final report

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Beef Mechanically Deboned Meat (MDM) DEXA Based Process Control

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Abstract

Bone cannons allow significant amounts of protein to be recovered from waste materials from the boning room. A means to optimise their output however does not currently exist. This project aimed to investigate the use of DEXA technology to be able to maximise yield output from the bone cannon by examining the waste product stream ('bone cake'). The system is able to identify some lean-containing portions on bone cake material, but a limitation exists whereby bone marrow, cartilage, tendon and ligament results in false positives. A number of measures may be able to improve performance, including investigating alternative hardware, sensing technologies and/or complex vision algorithms.

Executive Summary

Bone cannons are a machine used to recover as much protein as possible from products on the waste belt travelling from the boning room. However, these machines are not currently monitored for optimal performance. Measuring the waste stream of a bone cannon may allow its operating settings to be optimised and/or offer an opportunity to identify portions of 'bone cake' containing a significant amount of lean and redirect back into the bone cannon for reprocessing.

This project aimed to develop a dual energy x-ray (DEXA) system to examine the waste stream of the bone cannon in order to improve yield recovery. An inspection machine was upgraded with a number of hardware and software modifications, including the inclusion of a DEXA detector.

Fundamentally, DEXA is only able to provide two measurements at once. Bone, fat and lean therefore cannot be identified simultaneously. An attempt was made to model the fat and lean signals in the presence of bone to provide an estimate, but this was not able to be achieved with the data obtained with this system. As a result, the following criteria were applied to reduce the problem to two-compartment models. For any given pixel:

- if bone is present, identify amount of bone and soft tissue;
- if no bone is present, identify the amount of fat and lean.

The system was then calibrated to give measurements of bone, soft tissue, fat and lean. This was a difficult process which required a number of trials to be able to achieve an accurate result. Once this was achieved, algorithms were then written to estimate the amount of lean on the bone cake and identify significant portions. Initially this was done by using neighbouring non-bone containing pixels to inform the composition of the soft tissue signal in bone-containing pixels to estimate the amount of lean when bone was present. A number of issues however prevented this from working as intended – primarily that tissues such as bone marrow, cartilage, ligament and tendon all produce a soft tissue signal and also produce a lean signal. This resulted in these tissues being incorrectly flagged as portions of lean red meat. Bone-containing pixels were then simply masked out (a strategy used in other DEXA projects) but, given that bone cake is primarily bone, this significantly lowered the number of valid pixels to analyse for lean. Of the valid pixels, the issue of misclassifying cartilage, ligament and tendon as lean still prevented a successful result.

Despite the difficulties in analysis, the system was able to identify some lean-containing meat portions of bone cake. There are also a number of measures which may be able to improve the performance of the system. Different hardware can be utilised to achieve more accurate calibration and measurement. A MEXA (multi-energy x-ray absorptiometry) detector may be able to quantify lean in the presence of bone or enable mathematical models to provide accurate estimates. It may also improve the accuracy with which lean is differentiated from other soft tissues such as cartilage, ligaments, tendons and bone marrow. More complex vision algorithms may also be employed to improve the estimates of the system.

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1 Background

Within a boning room any material that contains residual red meat (and has been trimmed correctly) can be further yield recovered by placing the bones into a ‘Bone Cannon’ to develop mechanically deboned meat (MDM), a form of meat trim.

Bone Cannon yield recoveries are controlled by the manual pressure setting of the machine. Increased pressure forces more of the feed material through the separation plates. However too much pressure will also result in bone material fragmenting and passing through the separation plate. No bone material is allowed to be in the resulting MDM product and as such most processors operate the Bone Cannon at a reduced possible recovery rate.

Compounding this issue is that the type of cattle and the amount of fat on each carcase significantly impacts on the feed stock entering the bone cannon. A high red meat and fat ratio to bone of the feedstock requires the bone cannon to be operated at higher pressures. Hence to optimise bone cannon yield recovery, the pressure of the system needs to be adjusted constantly throughout the day. Alternatively, bone cake (the waste material from the bone cannon) containing significant amounts of lean meat can be redirected back into the bone cannon for reprocessing. As operational staff are either not available and/or cannot effectively subjectively monitor the feed stock or resulting product, the systems are usually left in a single pressure configuration for a shift (or at least a run of cattle stock).

2 Project Objectives

At the conclusion of this project, Scott will have:

- Developed and demonstrated a system (within the Scott Melbourne factory) that utilises DEXA to objectively measure the waste output of bone cannon material, supplied by a producer for the purpose of experimentation. Product containing an excess of lean meat is to be identified so that it can be diverted back into the bone cannon for reprocessing.

3 Methodology

The first stage of the project was to conduct pilot trials. A number of scans were performed on bone cannon waste material (‘bone cake’) using an existing x-ray machine. The results were then used to specify what hardware would be required to achieve the application and to formulate an engineering task plan.

The required hardware was ordered and installed into an existing XR3000 inspection machine, which served as a base unit for the system. Once the new hardware was commissioned and operational, the required software modifications for the hardware were implemented. This stage involved writing code to communicate with, and control, any new pieces of x-ray hardware. Certain parts of existing code also had to be upgraded to facilitate these code changes as well as the implementation of the algorithms required to perform the bone cannon x-ray analysis.

Once the equipment was operational, the x-ray response had to be calibrated. This was a critical part of the project, and involved constructing a suitable reference object with known characteristics which was then used to calibrate the response of the x-rays. Once the object was constructed, it was scanned and analysed to create the calibration for the x-ray system. This process was used to calibrate the response for bone, soft tissue, fat and lean – the four tissues we're interested in modelling for this application.

Algorithms were then developed for the identification of significant amounts of lean meat found amongst the bone cake material.

Factory acceptance testing was then performed, demonstrating the system's performance to the customer and MLA.

4 Results/Discussion

Using a Scott Automation & Robotics (SCOTT) DEXA inspection platform, test samples of bone cake material was scanned by the x-ray system.

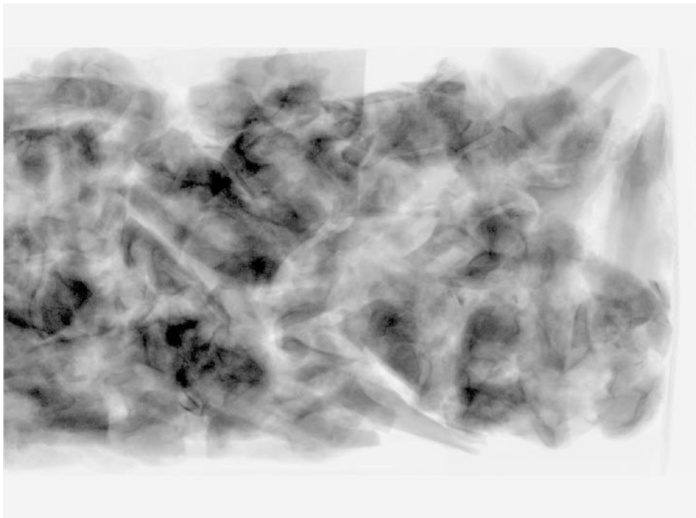

Figure 1: X-ray image of bone cake material at 120keV, 1mA.

From these trials, it was determined that a sandwich-panel dual energy detector would be utilised for the application. This style of detector involves the low-energy and high-energy detectors to be stacked on top of one another. They are both illuminated by one common x-ray source. This is in contrast to utilising a system with two distinct source-detector pairs for the low-energy and high-energy x-rays. The DEXA detector would be retrofitted into the inspection machine.

Figure 2: Scott Technology Australia's XR3000-C3 X-Ray Inspection Machine - the platform for implementing a Bone Cannon process control system. Note extra shielding hoods over conveyor for non-contact radiation shielding.

The dual energy detector was purchased and installed in the XR3000 inspection machine. While some modification was required, the retrofit was achieved with minimal issues with the system able to acquire images successfully.

A number of key software changes were then implemented in the XR3000 code. Firstly, some aspects of code were overhauled to enable more robust operation and compatibility for additional functionality. Communication and control of the new dual-energy detector were then added, including changes to how the triggering occurs with the system. Other functionality also had to be included such as implementation of calibration files for the bone, soft tissue, fat and lean calibrations, as well as DEXA image feedback in the user interface.

Another key software upgrade was the conversion from 12-bit to 16-bit processing. The original detectors provided 12-bit data while the new detectors are capable of 16-bit feedback. The effort required to convert the software for this change was significant but enabled the much higher quality data available to be used to its full potential.

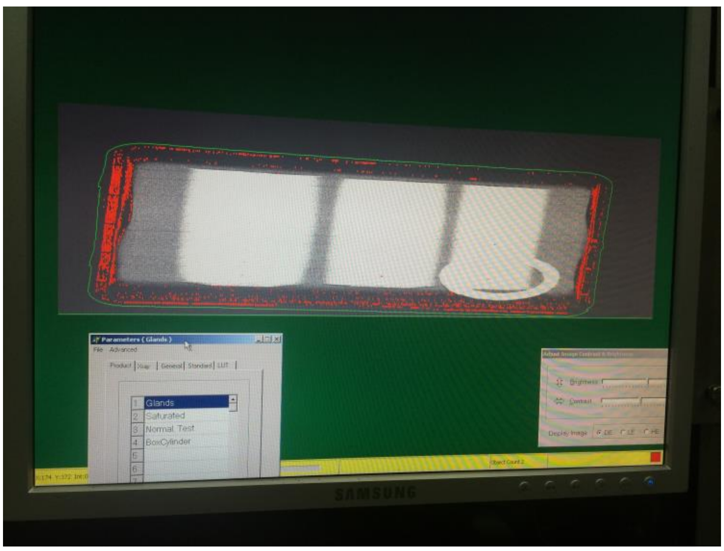

Figure 3: Revised user interface for the x-ray inspection software

The key enabler to this project is accurate measurement of bone, soft tissue, fat and lean using DEXA hardware. A significant amount of work was invested in developing a methodology for achieving this and assessing the requirements of the hardware used. The ability to accurately measure these tissues allows the total amount of material within a closed carton to be estimated.

DEXA can be used to differentiate materials in a sample based on differences in how they attenuate x-rays. There are two major processes involved in attenuating the x-rays - the photoelectric effect (PE) and the Compton effect (CE). These 2 process behave differently. PE depends upon chemical composition and falls rapidly as x-ray energy increases. CE depends only upon density and is relatively constant with energy. The difference in their energy dependence allows the relative amounts of PE and CE for a given mixture to be calculated by measuring attenuation at two energies. The attenuation of any pure substance is also a sum of PE and CE components.

If there are only two components in the mixture, it is possible to deduce from the relative PE and CE contributions of the mixture and thus, how much of each of the two substances are present. When more than two materials are present, their relative thicknesses cannot be determined from measurements. The exception to this is if one or more materials have measurable 'k edge discontinuities', which is a sharp discontinuity in the absorption spectrum of a substance. However, there are no useful k edges in biological materials within the diagnostic energy range. This is in contrast to mining applications where useful k edges may well be available. Figure 4 shows the absorption curves for fat, lean and iodine. Note the k-edge discontinuity for iodine – these do not exist for fat or lean in the practical energy level range required.

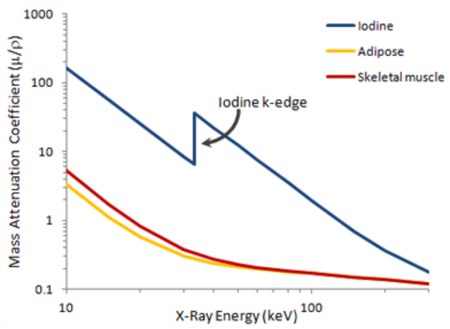

Figure 4 - Absorption curves for fat, lean and iodine (source: http://www.xrayphysics.com/attenuation.html)

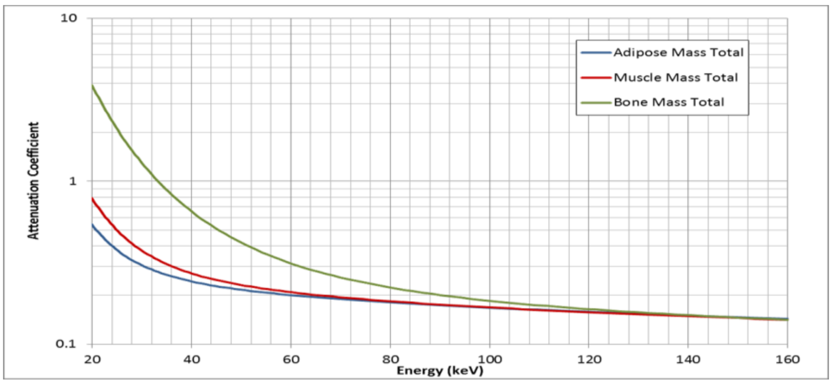

Figure 5 - Absorption spectrum for bone, fat and lean

Thus, at a fundamental physics level, DEXA is able to differentiate only between two materials. Two measurements can only calculate two unknowns. There are methods for overcoming this in a practical sense however. Firstly, the issue can be broken down such that, for any given pixel:

- if bone exists, identify the amount of bone and ‘soft tissue’; or
- if no bone exists, directly identify the amount of fat and lean.

From here, a number of methods are available to estimate the soft tissue composition. By reducing the problem into two-compartment models, DEXA is able to be utilised to generate measurements.

The hardware utilised has a significant effect on the ability of DEXA to be able to differentiate between materials. Ideally, the x-ray sources would be monochromatic – emitting only the energy levels of interest. However, this technology isn’t yet commercially feasible. Industrial x-ray tubes emit a spectrum across a range of energies. Figure 6 illustrates the difference between the two. This creates an overlap in the illumination of the two energy levels which must be overcome.

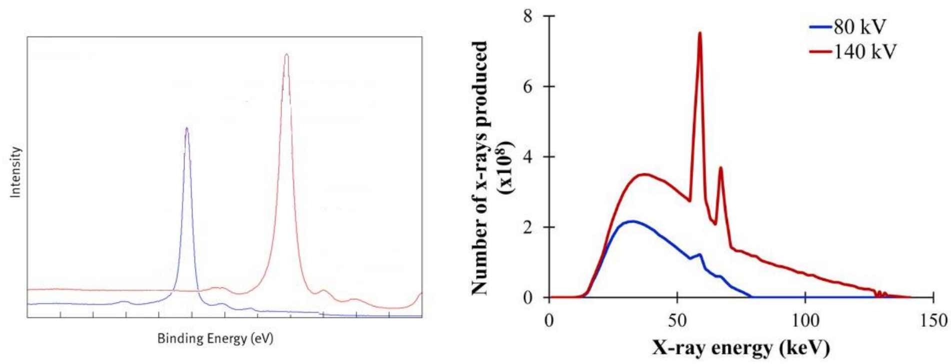

Figure 6 - monochromatic spectrum (left) vs polychromatic spectrum (right) (source: http://www.frontiersin.org/Journal/Abstract.aspx?s=322&name=experimental_pharmacology_and_drug_discovery &ART_DOI=10.3389/fphar.2015.00256)

One measure used to determine the amount of each material in a given part of an x-ray image is the R-value. The use of R values assumes that there is a constant ratio (R) between the high and low energy signals for a given material regardless of thickness. For monochromatic radiation, this is true. For polychromatic radiation, the ratio can vary hugely with thickness. The actual manner in which this happens is complex and depends upon the illuminating spectrum, the detector and the object. The simplest and most flexible methodology to account for polychromaticity is to utilise a look-up table to allow for accurate discrimination of fat and lean or bone and soft tissue.

A look-up table is essentially a map of how the low energy and high energy signals behave for a given material at different thicknesses. The way in which an x-ray signal attenuates through an object at different thicknesses and energies under polychromatic illumination is a complex process. The look-up table modelling process is therefore quite complex and the result must be cross-checked to ensure, like any model, it behaves as expected across the entire range of expected inputs. If not, the input data must be analysed and model adjusted in an iterative manner until successful before then being verified with samples.

Look-up tables (LUTs) are generated by acquiring data to model the response of the low energy and high energy detectors at a range of mixture compositions and thicknesses. As with any model, the more data points used, and the more accurate the input data, the better the model. Due to the complexity of creating accurate and reproducible calibration standards however, compromises may not just lead to an inaccurate model, it may also produce surfaces which are completely unworkable or feasible only in limited ranges. Whilst it is in principle possible to use any two materials as the so called basis materials, it is far better to use the exact materials being identified. Alternative materials can be used if they possess similar densities and atomic compositions.

The development of a calibration methodology to accurately measure beef characteristics using DEXA is therefore a complex task, but one which has far-reaching positive implications throughout all DEXA projects once achieved.

In order to perform the calibration, a number of materials and construction methodologies were trialled as reference objects (also known as phantoms). Eventually a methodology was found which was able to produce good results. These results were then verified using beef tissue samples which had been tested for chemical lean. These samples were constructed with varying thicknesses and with varying compositions of fat:lean.

Upon completion of this work, the system was calibrated to give measurements of bone, soft tissue, fat and lean. While it is known that a DEXA system cannot be calibrated for bone, fat and lean measurement simultaneously, a number of trials were conducted to attempt to model the relationship of the lean and fat signals in the presence of bone. It was hoped that a measurement of lean could then be estimated, with a certain level of accuracy, in the presence of bone. Unfortunately, no numerical models were able to be created to achieve this from the data that was obtained with this system.

An alternative method was investigated by estimating composition based on neighbouring pixel information. Within the image then:

- if there is no bone in a pixel, identify the fat:lean composition;
- if there is bone, identify the bone:soft tissue composition and estimate the composition of the soft tissue using adjacent non-bone containing pixels.

A number of scans of product were taken to assess the feasibility of this approach once accurate LUTs had been generated for bone, soft tissue, fat and lean.

The primary issue that arises is the presence of bone marrow. Figure 7 shows a scan of a femur bone which was scraped clean of any soft tissue on its surface. It can be seen that 22mm of soft tissue was still identified which would be the bone marrow composition of the bone. In this instance, making an estimation of the lean component of the soft tissue signal would result in an erroneous estimation of lean content.

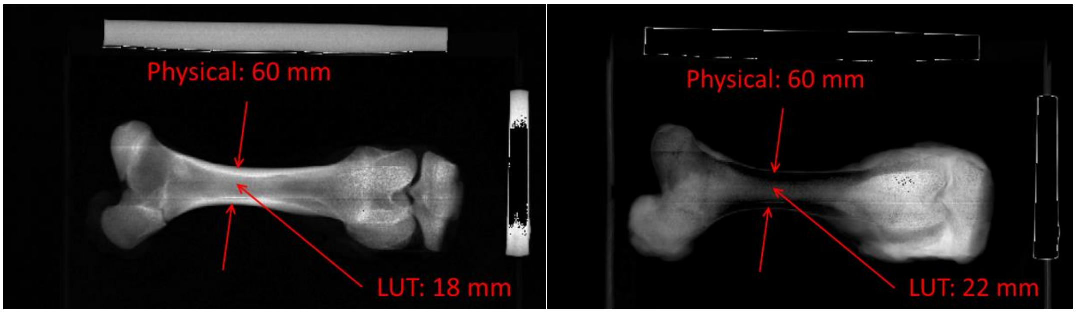

Figure 7 - X-ray image of a femur using the bone LUT (left) and soft tissue LUT (right)

This is the case for cartilage, tendon and ligament. All these tissues are detected in the image as soft tissue. Figure 8 shows a scapula which has been scanned with two pieces of meat placed on it. On the right is the resulting soft tissue x-ray image. Ideally, this would be black except for where the portions of meat exist. However, soft tissue signal can be seen across the whole bone.

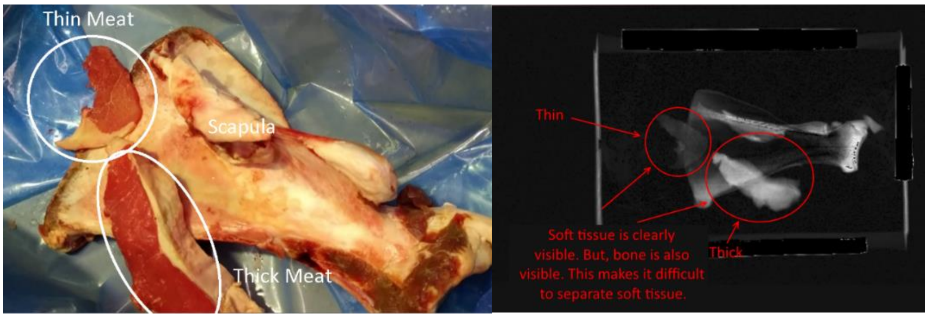

Figure 8 - Scapula with two pieces of meat placed on it (left) and the resulting 'soft tissue' x-ray image

It may be possible to utilise more complex vision processing however to try and isolate soft tissue areas of interest based on lean components found in non-bone containing pixels and make more targeted estimates accordingly.

As a result of these findings, the approach for analysis had to change. Bone-containing pixels were masked out to identify ‘valid’ pixels which were then analysed for lean content. This is the same approach used in the beef and lamb lean meat yield modelling for the same reasons.

A carton of ‘bone cake’ material was obtained from Teys. This carton was first scanned whole. A number of pieces were then removed from the carton and scanned spread out to simulate a controlled product flow. The results of the scans were then analysed using the aforementioned methodology.

Scan 1 – Carton

The scan of the entire carton yielded the expected results. Only 5.1% of the imaging region was deemed valid (that is, did not contain bone) although there were patches of lean which were still identified. In order for this application to have a chance of success, the product flow must be controlled such that the product is signulated, with minimal overlap.

Figure 9 - Carton of bone cake material

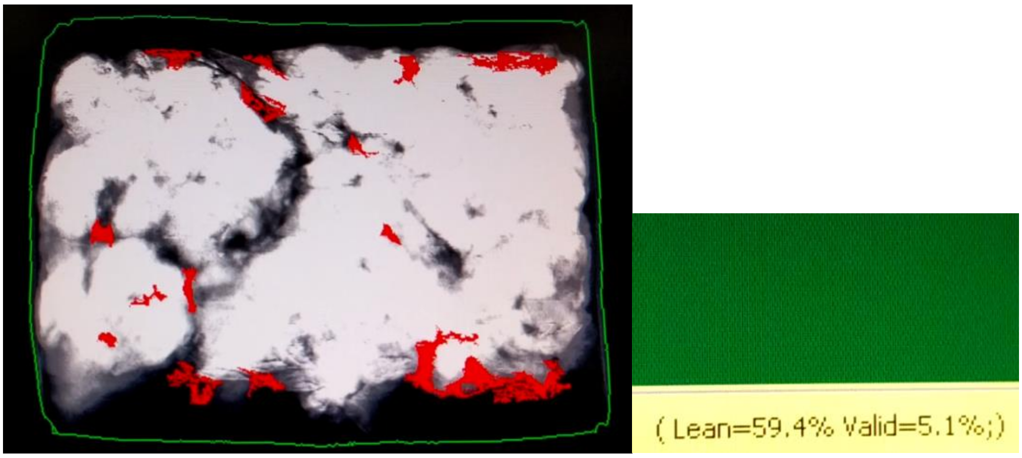

Figure 10 - Carton scan results

Scan 2 – Controlled product

A scan was then performed simulating a controlled product flow. The valid imaging region increased to 22.8% percent.

Figure 11 - Scan 2 - Controlled product flow of bone cake material

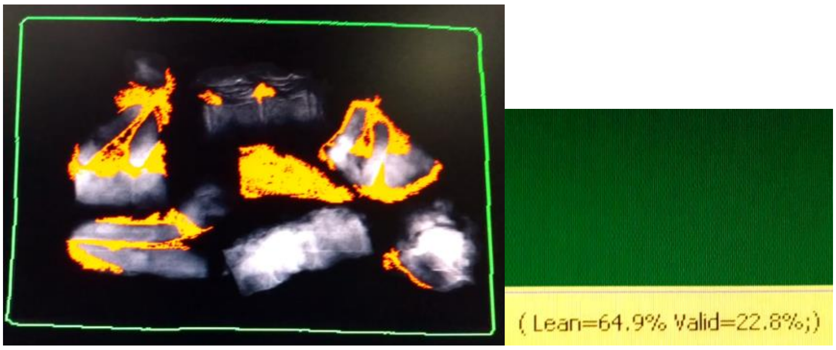

Figure 12 - Scanning result for controlled bone cake flow

As aforementioned, cartilage and other soft tissues (tendons, ligaments etc.) are flagged by the system as lean. Figure 13 shows a particular piece of bone cake which happened to be entirely cartilage. It can be seen in Figure 12 that this piece was flagged as containing a significant amount of lean across the whole piece with no bone. Looking at the lean tissue image (Figure 13) for the scan, it reported 4-8mm of lean across the sample which is approximately its thickness. This means that the system detected the entire sample as being lean meat.

Figure 13 - Cartilage sample (left) and the lean tissue x-ray image (right)

5 Conclusions/Recommendations

From a physics perspective, a DEXA system is unable to be calibrated for more than two unknowns. This means that fat, lean and bone cannot all be measured using DEXA within the same pixel. Thus the solution has been broken into two situations, reducing the problem to two-compartment models:

- If bone is present, measure the amount of bone and soft tissue
- If no bone is present, measure the amount of fat and lean

A number of methods were investigated to estimate the amount of lean when bone is present. No mathematical models were able to be formulated from the data obtained with the current hardware to be able to reliably quantify lean in the presence of bone. An alternative method was then examined whereby the composition of ‘soft tissue’ would be informed by the lean composition of neighbouring pixels were no bone was present. Once product testing commenced however, it became clear that the accuracy of this method is limited in this setup. The primary issue was that bone marrow within the bone is detected as soft tissue. Thus, the identification of lean-containing soft tissue is quite complex. This may be able to be achieved with more complex image processing algorithms however.

A masking algorithm was then implemented to remove bone-containing pixels. This method is currently utilised in the beef and lamb DEXA lean meat yield modelling. The scan of a full carton on bone cake yielded a 5% 'valid' region in the image. By spreading the product as it moves into the conveyor, this increases to 23%. In a production environment, this can be achieved mechanically just upstream of the system.

With this modification, the performance of the system improved significantly, identifying a number of 'chunks' of lean meat. One limitation however was that other soft tissues such as cartilage, ligaments, tendons etc. are identified as lean with the current calibration. This issue may be able to be overcome using different hardware.

More product can also be run through the system to acquire more data. This could then be used to further tune the system and its algorithms as well as gain a clearer understanding of whether the accuracy and performance of the system is suitable for on-line use in its current iteration.

Thus, the system was able to identify some lean-containing meat portions of bone cake. There are a number of measures which may be able to improve the performance of the system. Different hardware can be utilised to achieve more accurate calibration and measurement. A MEXA (multi-energy x-ray absorptiometry) detector may be able to quantify lean in the presence of bone or enable mathematical models to provide accurate estimates. It may also improve the accuracy with which lean is differentiated from other soft tissues such as cartilage, ligaments, tendons and bone marrow. More complex vision algorithms may also be employed to improve the estimates of the system.