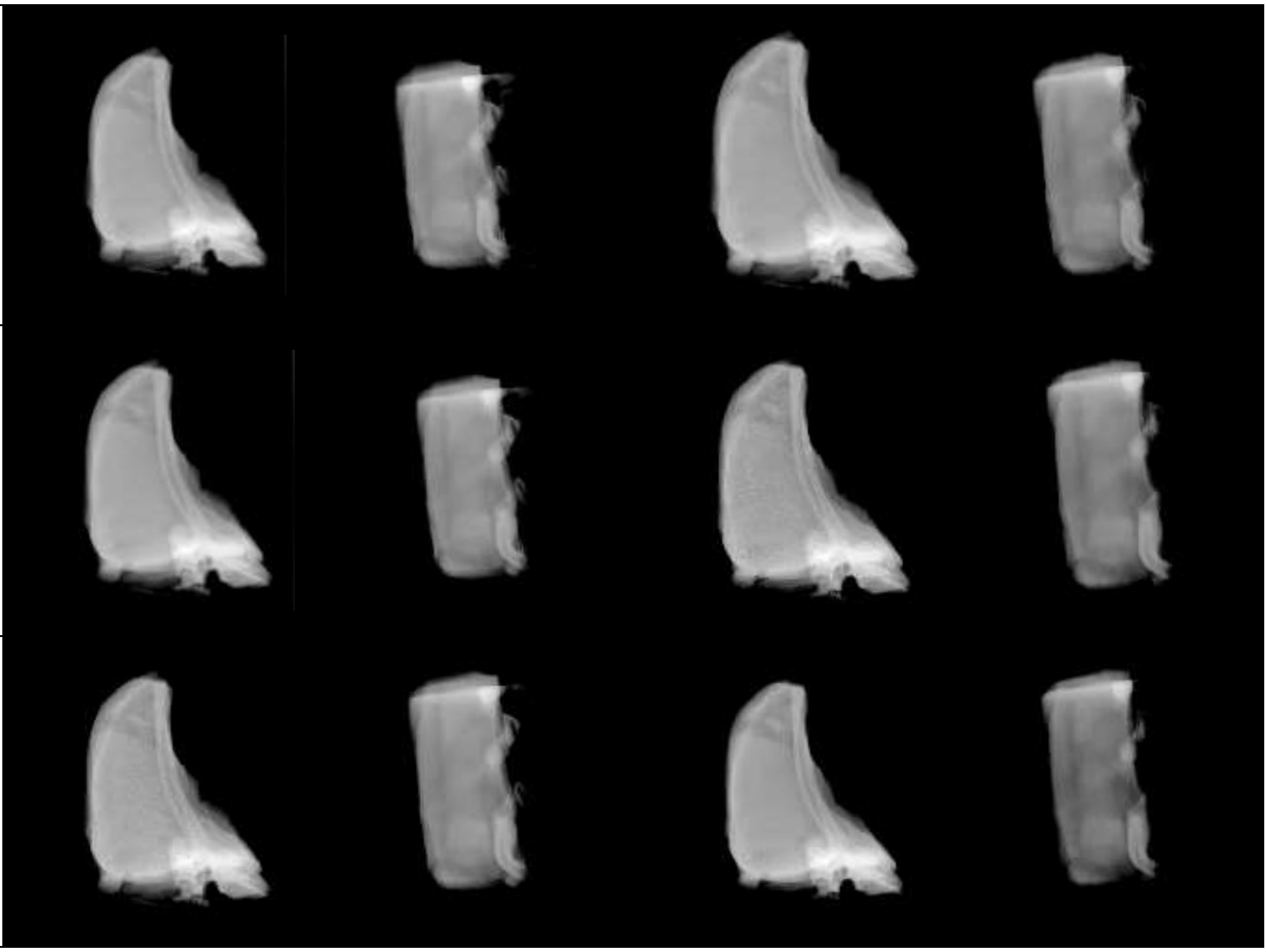
9	
10	
11	

Table 4 – Exposure Study

The X-ray images obtained at various exposure settings were examined. Image quality parameters, such as clarity and contrast, were evaluated to identify optimal exposure settings for meat samples of the dimensions given in Table 3 – Meat Samples.

Based on the image quality assessment, the following exposure settings were determined to be optimal for meat sample analysis:

a) Tube voltage: 100kVp

b) Tube current over time: 2-4mAs

These settings yielded images with the highest level of clarity and contrast, thereby enhancing the visibility of meat structures.

When the tube current was set too low, the intensity of the X-ray beam was insufficient to generate an adequate signal-to-noise ratio in the acquired images. As a result, the images lacked the necessary contrast for distinguishing subtle variations in meat structures.

Increased tube current, which influences the intensity of the X-ray beam, led to a higher dose of radiation being delivered to the meat sample. This resulted in an increased likelihood of overexposure, leading to the removal, or blurring of meat structures in the X-ray images.

It is worth noting that the influence of exposure settings on image quality can vary depending on the specific characteristics of the meat samples, such as thickness, density, and composition. Hence, further investigations should focus on tailoring exposure settings based on specific meat types or processing methods to optimize the trade-off between image quality and structural preservation.

6.2 Detector Linearity Investigation

The Detector Linearity experiment sought to determine how the detector pixel values were affected by changes in the mAs value. The results obtained from the experiment demonstrated a linear increase in pixel values with increasing mAs. However a deviation from linearity was observed. The deviation point varied depending on the specific gain setting. Beyond this point, the pixel values exhibited a plateau or limited increase, even as the mAs continued to increase.

The observed deviation from linearity in pixel values as mAs increased suggests that the dynamic range of the X-ray detector becomes saturated at higher mAs settings. This saturation occurs when the detector's electronic components reach their maximum capability to convert X-ray energy into electrical signals. Consequently, increasing the mAs beyond this point does not lead to a proportional increase in pixel values. Imaging with the current test bench curved detector is therefore limited to 0.9mAs to ensure the detector response remains within the operational range.

The use of flat panel detectors is expected to increase the operational range but would require modification to the current testbench hardware and software and is not within the scope of this study.

6.3 Meat CBCT Scan Results

This section provides the results of the CBCT scans of the cuts of meat defined in Table 3. A representative sample of the resulting images is provided with the full cross section given in Appendix 10.1 and Appendix 10.2.

6.3.1 Beef Loin with Chine Bone (Unwrapped)

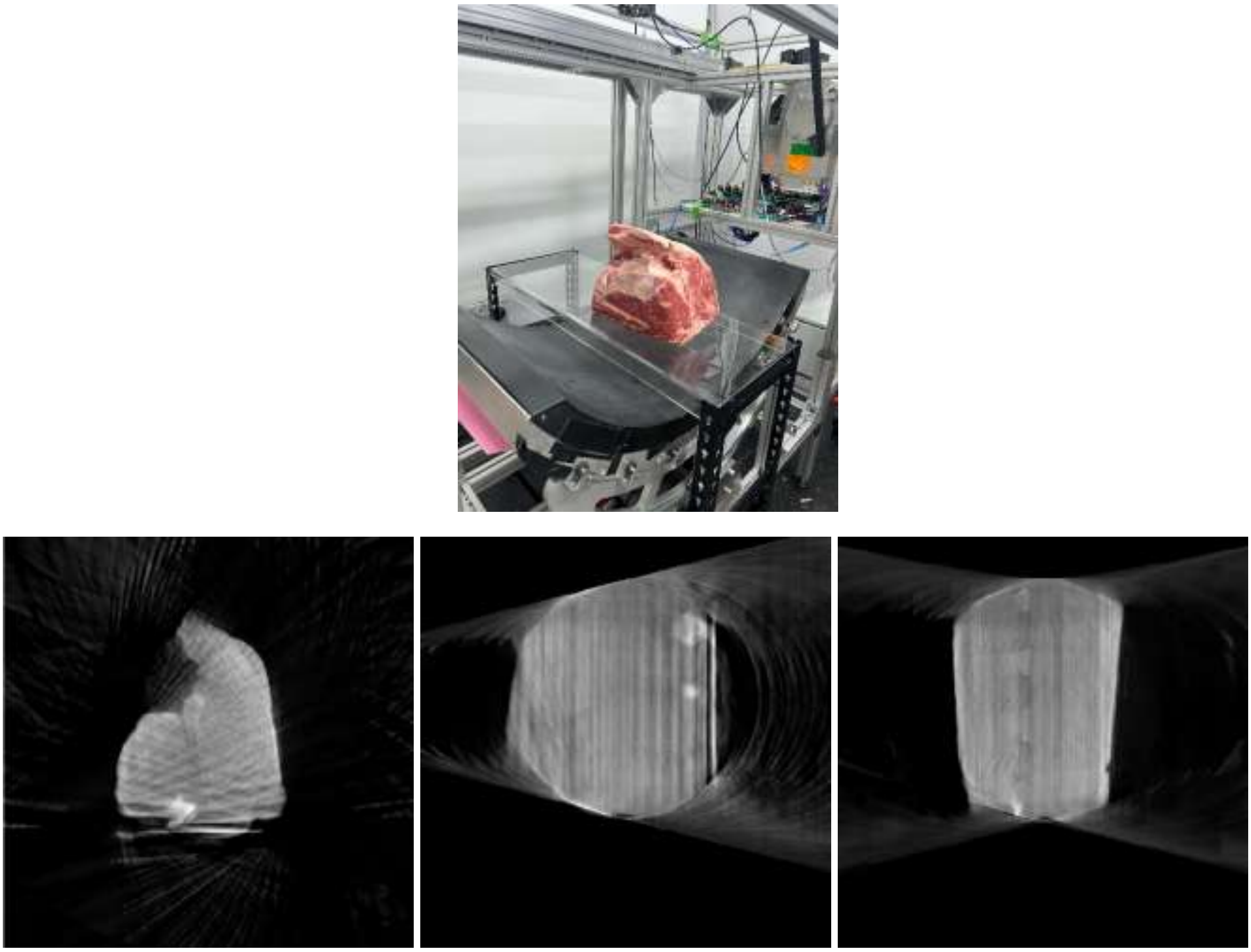


Figure 9: Beef Loin with Chine Bone

6.3.2 Beef Loin with Chine Bone (Wrapped)

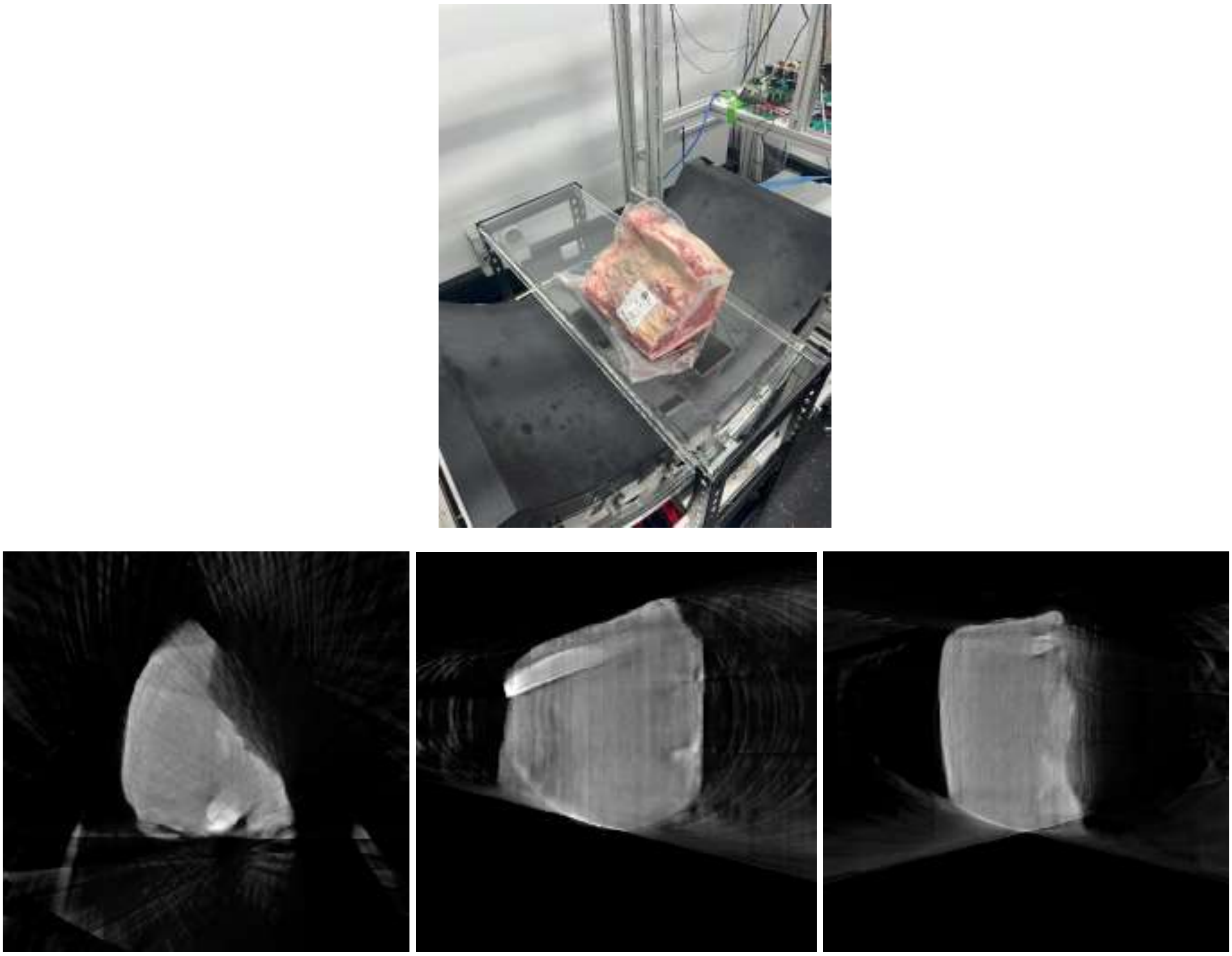


Figure 10: Beef Loin with Chine Bone Vacuum Wrapped

6.3.3 Tomahawk Steak (Unwrapped)

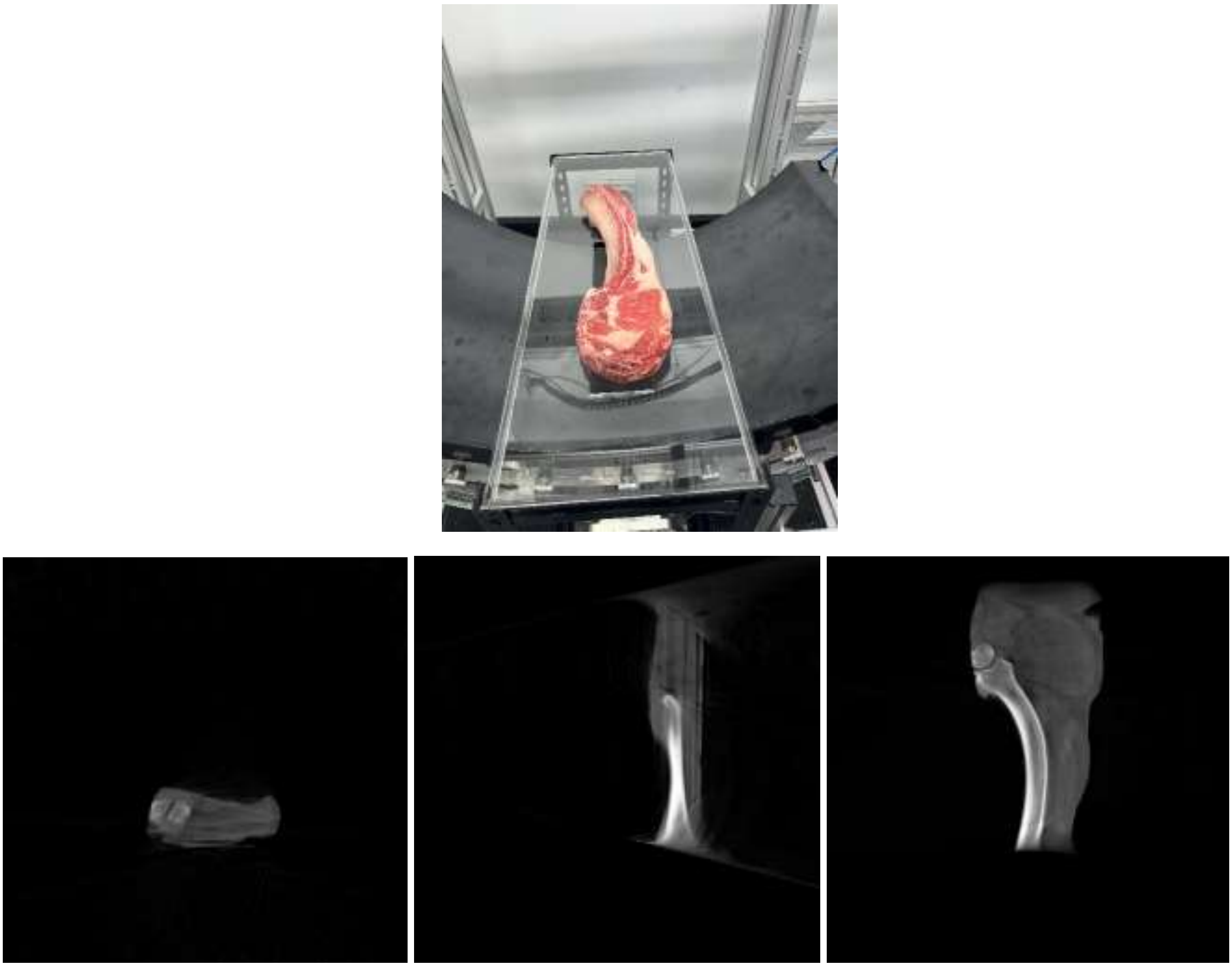


Figure 11: Tomahawk Steak

6.3.4 Tomahawk Steak (Vacuum Wrapped)

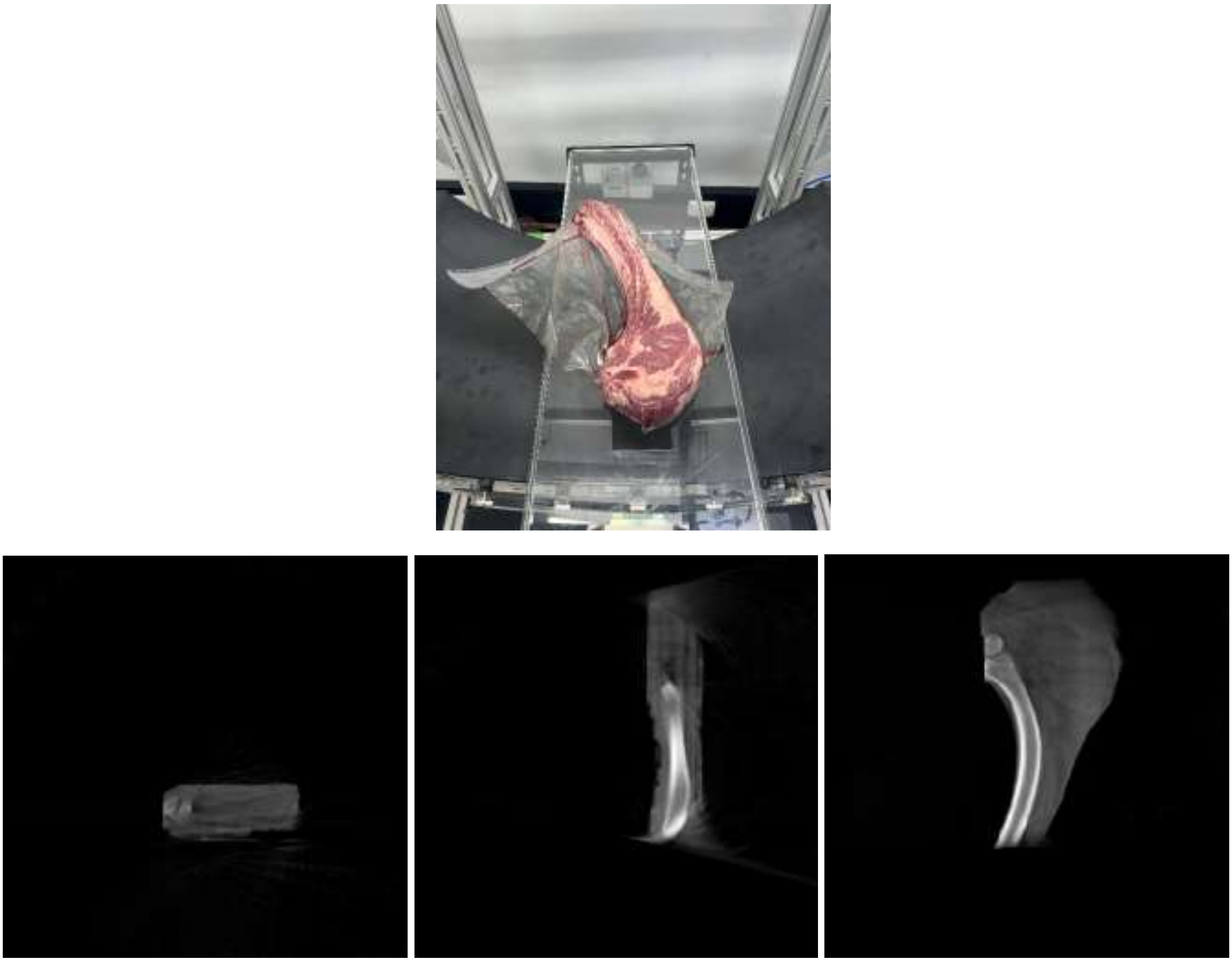


Figure 12: Tomahawk Steak Vacuum Wrapped

6.3.5 Lamb-Ribs Not Frenched (Unwrapped)

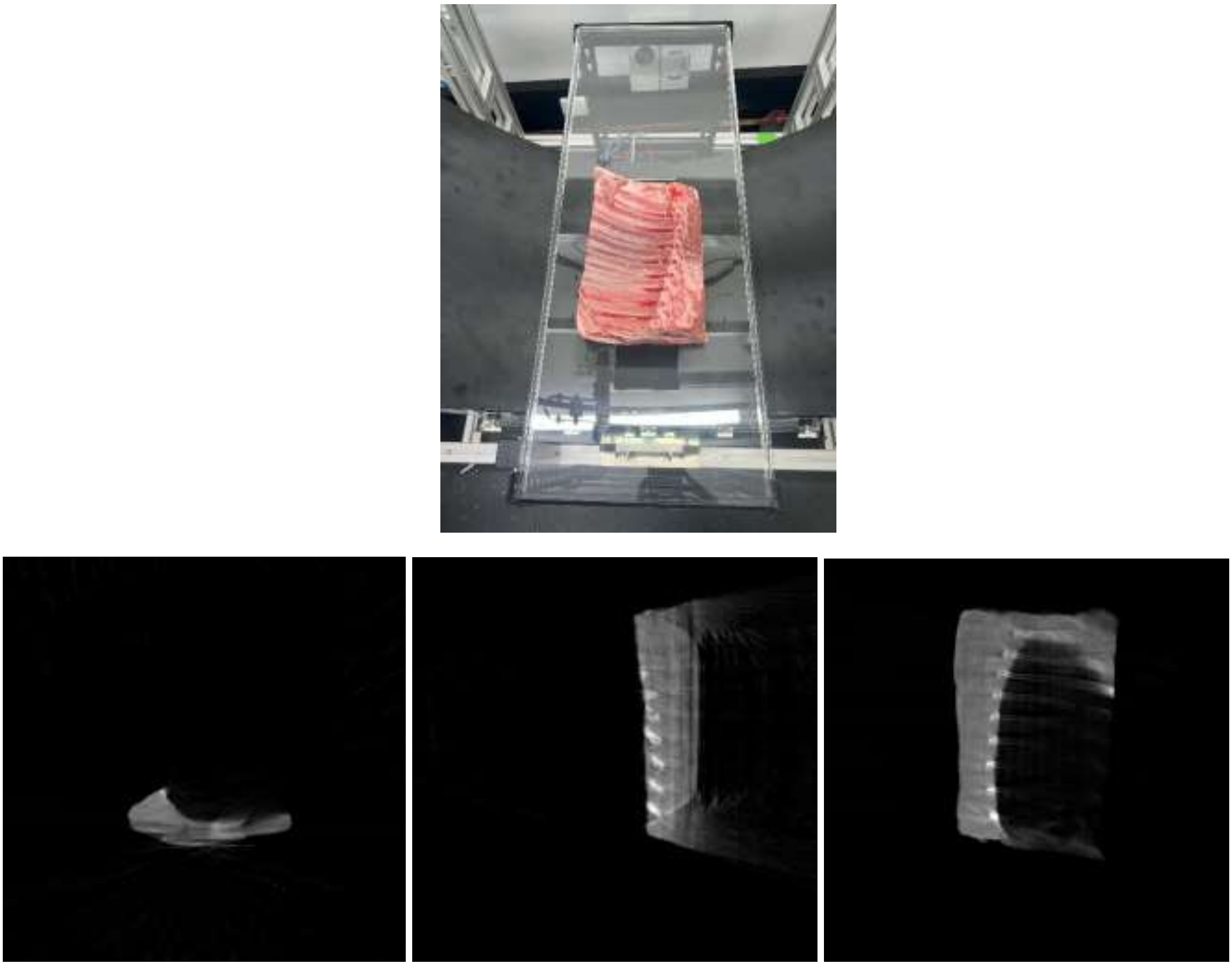


Figure 13: Lamb Ribs Not Frenched

6.3.6 Lamb Ribs Not Frenched (Vacuum Packed)

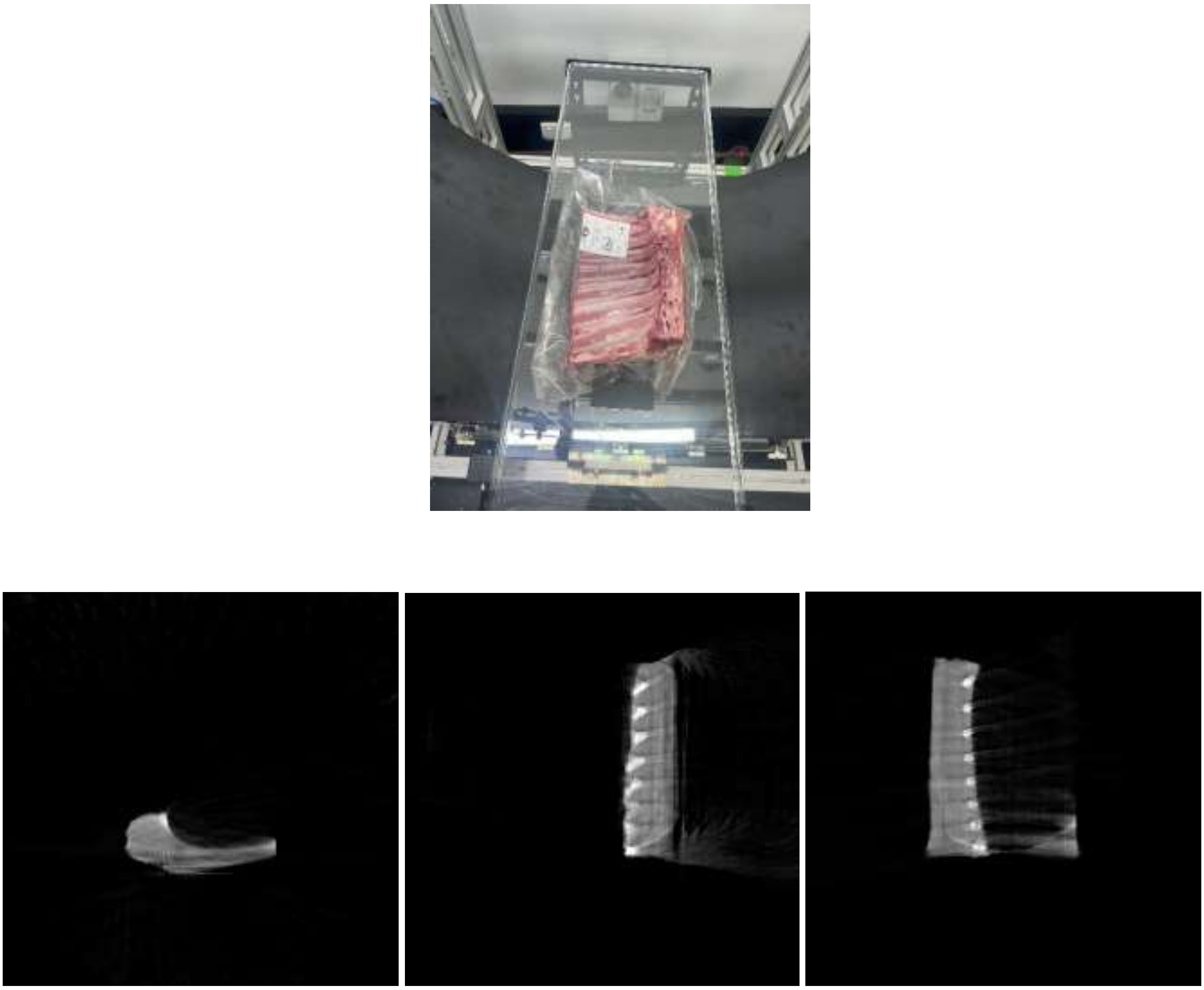


Figure 14: Lamb Ribbed Not Frenched Vacuum Wrapped

7 Discussion

The CBCT scans revealed that in thinner meat samples, the ribs and tomahawk steak, both muscle and bone structures were easily identified and appeared clear in the images showing the CNT technology allows for differentiation between muscle and bone components. However, streaking artifacts were observed in the CBCT images and most predominately in the thickest meat sample, the beef loin. Streaking artifacts are characterized by the presence of streaks or lines that distort the image quality and can hinder the accurate identification of structures.

The majority of the streak artifacts in the images were attributed to variations in bone and soft-tissue attenuation. Due to the limited number of views during imaging, these attenuation differences were not adequately accounted for, resulting in streaking artifacts. In the case of the thickest meat sample, the streaking artifacts observed can be attributed to the increased density and thickness of the meat, leading to greater photon attenuation and reduced image clarity. Upon visual inspection, it was also observed that the geometry of the meat samples appeared to be slightly misaligned. This slight misalignment contributed to the presence of streak artifacts in the images. This will be explored further in section 10.3.

It is important to note that the occurrence of streaking artifacts does not necessarily imply a limitation of the CBCT technology itself. Instead, it suggests that further optimization and adjustment of scan parameters may be necessary to mitigate such artifacts. Fine-tuning the CBCT settings, such as adjusting the mAs and scan protocols, could potentially minimize streaking artifacts and enhance the overall image quality for thicker meat samples. The current reconstruction algorithm employed in the study utilized a simple Algebraic technique. Significant improvements in imaging quality can also be achieved through the implementation of existing Micro-X software such as differing Penalized Weighted Lear Squares (PWLS) reconstruction, and scatter correction algorithms. These improvements have the potential to enhance the overall image quality and minimize the presence of streak artifacts in future CBCT imaging of meat samples.

It is recommended that future studies explore strategies to reduce streaking artifacts and enhance image quality as this would contribute to the successful implementation of the automated imaging and cutting system in the Australian Red Meat Industry.

It should also be stated that a designed solution optimised for the meat scanning application will allow better raw data to be captured and therefore will provide higher quality input to the reconstruction algorithms. This will result in an increase in the quality and resolution of the images provided by the system.

8 Conclusions / Recommendations

In conclusion, the study conducted to assess the performance of the Micro-X CNT technology on meat samples yielded valuable insights and recommendations for future imaging studies in the Australian Red Meat Industry. The analysis of X-ray images revealed that vacuum-wrapped meat samples did not interfere with the accuracy of the imaging process, making it suitable for future studies. Streaking artifacts were observed in CBCT scans, particularly in thicker meat samples, due to attenuation differences and slight misalignment, can be mitigated with software. This will not be as prevalent with the CBCT architecture proposed in the concept designs, as they are simply a limitation on the test bench. It was determined that further optimization of scan parameters, such as adjusting mAs, increasing number of x-ray views and employing advanced reconstruction algorithms, could reduce streaking artifacts and enhance image quality. Additionally, exposure parameter investigation highlighted the optimal exposure settings of 100kVp for tube voltage and 2-4mAs for tube current over time, improving clarity and contrast in the acquired images. Detector linearity analysis showed a deviation from linearity at higher mAs settings, indicating saturation of the X-ray detector's dynamic range. The use of flat panel detectors instead of the current curved detector is expected to increase the operational range but would require modification to the current testbench hardware and software.

The recommended next stage of project activity is:

1. Optimise Imaging reconstruction using PWLS and scatter suppression algorithms in development.
2. Construction of Concept Prototype for true representative CBCT imaging as per the concept designs with a high frame rate flat panel detector and a multi tube tower that Micro-X has developed for baggage scanning, however with the exposure settings identified in this report for meat imaging. This would be used for controlled/supervised testing in the factory environment but would not be suitable to fit in process line.
3. After the concept prototype, the next phase would be construction of an Integrated Prototype suitable for verification in process line, optimised for throughput and size, but not yet with full design for manufacture and reliability built in. This could be used for a longer-term trial in the factory location.

9 Bibliography

Andrzej Junkuszew a, F. R. (2004, March 8). *Computer tomography and ultrasound measurement as methods for the prediction of the body composition of lambs.* Retrieved from ScienceDirect: https://www.sciencedirect.com/science/article/abs/pii/S0921448804001130

E A Navajas, C. A. (2009, August 7). *Assessing beef carcass tissue weights using computed tomography spirals of primal cuts.* Retrieved from PubMed: https://pubmed.ncbi.nlm.nih.gov/20374751/

J. Kongsro a b, M. R. (2008, January 21). *Virtual dissection of lamb carcasses using computer tomography (CT) and its correlation to manual dissection.* Retrieved from ScienceDirect: https://www.sciencedirect.com/science/article/abs/pii/S0260877408000496

Jonathan Cook, F. A. (2017). *Beef and Lamb OCM with CBCT in situ further.* North Sydney: Meat and Livestock Australia Limited.

N Prieto 1, E. A. (2010, June 20). *Predicting beef cuts composition, fatty acids and meat quality characteristics by spiral computed tomography.* Retrieved from PubMed: https://pubmed.ncbi.nlm.nih.gov/20655149/

10 Appendices

10.1 Appendix 1 – GIFs showing full 3D scan.

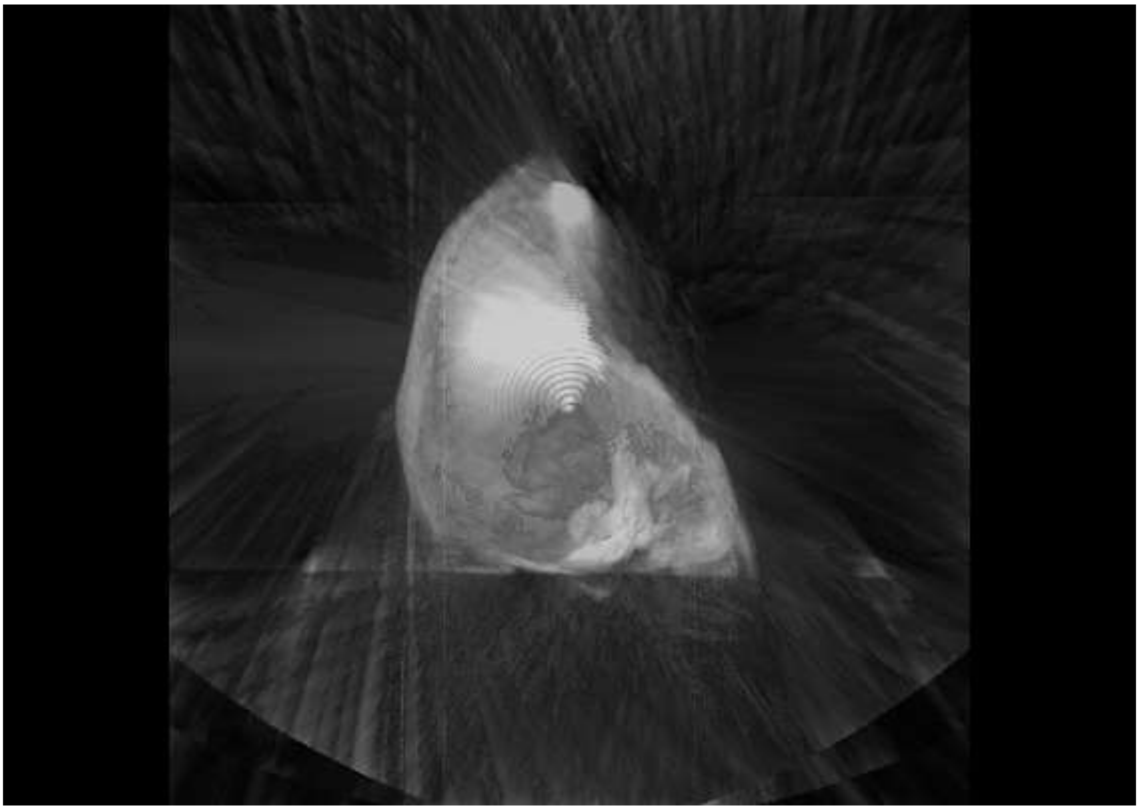


Figure 15 - Beef Chine (Wrapped)

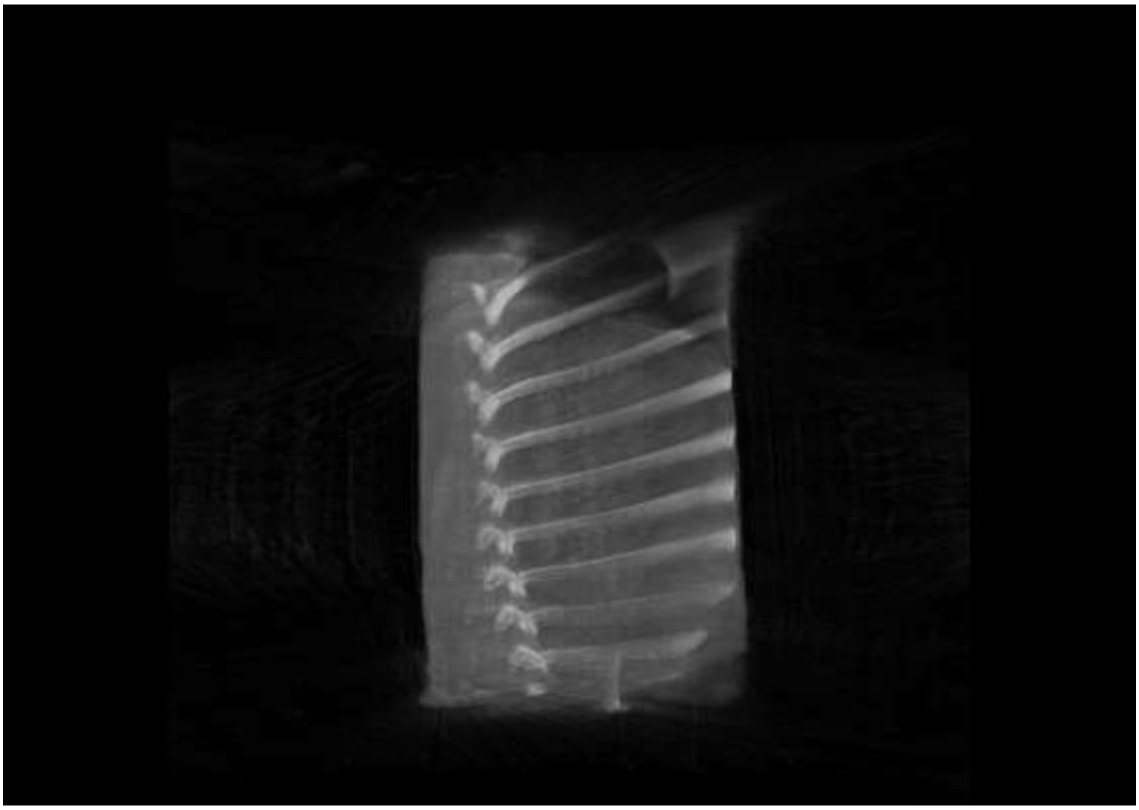


Figure 16 Lamb Ribs

Figure 17 Tomahawk Steak

10.2 Appendix 1 – CBCT Slices

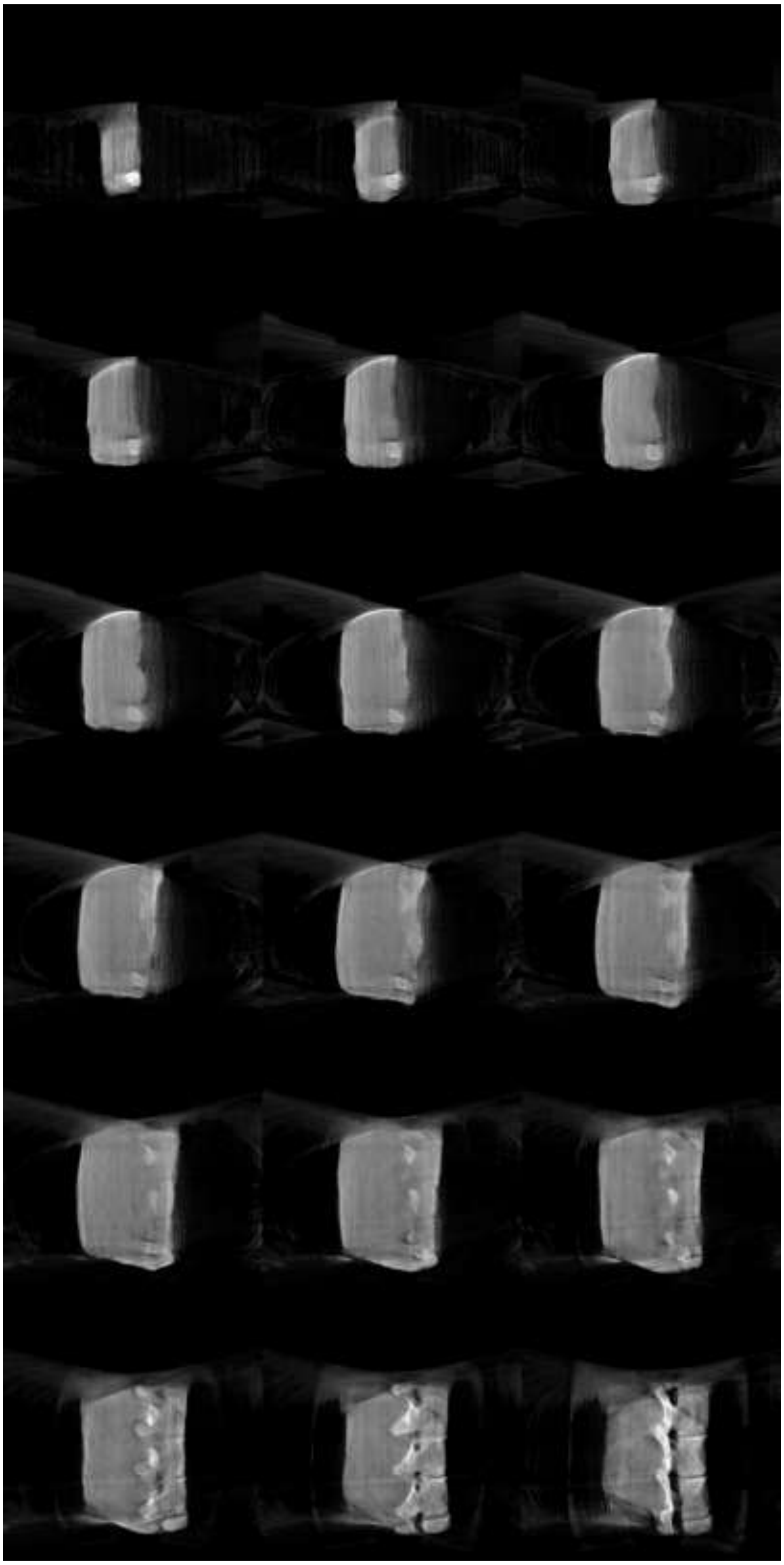


Figure 18: Beef Loin with Chine Bone XY, 100kV 0.4mAs

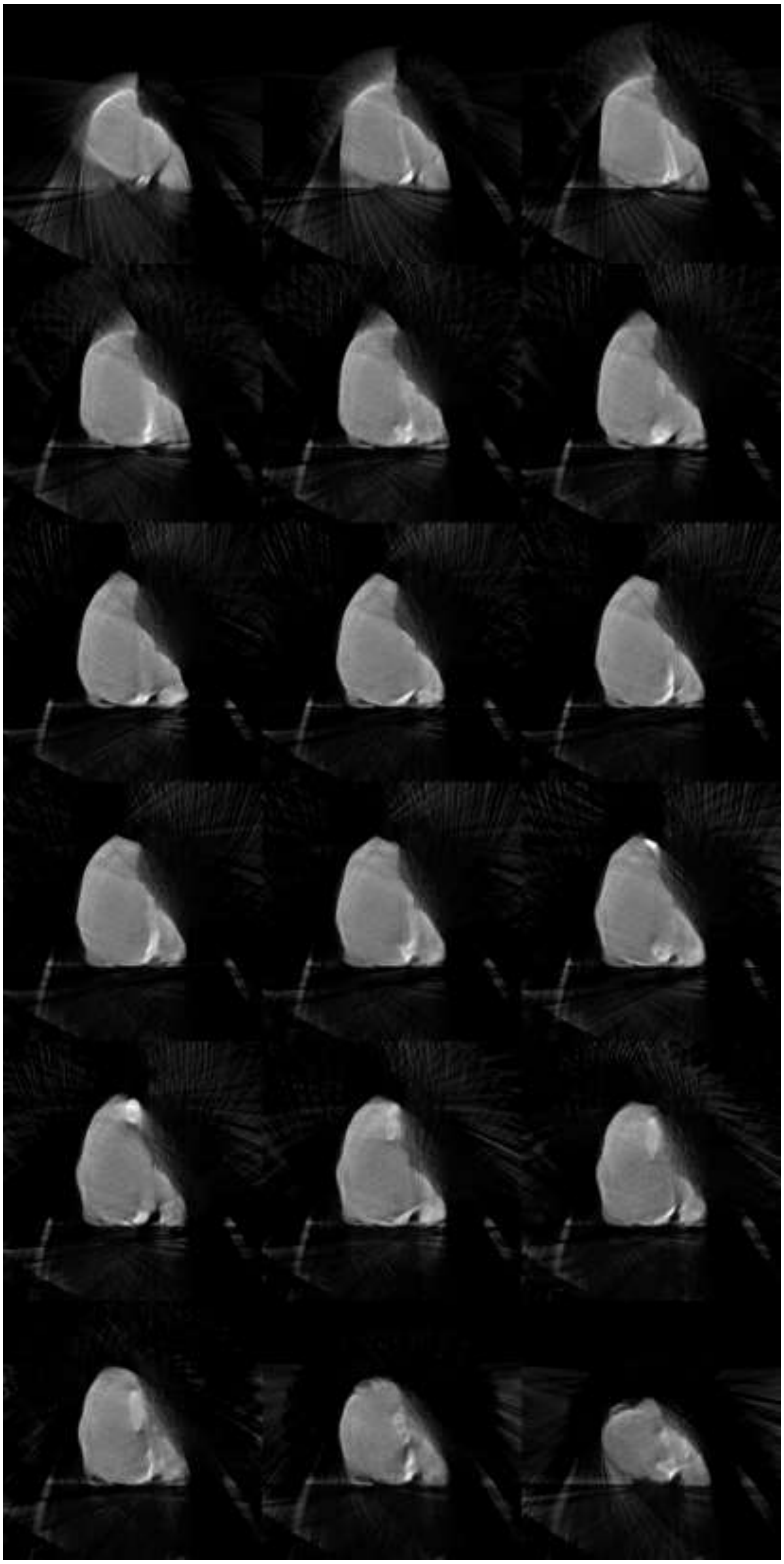


Figure 19: Beef Loin with Chine Bone XZ, 100kV 0.4mAs

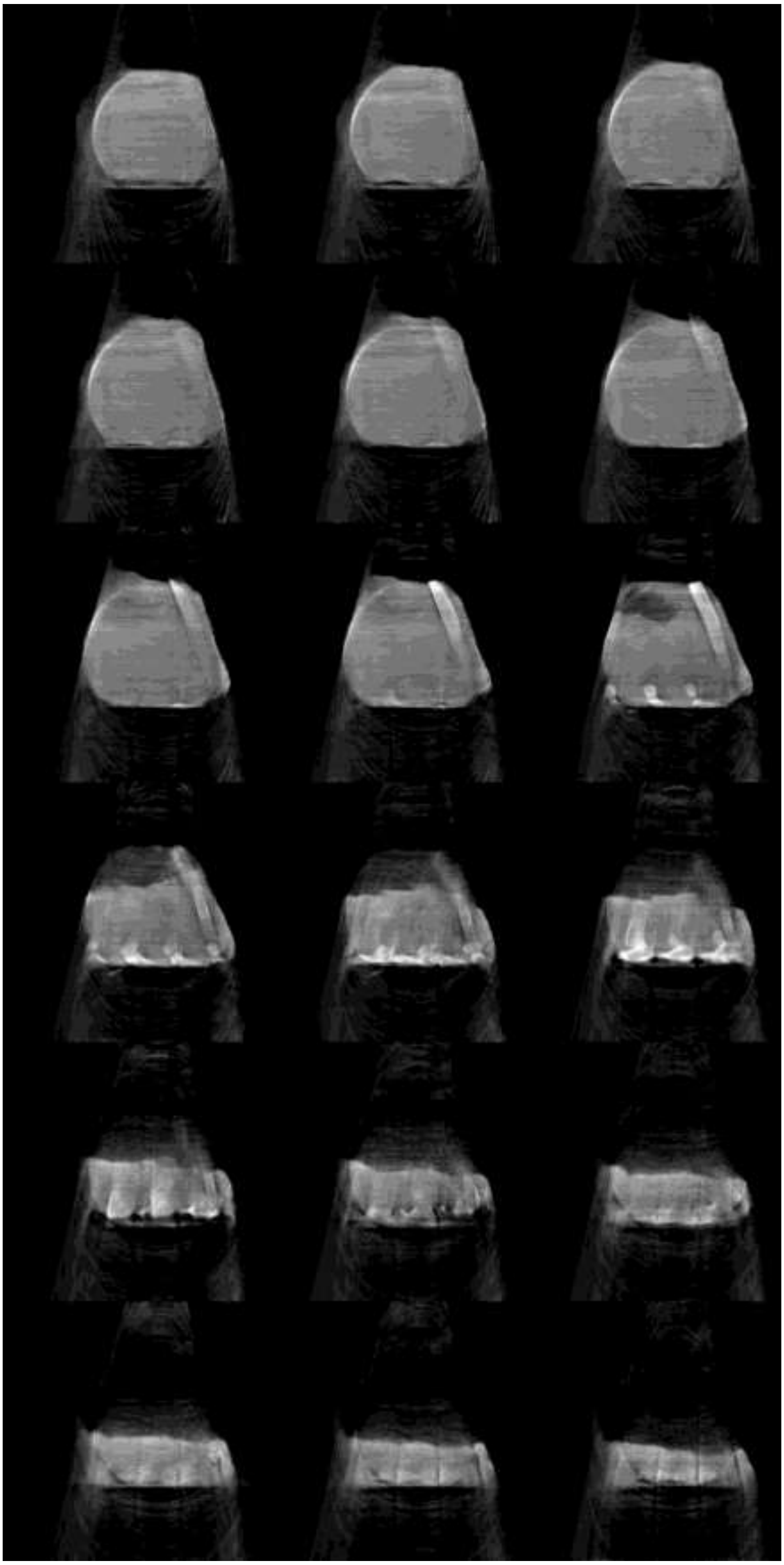


Figure 20: Beef Loin with Chine Bone YZ, 100kV 0.4mAs

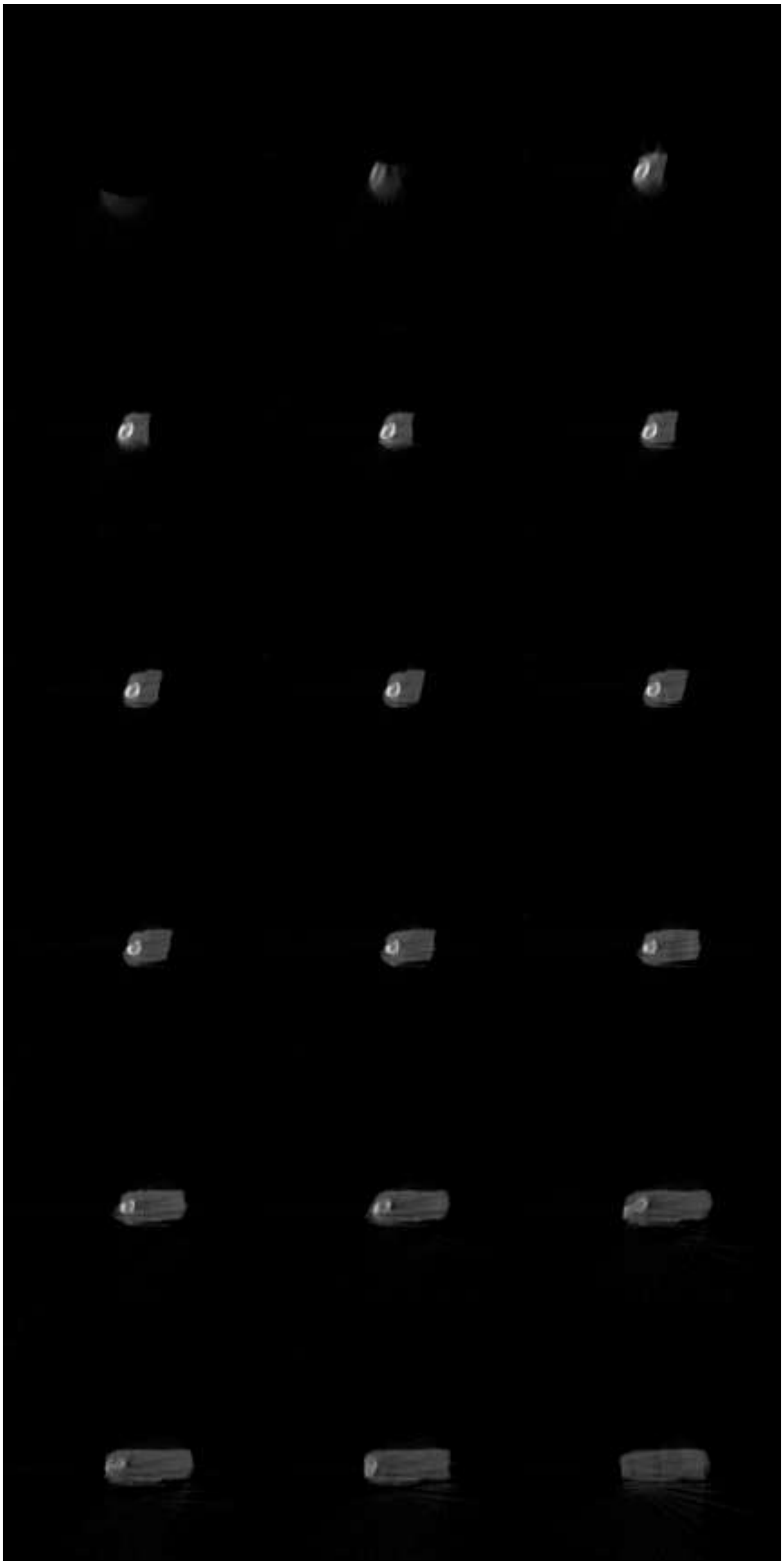


Figure 21: Tomahawk Steak XZ, 100kV 0.4mAs

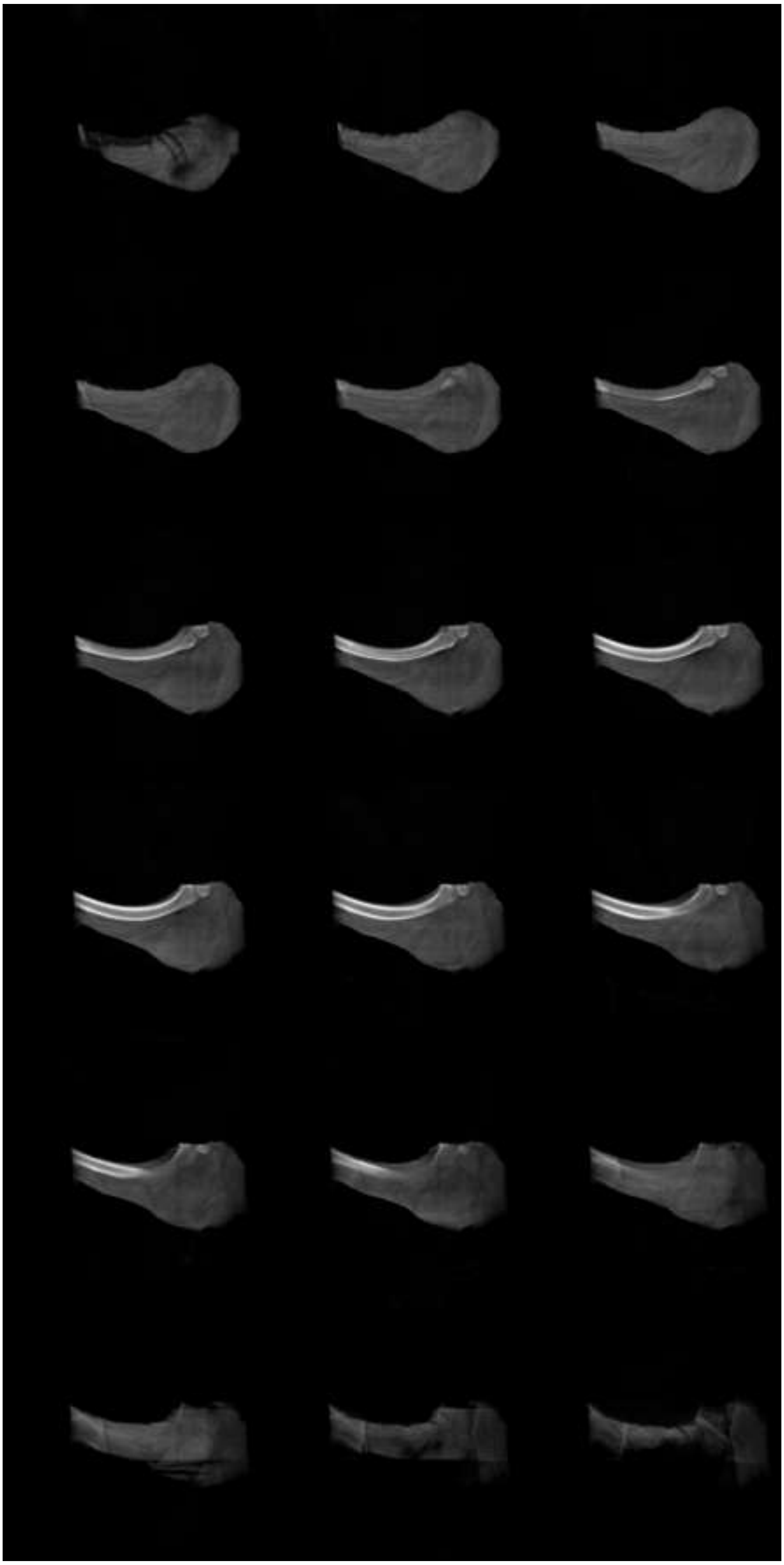


Figure 22: Tomahawk Steak XY, 100kV 0.4mAs

Figure 23: Tomahawk Steak YZ, 100kV 0.4mAs

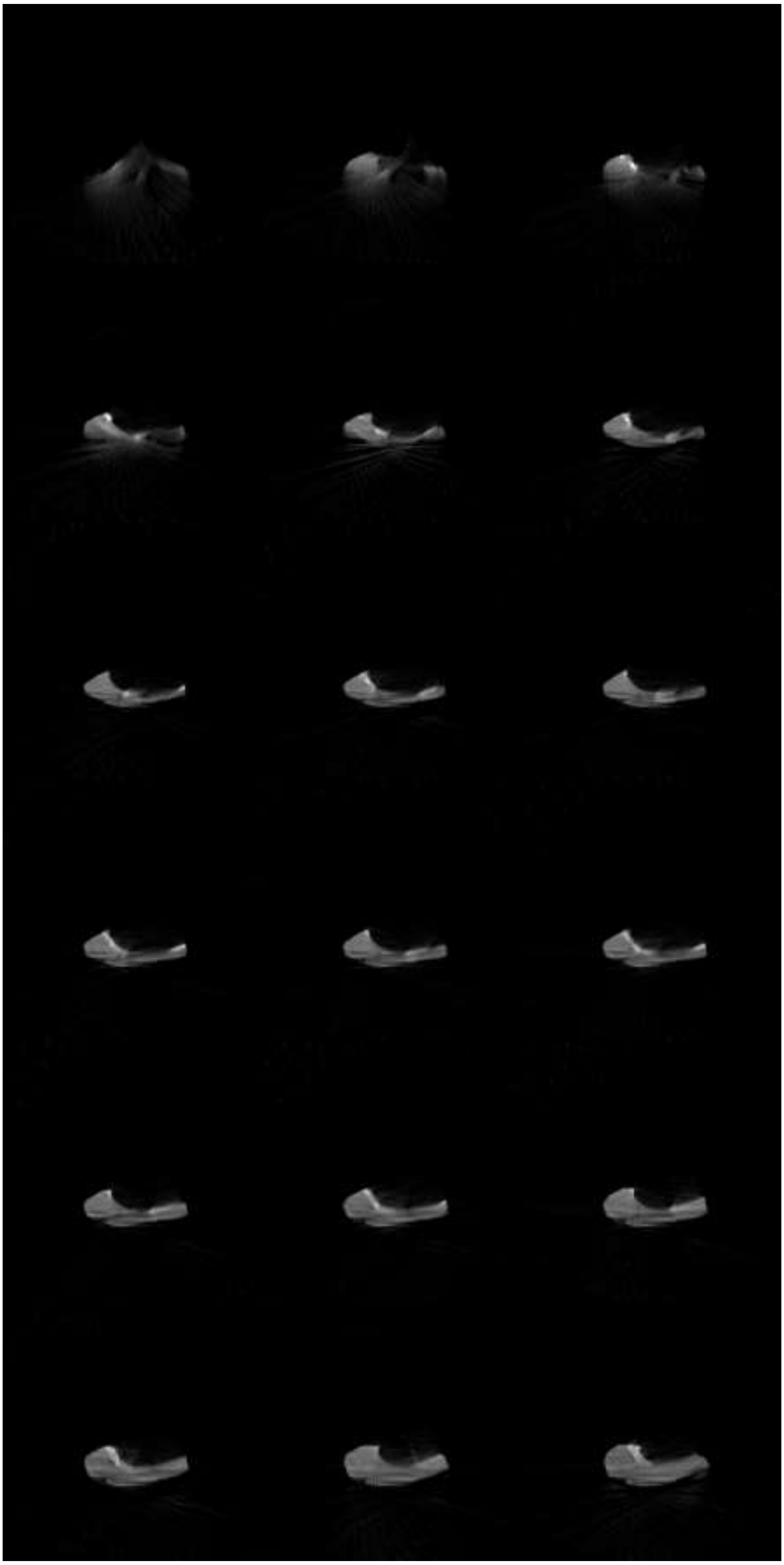


Figure 24: Lamb Ribs Not Frenched XZ, 100kV 0.4mAs

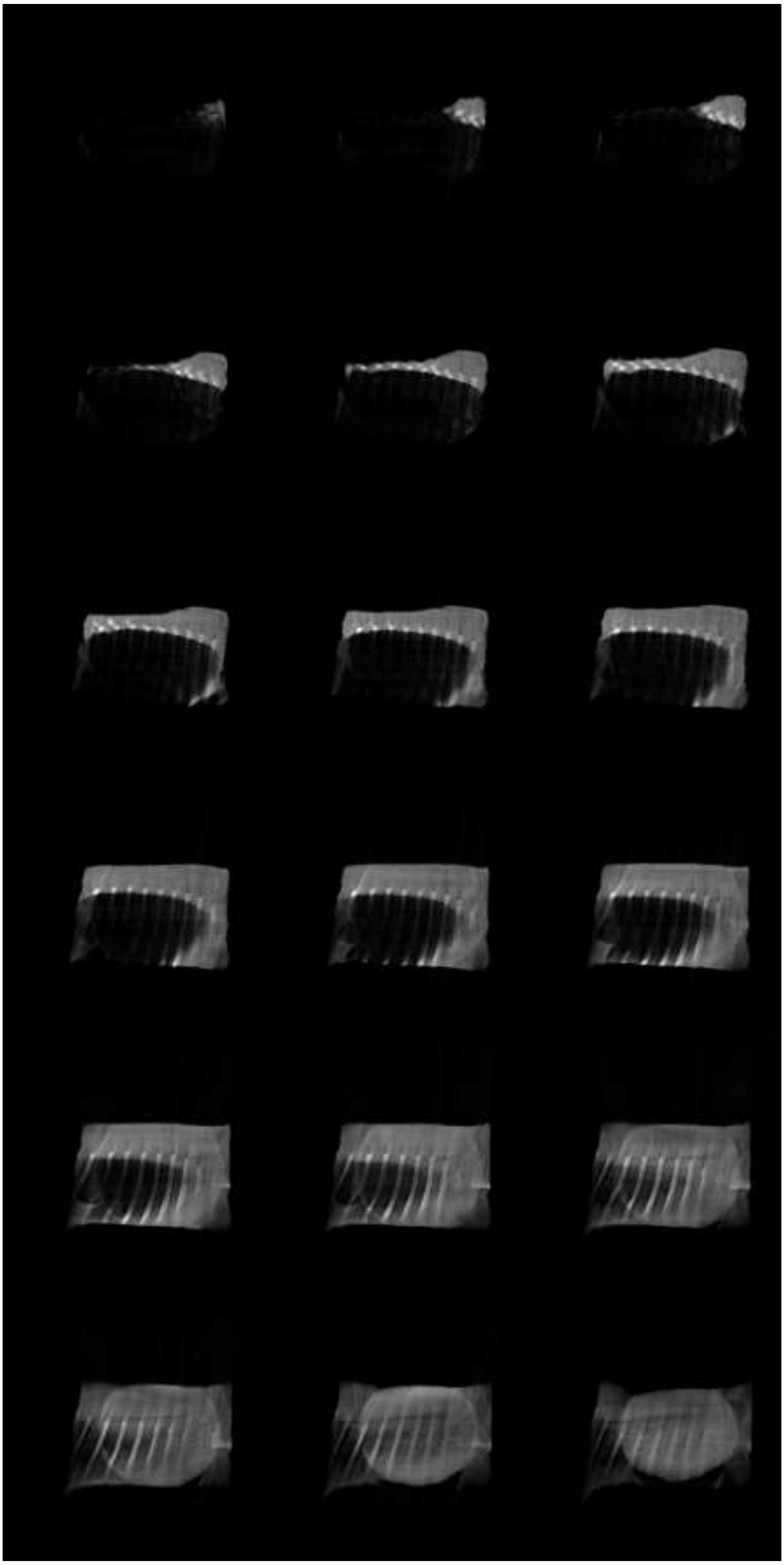


Figure 25: Lamb Ribs Not Frenched XY, 100kV 0.4mAs

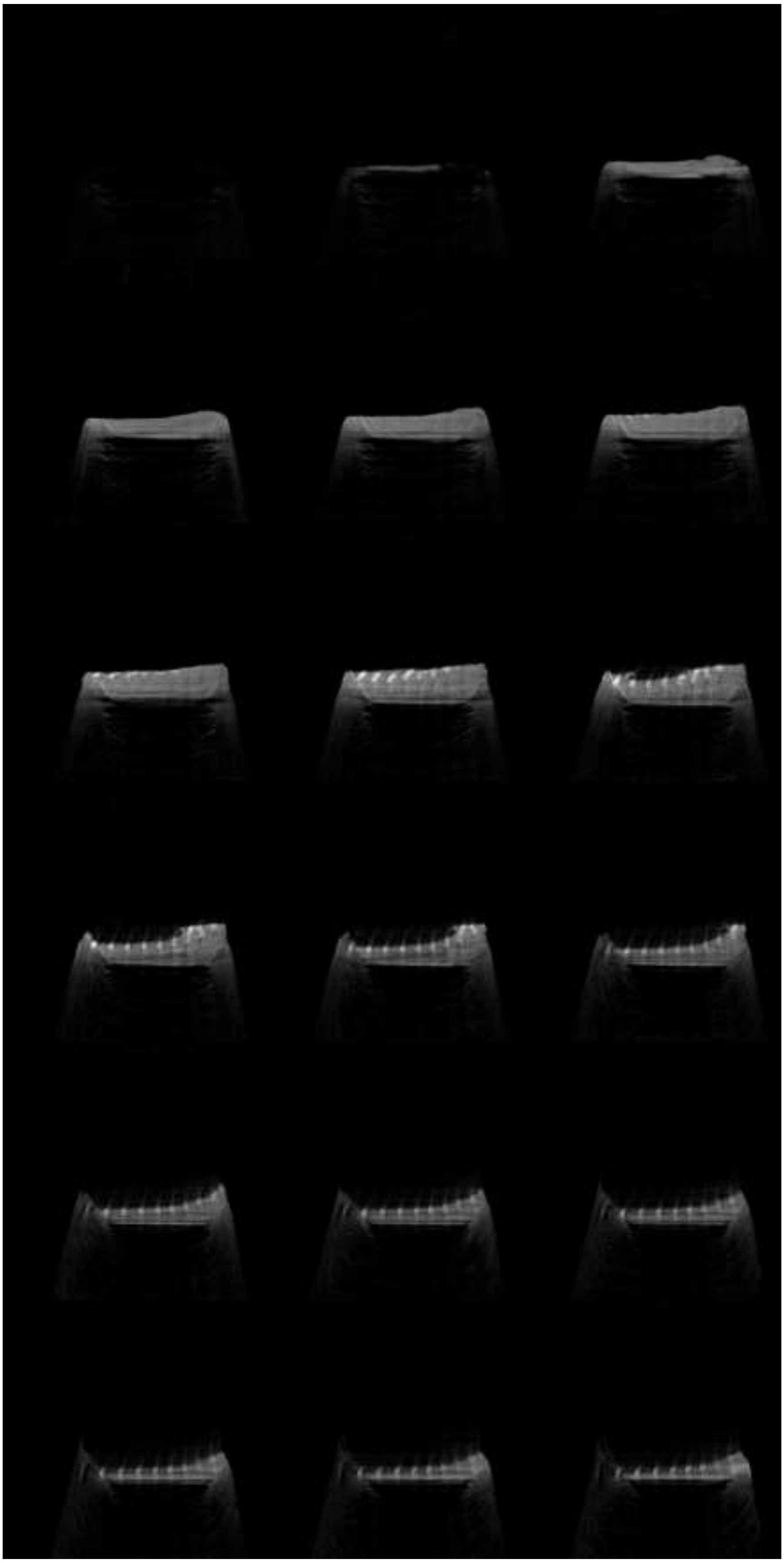


Figure 26: Lamb Ribs Not Frenched YZ, 100kV 0.4mAs

10.3 Appendix 2 - Geometry Alignment

Geometric alignment plays a crucial role in CBCT reconstructions, as it directly impacts the accuracy and reliability of the obtained images. After observing geometric alignment issues, which caused streaking in the images, specific measures were implemented to mitigate potential sources of geometric error.

To begin with, we addressed the issue of accumulative errors arising from motor sensors. These errors, if left uncorrected, can introduce significant distortions in the geometric alignment and subsequent reconstruction. To minimize this effect, we undertook the task of re-writing the code responsible for processing the motor sensor data and we were able to reduce the impact of accumulative errors on the alignment process. Furthermore, we identified another potential source of error in the form of tension from the anode cable, which could inadvertently move the X-ray tube during the CBCT acquisition. This movement can lead to misalignment and negatively affect the reconstructed images. To address this issue, a machined clamp was introduced to securely hold the anode cable in place, thereby minimizing any tension-induced movement of the X-ray tube.

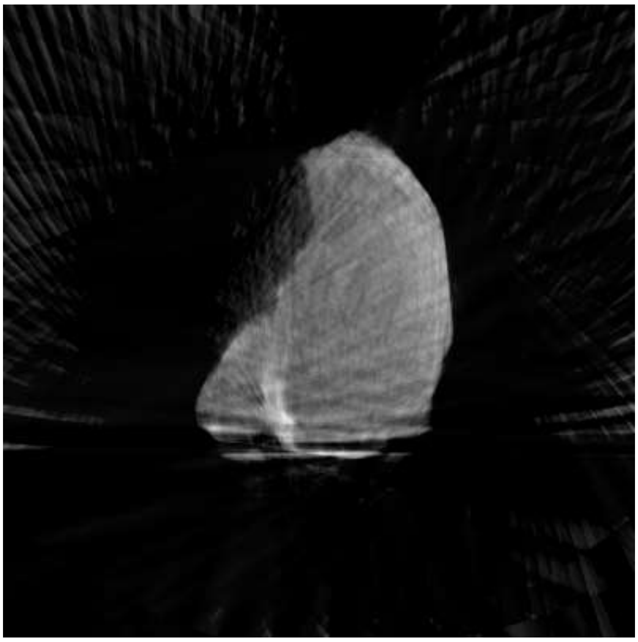


Figure 27: Beef Loin with Chine CBCT before Geometric realignment

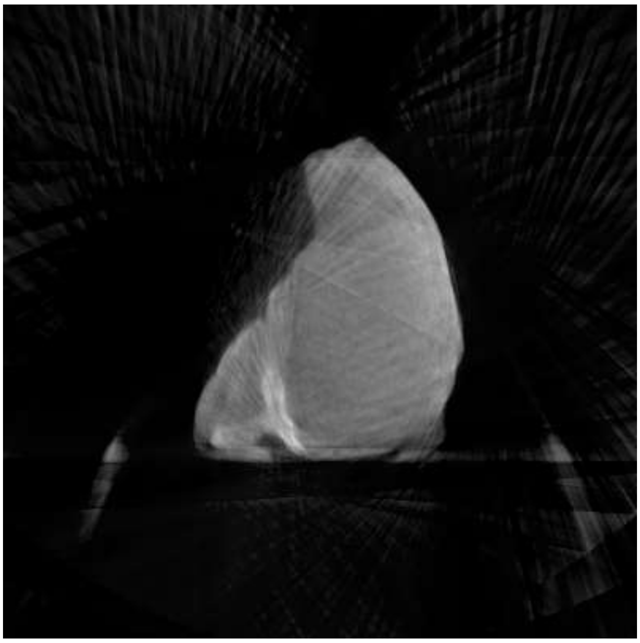


Figure 28: Beef Loin with Chine CBCT post Geometric realignment

In response to concerns regarding streaking artifacts observed we reperformed the CBCT scan with the implemented improvements in geometric alignment with the beef loin.

Upon re-evaluation of the reconstructed images, we observed a significant reduction in streaking artifacts compared to the previous scans. The streaking artifacts, which can arise from misalignment and inconsistencies in the acquisition process, were effectively mitigated through the enhanced geometric alignment procedures.

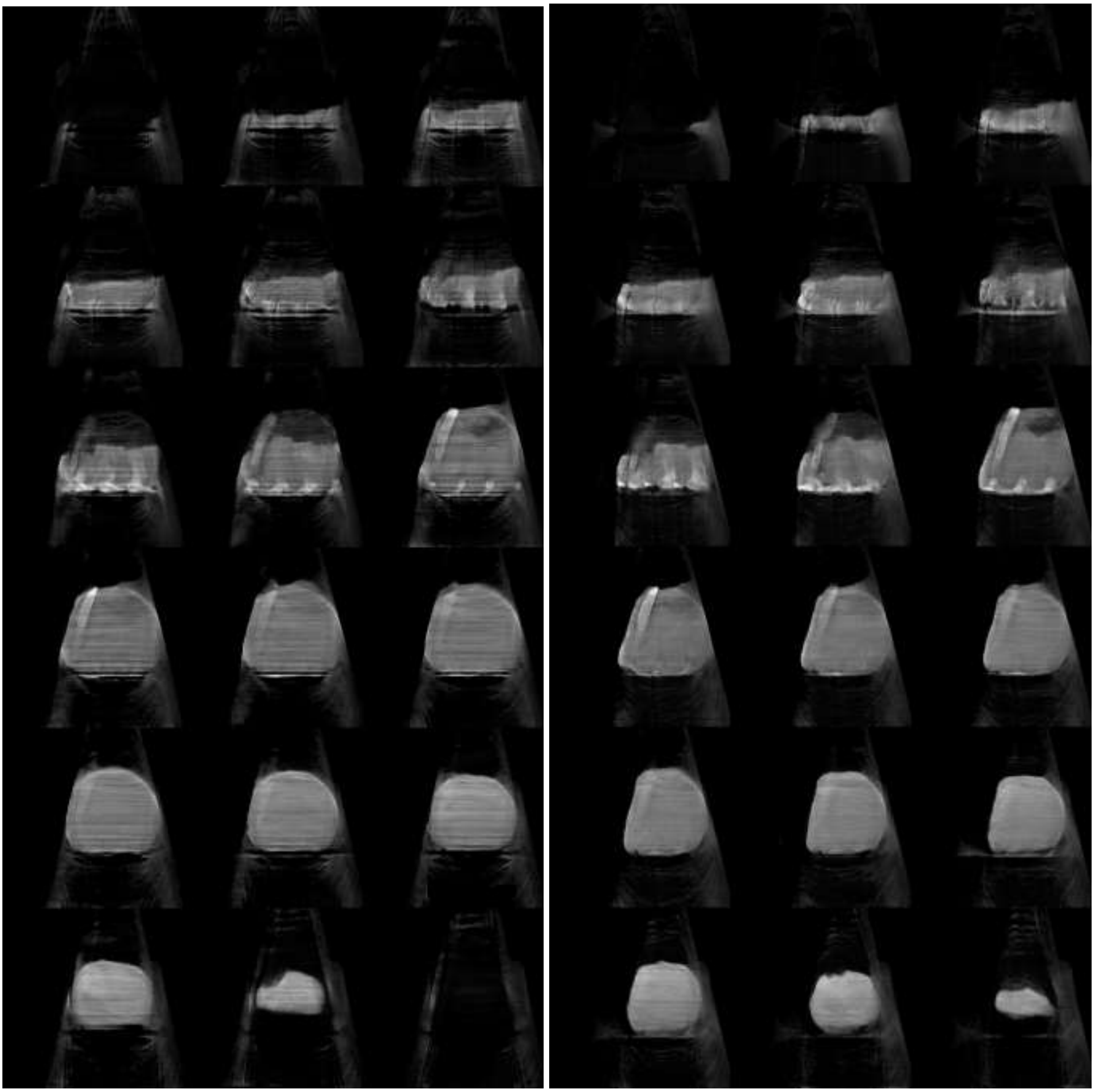


Figure 29: Comparison of Beef Loin CBCT Slices YZ. Left: Pre Realignment, Right: Post Realignment

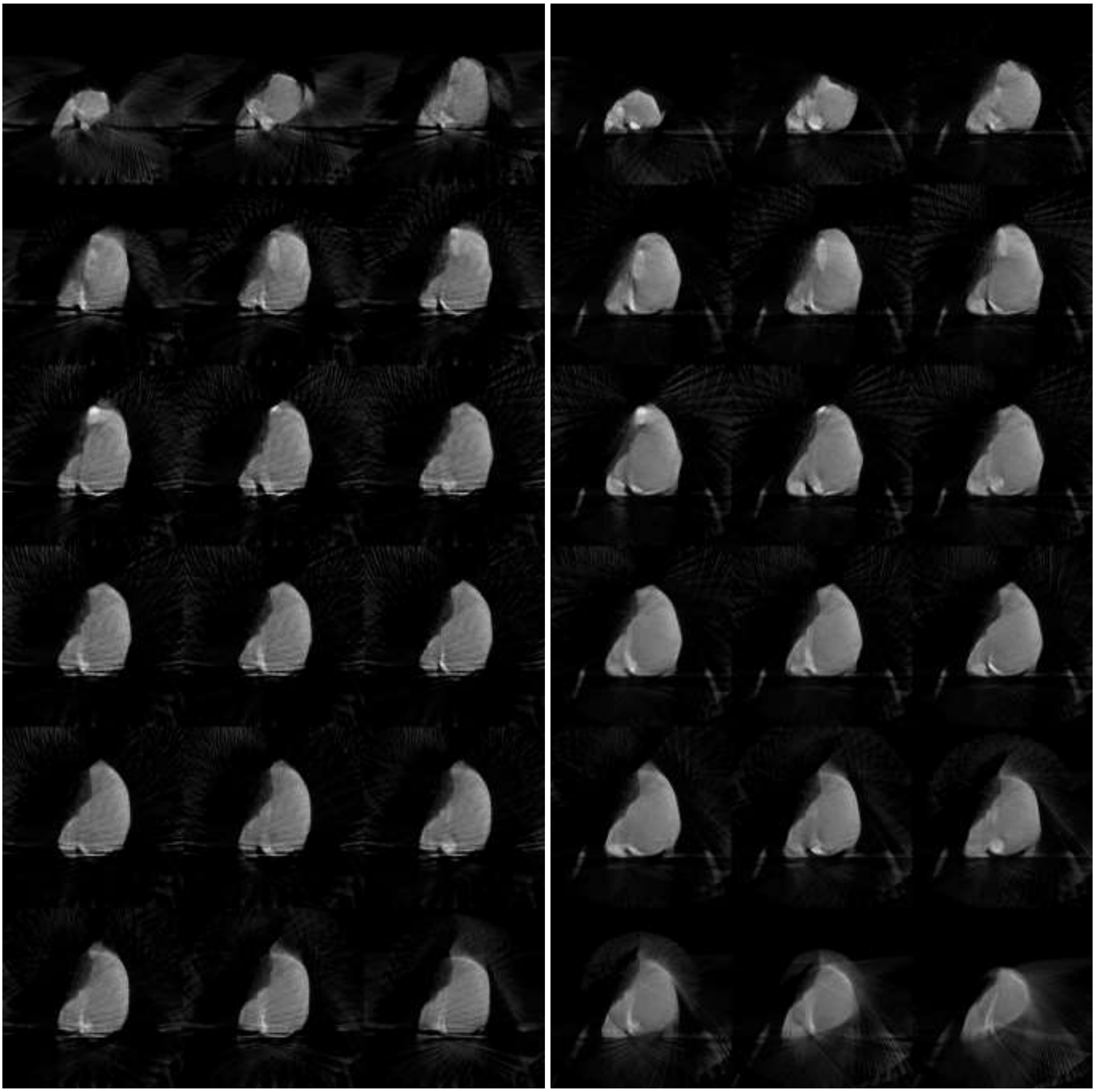


Figure 30: Comparison of Beef Loin CBCT Slices XZ. Left: Pre Realignment, Right: Post Realignment

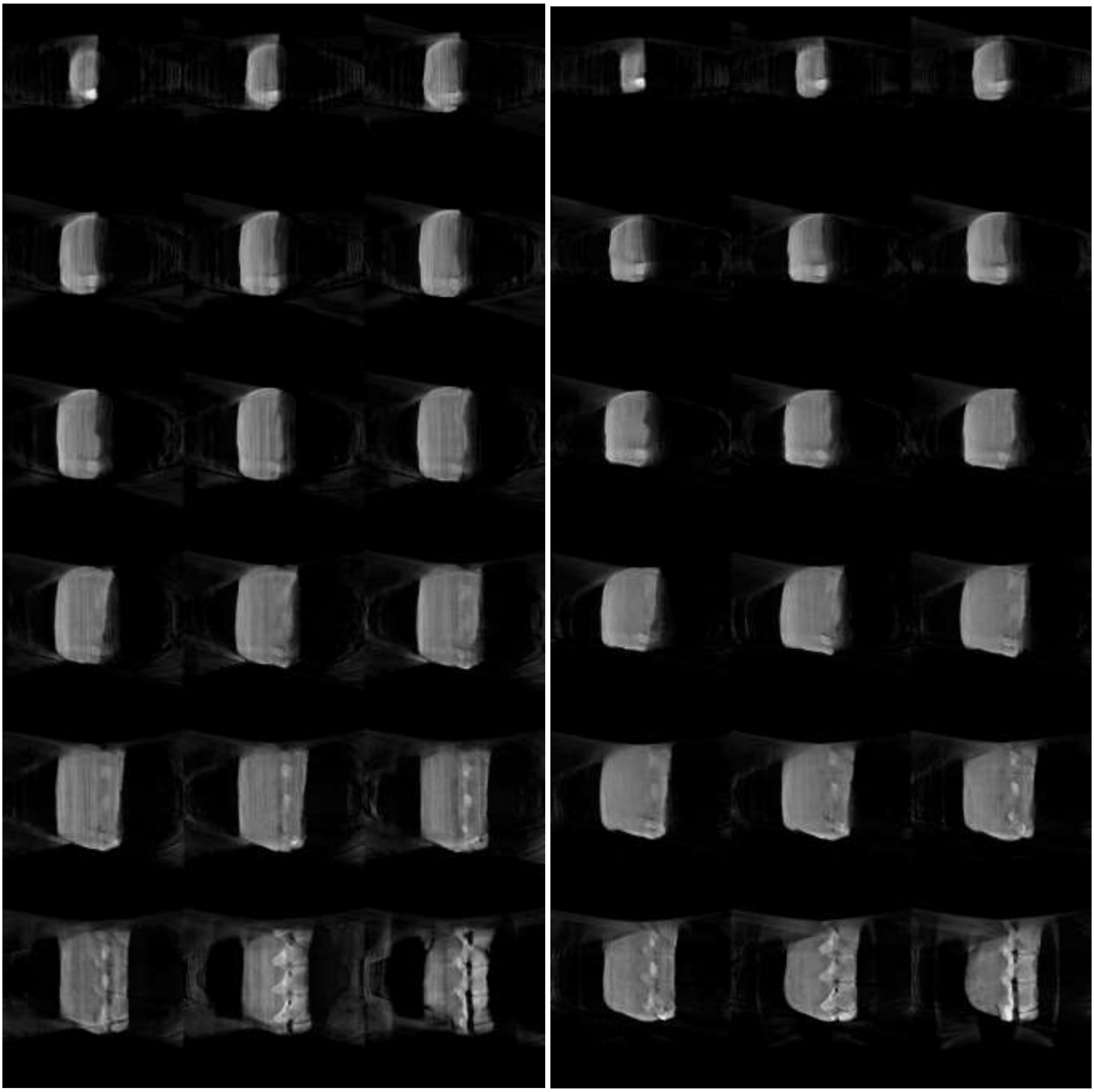


Figure 31: Comparison of Beef Loin CBCT Slices XY. Left: Pre Realignment, Right: Post Realignment