Final Report

Ovine IMF Measurement Production Prototype

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1.0 Executive Summary

The objective of this project was to design and build a prototype system for non-invasive, automated, percentage of intramuscular fat (IMF) measurement of lamb and to prove application in processor facilities. The equipment was installed near the end of the slaughter-floor, off-line, and in a location that allowed the measurement of hot carcases. The system measures carcass-specific IMF in the longissimus dorsi muscle near the 13th rib.

A single-sided Nuclear Magnetic Resonance (NMR) sensor was designed and built for this project, called Marbl™. Sensor design considerations included carcase curvature, carcase length, length of the loin, eye muscle depth, eye muscle width, c-site fat, sampling volume, depth of measurement, magnetic field strength, design of the radio-frequency (RF) coil, signal to noise and enclosure shape. Further design considerations included the electronic and data-management requirements for automated measurements.

The sensor was integrated into carcass materials handling and locating equipment. Key features of the balance of equipment (BOE) included:

- 4-axis adjustability of the sensor: vertical, horizontal (x2), and rotation around the vertical axis
- a walking rail
- guarding and safety screening
- a simple arm to push the carcase to the sensor
- electromagnetic interference management options

The resulting Production Prototype, *i.e*. Marbl™ sensor fitted into the BOE, was temporarily trialled with 100 hot carcases in a processing plant in New Zealand before being shipped to Australia.

The unit was installed in a chiller adjacent to the end of the slaughter floor where it was used to make non-invasive, automated % IMF measurements of carcases. Operation of the equipment required manual loading of the carcases onto the walking rail then the operator pushed a go button that initiated the automation measurement sequence.

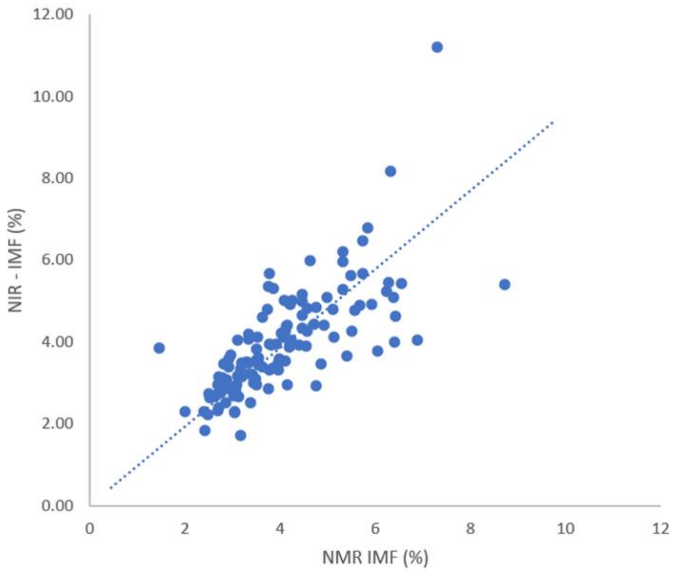
Carcases were redirected from the main chain into the chiller in batches of 8-25. The cycle time for operating the prototype equipment was 2 carcases per minute and a batch of 10-20 were typically measured within 15 minutes. Notably, in initial testing the focus was on validating the sensor for hot carcases, so the measurement time was longer than what will be necessary under commercial operation.

A wide range in carcase size, weight, shape and fattiness were deliberately chosen to explore the operational performance of the system (as compared to the design specification). Over 1000 hot carcases were measured that covered:

- Two different seasons (testing occurred in August and October 2022)
- Weights from 17.5 kg to 42 kg
- Fat score 2-5
- Breeds, including merino, first-cross, second-cross, and dorper

Building the validation data set involved the selection of reference carcases that spanned a wide range of IMF values. The right loin of the carcasses were tracked in the fabrication room the following day. The loins were characterized for c-site fat, eye muscle depth and were measured on-site using a bench top NMR (Oscar), and independently analysed by the University of New England using the proven NIR method [Anderson et al 2015, Harper & Pethick 2004, Perry et al 2001, Stewart et al 2021]. Using Oscar on the chilled loin sample provided immediate feedback while waiting for the NIR results. 65 loin samples were sent to UNE from the August trial, however, these samples degraded during transit. This was followed up with 142 sample from the October trial. Separate loin samples were provided for further measurements such as shear force, pH, and colour as available.

The key outcome from the reference testing is summarised by this graph showing the linear relationship of Marbl™ NMR IMF (%) versus NIR-IMF (%); N=137 of the October dataset



In analysing the data using the Scikit Learn python package, consideration was given to the impact of the wide variation in carcase size, weight, shape, and fattiness, as extremes were deliberately chosen for this data set. For example, with C-site fat it was found that the operational limit was significantly higher than the design specification of 8-10mm, due to compression of the fat during measurement. At the extremes, 5 carcases had around 3 times the design specification, so these points were removed. By selecting carcases with wide ranging attributes, the tests ascertained two limitations are carcases at the extreme end of c-site fat and very large carcases that do not fit well to the sensor.

The October data set was referenced against the AUSMeat accreditation requirements using the web app developed by Murdoch University. The data set (N=137) passed accreditation criteria between 2-6 % IMF. Due to a lack of samples outside the 2-6% IMF range, it was not possible to test below 2% and above 6%.

This project successfully demonstrated the measurement of % IMF of hot lamb carcases using a magnetic resonance method that is non-invasive, automated, and provides a direct measure of fat.

Over the course of this project the Marbl™ technology was advanced from a sensor that was being used in a workshop to a fully functional automated measurement unit that was trialled on site. The single sided sensor (Marbl™) was integrated into an automated prototype unit. This pushes the technology down the commercialisation path. With the improvements identified from this project, reaching cycle times of six carcases a minute with a single sensor, and twelve carcases per minute with a dual sensor system, seem achievable. These cycle times are in line with processor chain speeds.

2.0 Introduction

The Australian meat industry is seeking objective measurement devices capable of determining key traits that form the basis of the MSA eating quality grading system for lamb. The model that is currently being commercialised includes intramuscular fat, the trait which is the focus here.

In prior work, a prototype single-sided NMR sensor was specifically designed for the application and was shown to successfully measure intramuscular fat non-invasively and non-destructively [McCarney & Webster, 2021]. Work on the prototype (Marbl™) sensor progressed work that used a benchtop NMR system [Pooke & McCarney, 2019] where measurements of 15g samples of meat from the Kirby Resource Flock produced a correlation of R=0.84, R^2=0.71 and RMSEP of 0.53% (3-8% IMF) relative to IMF determined by calibrated NIR[1].

The alpha Marbl™ sensor was designed from fundamentals for non-destructive measurement of a volume of meat below the surface of a carcase at a nominated grading site, removing the need to take samples to a lab for analysis. The prototype sensor was used to measure both warmed and chilled lamb (chilled measurements were of saddles). The correlation and predictive linear models suffered from a lack of variation in that kill.

In other work using the alpha Marbl™ sensor to measure beef, it was shown that the prototype sensor was also effective at measuring IMF of chilled and warmed beef cuts. Compared with infrared measurements, in limited studies of beef short loins (20 samples), R^2 of a linear fit was >0.86 [McCarney & Webster, 2021], and for chilled striploins in a beef boning room, R^2 was 0.97 and RMSEP of 1.34% [McCarney & Webster, 2022].

Noting the strong correlations for beef and the limitations of prior studies of lamb, the sensor was refined. One focus area was the volume of meat being measured; the alpha Marbl™ sensor measured a volume of around 25 cm^3, which was good for larger beef cuts but too large for the size of the longissimus dorsi in lamb.

The Marbl™ sensor weighs around 40kg so for use in a processing facility, its use is best automated. Automation of the NMR measurement and the carcase handling was a key part of this project.

3.0 Project Objectives

The objective of this project was to design and build a prototype system for non-invasive, automated, percentage of intramuscular fat (IMF) measurement of lamb and to prove application in processor facilities.

A single-sided Nuclear Magnetic Resonance (NMR) sensor was designed and built specifically for this project. The system measures carcass-specific IMF in the longissimus dorsi muscle near the 13^{th} rib. The sensor is integrated into carcass materials handling and locating equipment. The equipment was installed near the end of the slaughter-floor, off-line in a location that allowed the measurement of hot carcases.

[1]IMF measurements using FTIR were conducted by the University of New England where the IMF was determined by calculating the total fat content (%) present within the sample of meat. This includes both visible fat stored in adipocytes, visible to the naked eye at higher levels of IMF% and also fats held in the form of structural triglycerides within the cell wall [Harper & Pethick, 2004]. Chemical IMF% was determined by Chloroform Soxhlet calibrated laboratory near infra-red (NIR) [Anderson et al., 2015; Perry et al., 2001; Stewart et al., 2021]. This technique involved weighing the wet tissue in a tube, freezing it at -20^{o}C, then freeze drying. After freeze drying, the sample and tube are weighed to calculate the dry matter percentage, then samples are ground to a homogenous powder. The ground, freeze dried meat samples are then placed into a calibrated benchtop NIR spectrophotometer to determine IMF %.

4.0 Methodology

4.1 Design

Sensor - The alpha Marbl™ sensor from prior work [McCarney & Webster, July 2021] was redesigned with a focus on the cross-sectional area of the longissimus dorsi (LD) muscle at the 13th rib of Australian lamb. ALMTech studies of the resource flocks were used to create a sample specification that included carcase curvature, carcase length, length of the loin, eye muscle depth, eye muscle width, and c-site fat, which were used to create a device specification including sampling volume, depth of measurement, magnetic field strength, design of the radio-frequency (RF) coil, signal to noise and enclosure shape. Further design considerations included the electronic and data-management requirements for automated measurements. A provisional patent has been filed covering the sensor design for this application [McCarney & Dykstra].

Balance of Equipment (BOE) – The sensor was incorporated into a materials handling system appropriate for conveying the carcases in and out and locating the carcase. In-plant health and safety, and hygiene was factored into the design. Design considerations and key features included:

- 4-axis adjustability of the sensor: vertical, horizontal (x2), and rotation around the vertical axis
- a walking rail
- guarding and safety screening
- a simple arm to push the carcase to the sensor
- electromagnetic interference management options

Models of the design of the Marbl™ sensor fitted into the BOE, forming the Production Prototype, are shown in Figures 1 and 2. The prototype was designed as a stand-alone cell for ease of use and installation. It was also designed larger than necessary for ease of working in and around it.

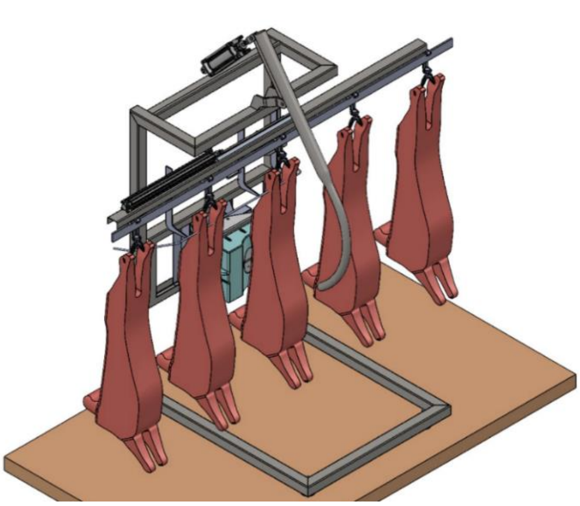


Figure 1 – Model of the key components of the prototype including: the walking rail, sensor, and pusher arm without the guarding.

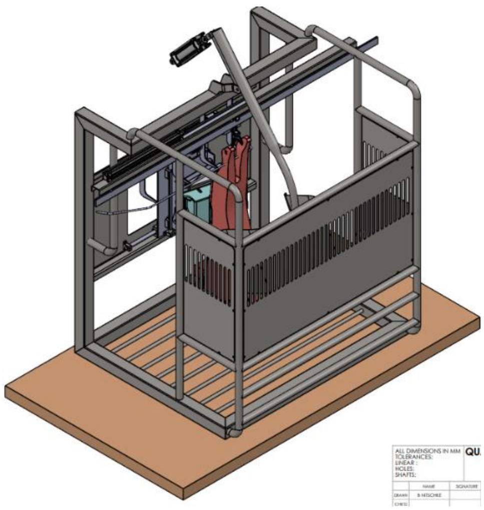


Figure 2 – Model showing safety features include guarding and cattle crossing to deter access.

4.2 Build

The beta sensor was built and functionally tested in the workshop. The performance of the sensor met the critical design specifications. Sensitivity isolated within the loin muscle was proven by measuring full saddles and then sequentially removing the bone and subcutaneous fat, Figures 3 and 4.

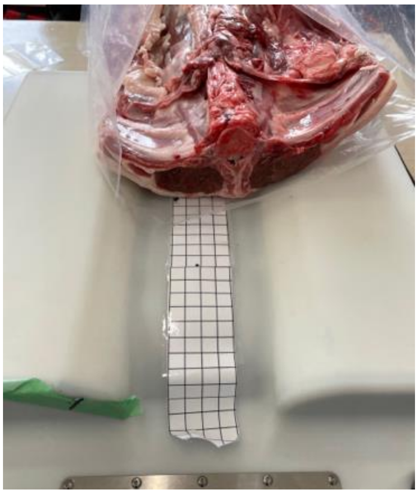


Figure 3- Optimal positioning of a saddle on the sensor requires that the spine is pushed into the groove of the sensor enclosure.

Figure 4 – Example of a saddle deconstructed to the loin muscle sample. The measurements were conducted in the workshop to identify whether there was contribution from subcutaneous fat and bone.

The structure and mechanical parts of the BOE were manufactured from stainless steel. Electrical, pneumatics, and basic controls were installed to permit dry-running of the equipment without the sensor. The only services required for the system were standard electrical supply (240V, 10A) and compressed air (120 psi). In response to initial testing we modified the ‘end’ of the pusher arm to optimise contact between the sensor and the carcase. The built Production Prototype is shown in Figures 5 - 8.

Figure 5 – Prototype installed for testing.

Figure 6 – Prototype installed for testing.

Figure 7 – Prototype in use measuring a lamb carcase.

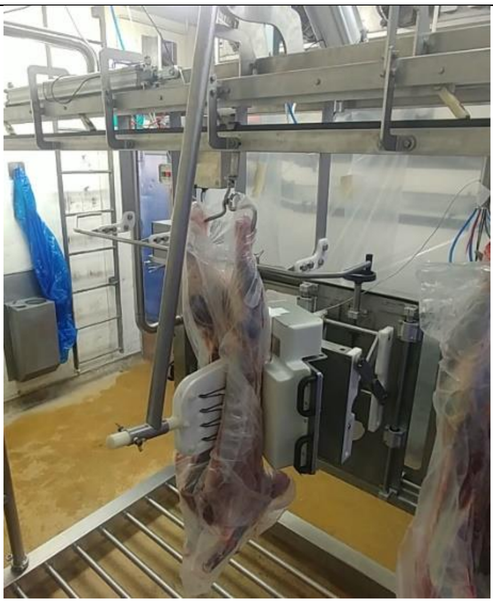


Figure 8 – Prototype in use measuring a lamb carcase.

4.3 Factory Acceptance Testing

The objective of the factory acceptance testing (FAT) was to confirm the BOE, automation and the IMF measurements were fully operational in advance of shipping the equipment to site in Australia. Testing to meet the FAT was two-staged: testing with the prototype in the workshop and testing the prototype in a nearby processing facility (in a temporary location).

Prototype in the workshop

This work focused on loading of carcases and the automation. Freshly slaughtered carcases were purchased and brought to the workshop for testing. The equipment was tuned to achieve consistent loading and alignment of carcases with the sensor.

Prototype in processor facility

To fully test the system using hot carcases, the equipment was temporarily installed in a processing facility local to the workshop where the equipment was built. Testing required complicated hygiene practices to protect and transfer carcases to and from the equipment. This resulted in only approximately 100 lamb carcases being measured. Of these carcases 22 were selected as references and their saddles were harvested for workshop measurements as described in Section 4.2. In addition to measuring % IMF using the sensor on the benchtop, measurements were taken using a traditional NMR benchtop instrument where 15g samples of the LD were sub-sampled and measured. This work showed the sensor within the prototype unit was effectively measuring IMF.

4.4 Installation & Commissioning

The equipment was crated, shipped and installed at JBS Bordertown in a chiller adjacent to the end of the harvest floor that was not fully utilised in day to day operation. The walking rail was integrated into rails in the chiller. The equipment was installed and was operational within four days.

Having the equipment installed in the chilled turned out to be ideal as:

- the carcases were hot, typically measured within minutes of final inspection,
- there was space for retaining measured carcases, from which some carcases could be selected to be tracked into manufacturing to obtain meat samples (for independent analysis)

4.5 Operation

Operation of the equipment required manual loading of the carcases into the first or second indexed positions of the walking rail. In manual mode, the user pushed a go button that initiated the automation sequence of:

1. Advance all carcases along the walking rail
2. Push the carcase in position three against the sensor
3. Acquire NMR data and reset the walking rail
4. Release the carcase in position three

The automation mode repeated the same steps until the stop button was pushed. Carcases were manually loaded on the beginning of the walking rail and removed from the end of the walking rail.

4.6 Testing on site

This system was installed in an Australian processor facility for five months and was used for two, two-week trials in that period. Over 1000 hot carcases were measured that covered significant variety including:

- Two different seasons
- Weights from 17.5 kg to 42 kg
- Fat score 2-5
- Breeds included merino, first-cross, second-cross, and dorper

A wide range in carcase size, weight, and shape and fattiness were deliberately chosen.

Testing occurred in August and October 2022. This is noted as the testing caught late-season and new-season lamb. In the first round of testing, the system was operated for 6 days and in the second round of testing it was operated for 7 days.

Carcases were redirected from the main chain into the chiller in batches of 8-25. The cycle time for operating the prototype equipment was 2 carcases per minute and a batch of 10-20 were typically measured in 15 minutes. Initial testing focused on validating the sensor for hot carcases, so the measurement time was longer than what will be necessary under commercial operation.

Automated % IMF measurements were made using the Production Prototype and selected carcases that spanned a wide range of IMF were labelled and set aside to build a validation data set through separate analysis of a meat sample from the loin. The right loin of the selected carcasses were labelled so that they could be tracked in the fabrication room the following day. The reference meat samples were collected and immediately measured for c-site fat, eye muscle depth, and % IMF using a bench top NMR (Oscar). They were then sent for independent analysis by the University of New England using a proven NIR method [Anderson *et al*. 2015, Harper & Pethick 2004, Perry *et al*. 2001, Stewart *et al*. 2021]. Using Oscar to measure the chilled loin sample provided immediate feedback while waiting for the NIR results. Sixty-five loin samples were sent to UNE from the August trial, however, these samples degraded during transit. This was followed up with 142 sample from the October trial. Separate loin samples were provided for further measurements such as shear force, pH, and colour as available.

5.0 Project Outcomes

5.1 Reference meat samples

Reference meat samples collected for gold standard IMF measurements were performed at the University of New England. Unfortunately, the samples collected in the August trials (N=64) degraded due to preparation errors. These samples provided promising qualitative results that were followed up by more samples in October (N=142). The results from the October reference samples are provided below.

Table 1. Sample statistics

N=142	Mean value	Standard deviation
Carcase weight (kg)	25.8	5.1
Fat score (2-5)	3.13	1.06
NIR - IMF (%)	4.15	1.37

This data was used to develop predictive models and these were tested and validated using the Scikit Learn python package. The final test datasets were tested for predictive accuracy using the Murdoch University Device Accreditation Analysis – IMF% Sheep Meat web app.[2,3]

A large range in carcase size, weight, shape, and fattiness were deliberately chosen including extreme examples. Due to this, five samples were removed from the October dataset (summarised in Table 1) as these samples had C-site subcutaneous fat that well exceeded (three times) the thickness of the design specification. These five carcases represent a tiny minority of carcases based on weights and fat scores of the 1000 carcases measured. This data set (N=137) passed accreditation criteria between 2-6 % IMF.[2],[3] Due to a lack of samples outside the 2-6% IMF range, it was not possible to test accreditation below 2% and above 6%.

By selecting carcases with wide ranging attributes, the tests ascertained the limits of the equipment. Two limitations are extreme c-site fat and carcases that don’t fit well against the sensor.

Figure 9 shows a linear fit of the NMR prediction against the NIR data. There is considerable scatter, which is in line with one objective of the trial being to find the limits of the current design. The data showed that the equipment was able to measure well beyond design specifications for size and fat thickness. The sensor was designed to exclude about 8-10mm of subcutaneous fat. The results showed that it was possible to easily measure carcases beyond this specification, presumably because the fat was compressed when the carcass was pushed against the sensor. Plots in Figure 10 shows the data points coloured by carcase weight and c-site thickness to highlight that over prediction is related to extremes in these categories.

[2] ALMTech II Final report 2023. KPI 3.6 Accuracy and accreditation standards for IMF% devices in lamb. Meat and Livestock Australia, Sydney, Australia.
[3] ALMTech II Final report 2023. KPI 3.6 Amendments to the accreditation standards for IMF% in sheep meat. Meat and Livestock Australia, Sydney, Australia.

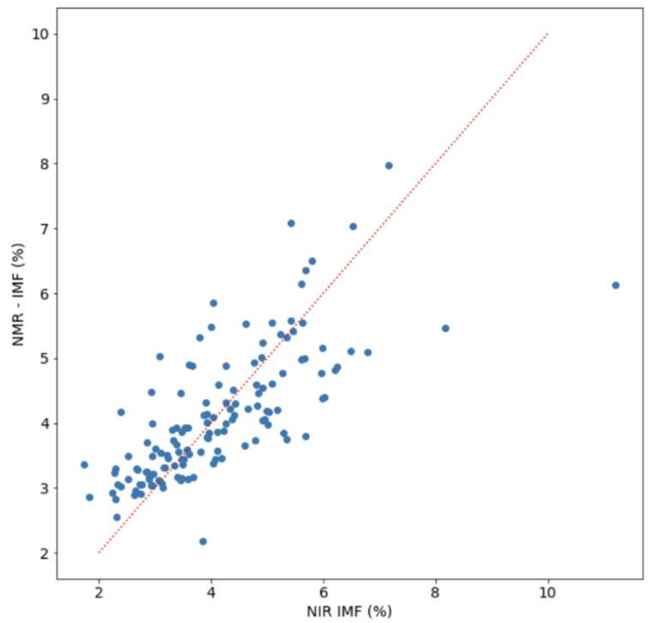


Figure 9. Linear fit of NMR IMF against NIR IMF.

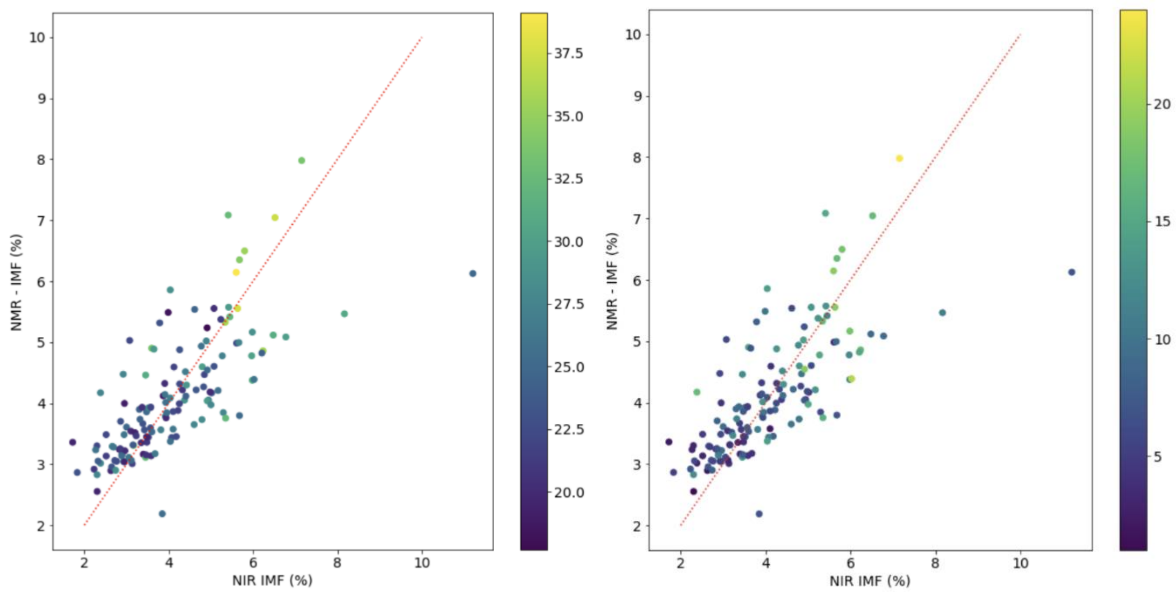


Figure 10. Plots of IMF prediction coloured by carcase weight (kg, left) and c-site fat thickness (mm, right).

With the removal of the five most obvious outliers the data set was tested against accreditation criteria using the Murdoch University web-app.[2,3]

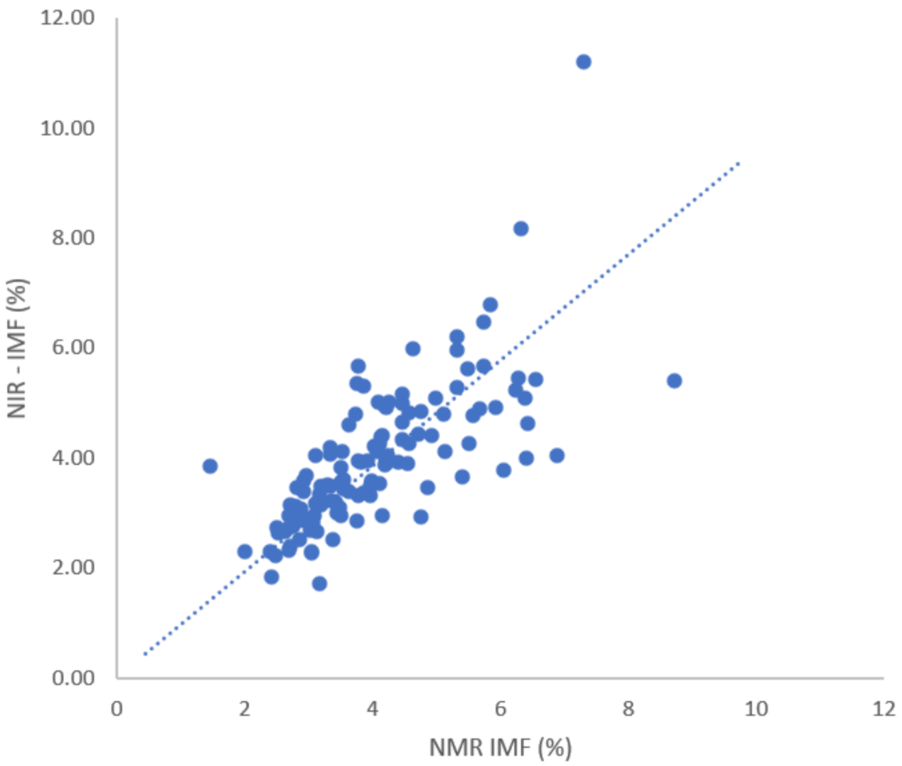


Figure 11. IMF reference data set with samples that had thick c-site samples removed.

The reduced NMR data set was then used to create a 200 point test data set from train-test cycling of a linear model validation. (Figure 11 shows the prediction of all data from just one of these train-test models.) The 200 test points were imported into the Murdoch University lamb IMF accreditation web app.[2,3] There were sufficient sample counts to meet the minimum 20 samples per IMF unit criteria between 2% and 6%. Within this range about 70% were within 1% IMF and about 96% were within 2% IMF across the four quartiles. The fit mean was less than 0.4 % IMF from the true value for all quartiles. This data set passed the minimum requirements for accreditation, improvements can be made by improving the overlap of the sensitive region of the NMR system with the interior of the loin muscle.

5.2 Sampling rate/Cycle time

The priority for this project was proving that the sensor could measure % IMF of hot carcases, therefore a relatively long measurement time was used, *i.e.* two carcases per minute. A small secondary study was conducted to test reductions in measurement, however, equipment limitations meant it was not possible to reduce the carcase handling times and fully explore cycle time parameters. It was shown that a reduction in measurement time from 24 seconds to 7 seconds had an acceptable increase in error. With the identified minor sensor improvements, a path to decrease the measurement time is feasible, *e.g.* six carcases a minute with a single sensor and twelve carcases per minute with a dual sensor system.

6.0 Discussion

6.1 System Performance

Testing in October focused on production readiness where a goal was to determine how the equipment handled the carcase variation of a processing facility and as a result the limits in some instances were well beyond design specifications. Doing so permitted the development of a working specification - expanding the initial design specification and the identification of further improvements. For example, the design specification for C-site fat was 8-10mm however due to compression of the subcutaneous fat as the pusher arm locates the carcase against the sensor, it was determined that the working specification was significantly higher.

Despite pushing beyond the limits of the design specification in October, having the data-set meet the accreditation criteria between 2 and 6%, with only the removal of 5 extreme carcases, highlights the capability of this non-invasive IMF measurement method. Further the only reason that a larger range was not met was due to the lack of carcases with outside the 2-6% range.

The BOE including the automation and carcase handling equipment, was designed for flexibility and for the life of the prototype project. It performed extremely well. The equipment measured over 1000 carcases and coped with in-plant use well. There were only minor performance issues *e.g*. a few carcases misaligned, intermittent electronics fault *etc*. These matters were identified and will be designed for in the future. The fundamental design is fit for purpose so focus can now go into use on a main chain. In this regard, priorities will be downsizing the equipment footprint and speeding up the carcase handling. Based on work completed in this project, a cycle-time of 6 carcases/minute for a single sensor should be achievable and 12 carcases/minute for a dual sensor set up. The latter is in line with Australian lamb processor chain speed.

The performance of the sensor, the design of the BOE, and the automation all contributed to the success of this project. With respect to the Marbl™ sensor and the use of magnetic resonance, this project has shown that the method is robust, accurate and appropriate for hot lamb IMF grading. Points of note with respect to this magnetic resonance measurement method are:

- It is non-invasive
- It is automated
- It directly measures fat and once calibrated, no further calibration is required.

6.2 Next steps for ovine carcase measurements

In the next year the technology development plan includes in-line installations in processing facilities. These will be located at the end of the slaughter floor and will measure hot carcases. Variants of the system will include a single sensor system that works at up to 6 carcases per minute and a twin sensor working at up to 12 carcases per minute. The sensor and BOE will be designed for continuous in-line use with minimal footprint.

Once commercial, equipment such as this will be available with an operating specification, including carcase attributes. With that said, the goal is to measure the widest possible variation of carcases, therefore the intent is to make minor adjustments to the sensor to further improve subcutaneous fat exclusion and carcase fit against the surface. In addition, future testing will include building on the reference sample data set to more fully evaluate the IMF prediction model, reducing measurement time and reducing carcase handling times.

Other next steps would include working with processors and producers to gain value from the % IMF objective measurement. From a processor perspective, as the % IMF measurements are made hot, the data can be used for grading and sorting into chillers and from a producer perspective the data could be used for quality screening.

7.0 Conclusions / Recommendations

This project successfully demonstrated the measurement of % IMF of hot lamb carcases. Notably the magnetic resonance method used is non-invasive, automated and provides a direct measure of fat.

The measurement of % IMF is a key trait in the MSA ovine model and technologies such as this are needed for objective measurements. In this project, data that targeted carcase variation, was referenced against the accreditation guidelines and was found to meet the 2-6% IMF accreditation requirements (N=137, 5 points removed).

Over the course of this project the Marbl™ technology was advanced from a sensor that was being used in a workshop to a fully functional automated measurement unit that was trialled on site. The single sided sensor (Marbl™) was integrated into an automated prototype unit. This pushes the technology down the commercialisation path. With the improvements identified from this project, reaching cycle times of six carcases a minute with a single sensor, and twelve carcases per minute with a dual sensor system, seem achievable. These cycle times are in line with processor chain speeds.

In the next year the plan is to:

- Down-size the equipment footprint, decrease the measurement time and decrease carcase handling times to achieve systems that can operate at up to 12 carcases per minute.
- Have a system operating in-line, at speed.

8.0 Acknowledgement

inMR wishes to acknowledge the support of AMPC, the ALMTech team at the University of New England and JBS Australia Pty, in particular their Bordertown plant and team.

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