Final report

Prototype Single-sided NMR Sensor for non-destructive IMF measurement – Design, Build & Test

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Abstract

This project was undertaken to develop a single-sided Nuclear Magnetic Resonance (NMR) sensor and prove its application for non-destructive measurement of intramuscular fat (IMF) of lamb carcases. The project included the design, build and test of a magnetic sensor specific to the application. The design focused on the magnet being able to measure a volume of meat with a projected magnetic field. This magnet was integrated with a spectrometer and computer into a prototype instrument. The equipment was integrated and the measurement optimised prior to testing of samples from the MLA Resource Flock, and also in a meat processing facility.

The sensor was proven to measure IMF% and the results were consistent with prior work. Once the sensor is further developed, the benefit to the industry will be the opportunity to objectively grade lamb and include an IMF% measurement (a key contributor to a cuts-based MSA grading system of the future grading of lamb). Significantly, grading using this NMR tool is non-destructive and can be done without the need to examine a cut surface of meat; additionally, it can be done on a hot or cold carcase. Further, the NMR technique is direct and does not require on-going calibration.

Executive summary

Background

The Australian meat industry seeks objective measurement of key parameters that can contribute to a cut-based MSA grading system for lamb. One such parameter is intramuscular fat percent (IMF), which is highly correlated to several sensory scores and consumer experience. Nuclear Magnetic Resonance (NMR) is used for measuring fat in food products. Benchtop NMR systems that measure total fat content of a sample of meat are available and prior work using a bespoke NMR system showed NMR could accurately measure intramuscular fat (IMF) of 15g meat samples from the Resource Flock; r=0.84, r^2=0.71, RMSEP = 0.53% (3-8 IMF%).

Our approach was to use a fundamental understanding of the NMR technique to design a single-sided NMR sensor that could be used to non-destructively measure IMF. The sensor was designed for measuring lamb carcases and could be used in the future for grading purposes in meat processing plants.

Objectives

The aims of this work were to:

- Design a prototype magnetic sensor that would project a magnetic field into the meat permitting non-destructive measurement of a volume of meat behind the subcutaneous fat cap. The design needed to allow measurement of lamb carcases.
- Integrate the prototype sensor with a spectrometer and a computer and optimise measurement protocols for IMF.
- Prove the equipment to the application.
- Provide consideration to where the equipment might be used in a plant

The project successfully built the prototype and proved the application.

Methodology

Our approach included:

- defining a specification for the permanent magnet based on carcases, *e.g.*: field strength, measurement volume, signal-to-noise, weight
- modelling magnet designs
- designing NMR probe and application specific software
- tailoring an MRI spectrometer for our Low Field NMR application
- building the magnet and referencing the build measurements versus our model, original specification, and prior designs
- testing of >200 Resource Flock lamb samples with statistical analysis
- testing of carcases in plant.

Results/key findings

The sensor design and build resulted in a magnet with a field strength of 0.12T and a measurement volume of 19 cm^3, with the centre of the measurement volume being 18 mm from the magnet enclosure surface, and a signal to noise ratio that exceeded anticipated needs. The prototype equipment was tested on hot and chilled samples/carcases.

The key findings were as follows:

- A prototype single-sided NMR sensor has been designed, built and tested for use in non-destructive IMF measurements in lamb.
- The sensor has been shown to be able to predict IMF.
- In other work, the system has been proven to accurately measure IMF in beef with correlations for hot and cold applications. From this work it was not possible to expand on the known correlation of NMR with NIR as the samples had a low variation in IMF.
- We have learnt that hot carcases will be easier and more accurate to measure than chilled carcases.

Benefits to industry

The industry seeks objective measurement of IMF% in lamb to better describe eating quality traits and thus value to the meat. MARBL™ is a non-destructive tool based on NMR that permits direct measurement of meat below the surface of a carcase at a nominated grading site. The design of the sensor is robust, does not require repeated calibration and it has the potential for measurement speeds that align with processing line speeds. Further, it has been shown that measurements can be conducted on hot carcases, permitting grading or sorting information to be available before carcases enter the chiller.

Future research and recommendations

Further work, that can grouped into the following areas, has been identified:

i) Sensor – test alternate pulse sequences and magnet design for improved application to lamb measurement.
ii) Sample -
  - understand the industry needs of the measurement site
  - work with the Resource Flock and industry to build the knowledge base of the NMR measurement method.
iii) System – there is an opportunity to automate tuning (in this work it was a manual step) and to decouple the sample and sensor.
iv) Site - Measurement time alignment with line speed. We did not set a measurement rate goal for this project, but we are aware this is important for implementation within a meat processing plant. We can make the required measurements within 3 seconds when extraneous noise is managed and signal to noise is optimised.

The natural progression of the proof of the sensor prototype work conducted here is to integrate an improved sensor into a production prototype unit. In parallel, the knowledge base could be built by having sensors in use with early adopters.

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1. Background

1.1 Industry position – IMF & Lamb

In 1998 the Australian meat industry implemented MSA grading for beef eating quality and is reaping the benefits. In 2020 the value of the benefits at farm gate were valued at $172M [Strong J, 2020]. The industry seeks to implement a similar grading system for lamb and significant investment is going into objective measuring methods through the ALMTech programme.

Intramuscular fat (IMF%) is a trait underpinning value differentiation. As detailed in a variety of on-line news articles (see websites in references):

- in New Zealand processors are paying a premium for lamb based on pH and IMF% and producers have developed premium brands, e.g. TeMana Lamb, through genetics and finishing that are distinguished by their higher than average IMF values (averaging 3%).
- in Australia, producers see potential for capturing value from lamb with high IMF (proposing 12% IMF lamb could return $120/kg) and
- in the USA there are niche examples of lamb with 37% IMF attracting >$100/kg, nearly three times the standard price.

Other research in New Zealand that reinforces the value of IMF includes:

- Lambs with low fat and high breeding values make for poor eating [Craigie CR et al, 2017]
- There is an antagonistic relationship between muscle growth traits and fat content across the lamb carcase. The New Zealand sheep industry has selected for muscle growth traits for decades to improve production efficiency and reduce extremes of carcase fatness historically observed. However, this is now regarded as being to the detriment of eating quality (Craigie et al, 2017, Realini, 2020), where:
    - in 2017, the average IMF% was 2.69% (Range 0.91-6.42%) and IMF% positively correlated with carcass weight and negatively correlated with predicted lean meat yield percentage.
    - while in 2020 consumer sensory studies showed that 4% IMF (amongst other attributes) contributed to maximum overall liking and minimum IMF for consumer satisfaction was 3%[1], and
    - continued selection of leanness without inclusion of quality could lead to decreased IMF and consumer liking.

The examples above of new lamb breeds, processors paying a premium and the opportunities to create value from eating quality attributes, highlight the opportunity of measuring IMF.

Prior industry surveys highlighted the potential value that NMR could provide to the meat industry for sorting and grading (North et al, 2008a). Subsequent initial studies, using off the shelf equipment, produced mixed results (Devine et al, 2006; North et al 2008b, Pearce 2007).

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[1] In this work there were two consumer segments; IMF lovers (n=111) where overall liking increases with IMF and IMF optimisers (n=54) maximum overall liking of 2.5-3.5% IMF. Continued selection of leanness without inclusion of quality could lead to deceased IMF & consumer liking.

More recent work has been successful with respect to the measurement of IMF. For example:

- In project *P.PSH.0878* the NMR measurement was shown to provide a predictive correlation of *r=0.93* for intramuscular fat in a set of 25 beef samples. (NMR was also able to predict total moisture content with *r=0.88* and drip loss with *r=0.79*.) In a subsequent trial in collaboration with AgResearch a predictive correlation of *r=0.96* (and a root-mean-squared error in prediction (RMSEP) of 1.1%) was achieved for a set of ~150 beef samples ranging from Wagyu to bull beef.
- An ALMTech trial (V.RDP.2110) at UNE using MLA Resource Flock lambs was directed at IMF in lamb loin samples, achieving a predictive correlation of *r=0.84* and an RMSEP of 0.5%.
- In all these trials, small (~15 g) loin samples were measured in an enclosed magnet in a laboratory environment, requiring subsampling of the loins cut from the carcase. While not commercially applicable, this provided proof-of-concept using existing hardware designed for other purposes.

These recent studies have been successful due to an understanding of the NMR measurement methodology and equipment requirements.

Following the ALMTech trial it was recommended that further investment should focus on development and pre-commercial testing of a prototype 'single-sided' NMR configuration to assess the accuracy and precision of IMF measurement from a configuration that could potentially be applied to the loin of an un-cut lamb or beef carcase.

As covered in this report, our approach was to use a fundamental understanding of the NMR technique to design a single-sided NMR sensor that could be used to non-destructively measure IMF. The sensor was designed for measuring lamb carcases and could be used in future for grading purposes in meat processing plants.

2. Objectives

The aims of this work were to:

- design a prototype magnetic sensor that would project a magnetic field into the meat permitting measurement of a volume of meat below the fat cap non-destructively to allow measurement of lamb carcases
- integrate the prototype sensor with a spectrometer and a computer and optimise measurement protocols for IMF
- prove the equipment to the application while
- consider where the equipment might be used in the plant and, most significantly, whether measurements would be made of hot or chilled carcases

The project successfully built the prototype and proved the application. Further work has been identified.

3. Methodology

3.1 General

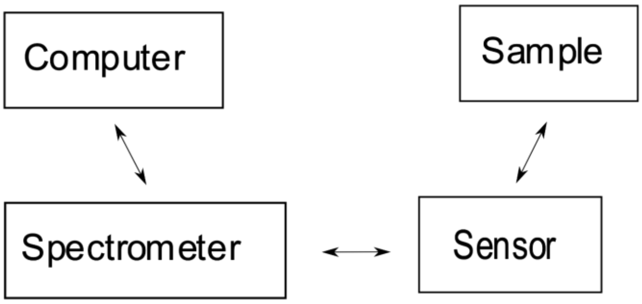
Our approach was to:

- define a specification for the permanent magnet *e.g.*: field strength, measurement volume, signal-to-noise, weight
- evaluate several magnet designs
- design tuning electronics, radio frequency module and controls software
- tailor an MRI spectrometer for our application
- build the magnet and compare the build to our model, our original specification, and prior NMR systems
- test >200 MLA Resource Flock lamb samples to complete a statistical analysis of the results
- measurement of carcases in plant

3.2 NMR system description

The NMR system is comprised of a spectrometer and sensor that are controlled by a computer (Fig. 1). The spectrometer produces strong radio frequency (RF) pulses that the sensor transmits into the sample. The sample produces a weak RF response that is then detected by the sensor and amplified by the spectrometer. The computer controls the spectrometer and retrieves the data collected at the end of each measurement. The computer then processes the NMR data to make predictions about the sample. In this work we are predicting IMF from the collected data, however, NMR is often used for predicting many chemico-physical properties.

Figure 1: Block diagram of system with sample. The computer controls the spectrometer. The spectrometer sends and receives RF signals from the Sensor. The Sensor receives the signal from the sample and sends it back to the spectrometer. The computer pulls the data off the spectrometer and calculates the meat properties from that data.



Relevant information pertaining to the design, modelling and building of these various items are covered in the following sections.

3.3 Sample considerations

The goal of the prototype single-sided sensor is to enable IMF measurements of lamb carcases in a production facility; therefore, our sensor enclosure was designed to accommodate carcases.

An accepted location for measuring IMF of sheep is the longissimus dorsi at the 13th rib. For our non-destructive measurement we have designed the region of investigation (ROI) to be the longissimus dorsi muscle, around the 13th rib. The sensor must accommodate the natural variation of shape and size of a lamb carcases.

From a design perspective it is important that the measurements are of the meat without interference from subcutaneous fat, while also not projecting beyond the meat into the bone. Tailoring the enclosure to accommodate the shape of carcases was a further design consideration. We opted for our sensor to have housing with a curvature diameter of 250 mm that would accommodate most carcases we encountered in this project. We did not design specifically for carcase weight but expected we should be able to accommodate carcases up to 30 kg.

3.4 Spectrometer

We started with a spectrometer optimized for a frequency range of 5-10 MHz and added a 250 W high power RF amplifier. The spectrometer was equipped with an integrated temperature control feature for stabilizing the magnet temperature (see Section 4).

3.5 Sensor description

The sensor was designed for the application. The sensor includes the following components that are housed within an enclosure that also aids sample positioning:

- a magnet with a “sweet spot” (or measurement volume) that projects into the lamb carcase.
- an RF transceiver coil

3.5.1 Magnet Design

The magnet is designed so that we only receive signal from the region of interest (ROI) and essentially exclude the rest of the sample from the measurement. The sensitive volume within an NMR magnet is a region of the magnetic field that has a magnetic flux value within a specified range that the instrument will detect exclusively. The sensitive volume of the NMR is specified to have the same dimension as the ROI and is the same distance from the sensor surface as the ROI is from the carcase surface. This means that when the sample is positioned correctly on the sensor, the ROI and sensitive volume are collocated.

The sensitive volume of a permanent magnet system is created by the magnet geometry and how individual magnet blocks are arranged. Many magnet geometries exist, and in this case, we use a semi-Halbach geometry. The sensitive volume was designed using Biot-Savart equations that estimate permanent magnets as current loops followed by finite element analysis simulations to finalize the designs.

The field homogeneity was optimized by breaking up the magnets into smaller magnets and adjusting their position. There is a compromise of price, weight, ease and safety of build, field strength and size of the sensitive region. We set a magnetic field target of 0.2 T and sensitive volume of 5 cm^3.

We considered four magnets at different performance and price points. We settled on a design that provided space around the magnet material to provide a strong housing, temperature control, insulation, and room for the RF electronics; all ideal for a prototype. This design is also more appropriate for a prototype due to the flexibility in carcase size acceptance and range of penetration depth, which can be adjusted by redesigning the enclosure and RF coil assembly.

3.5.2 Comparing the design to magnets used in other work

A second part of the design phase was to compare MARBL™ with magnets used in prior work. This was important as in prior work there were both mixed results (Pearce, 2007) and successful results. We used this information to confirm our specification and design.

The designs reviewed were:

Preliminary Halbach
The work reported in P.PSH.0265 (Devine et al 2006) used an NMR system based on an 11.8 MHz Halbach magnet created by Magritek. This was a preliminary study that showed NMR could collect data on the samples. The main problem was that the sample needed to be cut. They speculated that the solution was to use a unilateral magnet system that was in development at the time called the NMR MOLE.

NMR MOUSE
The work reported in P.PSH.0229 (North et al 2006) used the NMR MOUSE which is a unilateral magnet design that has a strong magnetic field gradient perpendicular to the surface of the magnet. The NMR MOUSE operates at a frequency of approximately 18 MHz, which is sufficiently high. The problem with the NMR MOUSE is that the magnetic field contains a strong gradient that is used for profiling solid materials. The report concluded the NMR MOUSE lacks enough sensitivity for the measurement, however it did not expanded on the cause for lack of signal.

Oscar 2.0
The work reported in V.RDP.2110 (Pooke and McCarney 2019) used Oscar 2.0 which is another full Halbach magnet operating at 12.3 MHz and utilizes an idea solenoid coil shape for detection. This system had a signal to noise so high that it was not a factor in measurement variance. However, this system requires that the sample be excised from the carcase for the measurement. This means that the system does not meet the design requirements for an in-line measurement at a processing facility.

Test Magnet
We also compared our design with a “Test Magnet” of a unilateral design that we had access to. This magnet was designed by others for MRI studies of the brain.

3.5.3 RF design

The NMR probe sensor is the component of the sensor that sits above the magnet and transmits and receives signal to and from the ROI. It is composed of a coil (antenna) and a tuning circuit. The coil is designed to optimize efficiency and sensitivity. We trialled two coils to determine electrical properties and sensitivity using the Test magnet. We built a 13-turns coil with 67.5 and 37.5 mm for the major and minor radii, respectively as compared to 16-turns and 80 and 50 mm radii. A picture of a 6-turns coil is shown in Fig. 2.

Figure 2: RF coil - 6 turns

The real-world parameters we wanted to explore in these tests were the voltage expected across capacitors, probe dead time, and sensitivity. For test purposes a probe was built up with lower working voltage capacitors for design tests.

The best way to determine the sensitivity is by determining the power required to produce a 180-degrees pulse. If the coil requires less power to produce a 180-degrees pulse, it will also be more sensitive. This method removes the impact of many variables such as RF interference noise and frequency drift on sensitivity measurements.

The probe dead-time will be related to the quality factor, Q, which is a standard RF resonator measurement. Higher Q usually means greater sensitivity but also longer dead-times. A short dead-time allows for more data acquisition that can result in higher sensitivity if more data can be collected after the probe recovers from the high power pulse. The ideal design has a dead-time just shorter than when the signal arrives.

Voltages that slightly exceed the working voltages of the electronic components used can result in degraded performance and degradation of the system. Voltages that far exceed the working voltage can burn out components and break the system. High voltage components become very expensive and are physically large. We therefore prefer to design a system that is well within the specification of the electronics components. In design tests the voltages across capacitors were measured at lower power and voltages. These were then scaled to the power needed for to make the measurements specified in the design.

Our work showed that three different coils (13-turns, 6-turns and 6-turns balanced) have roughly the same sensitivity from their 180-degrees power. After reviewing various aspects of performance we settled on a 6-turn design for MARBL™

3.5.4 Other Parts

The connector panel sub-assembly is shown in Fig. 3

Figure 3. The connector panel sub-assembly.

3.5.5 Optimization of performance NMR

Signal to noise ratio (SNR) is an important attribute of the measurement. SNR is dependent on the sample, magnet design, and the RF design (Casanova *et al*. 2011). In this project, the sample is always meat, which will be considered constant. This leaves the optimization to the magnet and sensor designs so SNR was a design criteria.

SNR of the NMR measurement will be proportional to according to the equation:

$$SNR \propto B_0^2 V \frac{(B_1/i)_{xy}^{4/3}}{L^{2/3}}, \tag{1}$$

where B_0 is the magnetic field strength, V is the sensitive volume of the magnet, $(B_1/i)_{xy}$ is the RF coil efficiency, and L is the RF coil inductance. The B_0 and V are dependent on the magnet design, while $(B_1/i)_{xy}$ and L are dependent on the RF coil design. This process assumes that the sample and RF circuitry has been properly shielded from external RF interference (noise).

One of the goals of the design phase was to maximize the SNR using Equation 1.

3.5.6 Magnet temperature stabilization

The magnetic field produced by permanent magnets drifts with temperature. The magnet material used will drift by approximately 1200 ppm/ °C. In order to keep the field from changing more than five percent, the field must be kept stable to about 0.2 °C. The magnet is temperature stabilized using a heat source, thermal isolation, a temperature sensor, and a controller. We also include a thermal fuse to further protect our magnet.

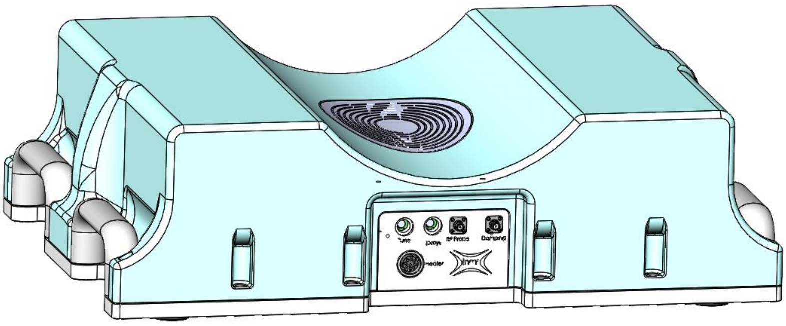
The heat source is wound around the magnets. A surface PT100 sensor is used to measure the magnet temperature and a thermal switch to prevent the magnet from exceeding a defined maximum temperature. These components are controlled and driven by the NMR spectrometer.

3.5.7 Sensor Enclosure

The sensor enclosure brings all the components together. It positions the sample (i.e. lamb carcase) so that the ROI and the NMR sensitive volume are collocated. It positions the RF coil as close to the

ROI as possible to achieve the optimal SNR. The tuning circuit is positioned close to the RF coil to minimize signal loss. The housing holds the temperature control components including the resistive heating elements attached to the magnet chassis to warm the magnets above ambient temperature and insulation to isolate the magnets from temperature changes in the local environment. Connectors for the sensor and temperature control are located on the front panel of the housing. A CAD drawing to the enclosure is shown in Fig. 4. The curved surface of the enclosure is to accommodate a carcase.

Figure 4. CAD drawing of the enclosure and associated parts.



We used the latest 3D printing technology to create the outer enclosure of the NMR sensor, coil former, and other complex custom parts. For the prototype consideration was not given to cleanability and food safety requirements.

3.6 Work flow, Software interface & Data Collection

The NMR data is acquired in a custom interface where the raw data is processed and analysed. The first iteration of the software displays raw data, processing, and analysis so that we could troubleshoot issues. The software runs in a Python environment. This will initially be a Jupyter Notebook or Jupyter Labs, but can easily be transitioned to a graphical user interface once the workflow is established. Our ultimate goal is to produce an IMF% that is entered into the processor's database with the matching carcase ID.

For site work, a software workflow was created in an iPython notebook specific for the measurement programme. The notebook provided a workflow that included: data handling, pass/fail instrument performance checks, data acquisition, and rudimentary processing and analysis. This was used as the main data acquisition interface, while several tools were developed for optimizing the acquisition parameters and system performance.

3.7 Testing MARBL™

3.7.1 On-site

On-site testing was conducted at an abattoir in New Zealand. The testing methodology included two days of in-plant trials. The equipment was located at the end of the slaughter floor, after grading and before the final wash prior to entering the chiller. Carcases were removed from the chain, measured and returned to the chain; carcases were handled hygienically by wrapping in plastic. We sought to measure IMF% in the longissimus dorsi around the 13th rib.

The primary goal of the site work was to understand how to handle and manage hot carcases.

Points of note:

1. Electricity - We only required a standard 240V plug to operate the system.
2. Transporting equipment - The equipment was moved in the shipping cases with a 2-man lift. The sensor case was fitted with iron sheets to shield the magnetic field when in transit.

3.7.2 MLA Resource Flock

Testing of samples from the Resource Flock was conducted at the University of New England, Armidale, New South Wales. Data were collected on 221 unique lambs from the Resource Flock that the UNE Meat Science team characterized as part of the May 2021 kill.

Five full carcases of varying sizes and a full saddle from the remaining 216 carcases were retained from the processor. NMR data was collected on the right loin muscle of each saddle and both loins of the full carcase. The saddles from each full carcase were removed after the data was collected and NMR data were then collected on their right loin muscle.

Saddles were visually evaluated during boning to try and find extremes in IMF. A collection of 25 saddles was chosen to include ten high, ten low, and 5 intermediate fat content samples. These samples were measured daily starting about 30 hours and ending four days post mortem. After the final measurement, these samples were halved and then the right half was heated to 25-30 C and NMR data was collected on the warmed loin.

The UNE Meat Science team measured IMF measurements using established NIR methods.

4. Results

4.1 Build

The magnet was integrated with the RF coil, controls, enclosure and spectrometer, Fig. 5.

Figure 5 - The MARBL™ Prototype.

4.2 Design versus Build

The built magnet was measured and mapped. As outlined below, although there were some variations between design and build, we determined the magnet was more than sufficient to complete this proof of concept project.

Differences noted between the design and build included:

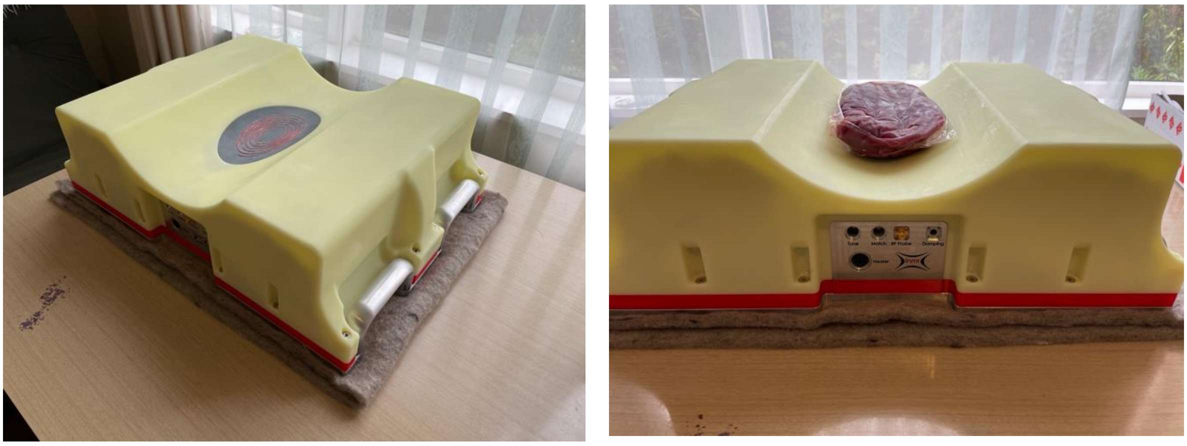
- Field strength was less than expected; 0.121T built versus 0.16T by design
- The sweet spot was higher up on the z-axis than modelled; 43 mm built versus 35 mm by design, and
- The homogenous field volume is larger than designed; 19 cm^3 built versus 13.7 cm^3 by design.

Noting these variances between design/specification and build we conducted a design review. We did so to ensure we could take learnings into future builds. We were able to determine the origin of the variations and we now know some key parameters to specify and manage to ensure that with the next build the outcomes between the build and model will be much closer.

The variations in field strength and homogeneous volume were not of concern. The lower magnetic field strength can be managed by slightly longer measurement acquisition times and the increased homogenous volume can be managed with electronic/signal management methods. However, a larger measurement volume is in the main favourable as it assists with averaging the natural heterogeneity of meat [Stewart S et al, 2020]; MARBL™ measures 70mm down the length of the longissimus dorsi.

The variation in penetration depth did warrant a small design adjustment. Our design adjustment was to lift the enclosure by 5mm by adding in a spacer between the aluminium plate and the enclosure (Fig. 6)

Figure 6. Red coloured spacer evident between the enclosure and aluminium base and on the right, an example of a vacuum-packed meat sample being used for tuning.



SNR was another key design parameter and in our design as this strongly influences measurement acquisition time. Our estimate of the MARBL™ SNR was 430.

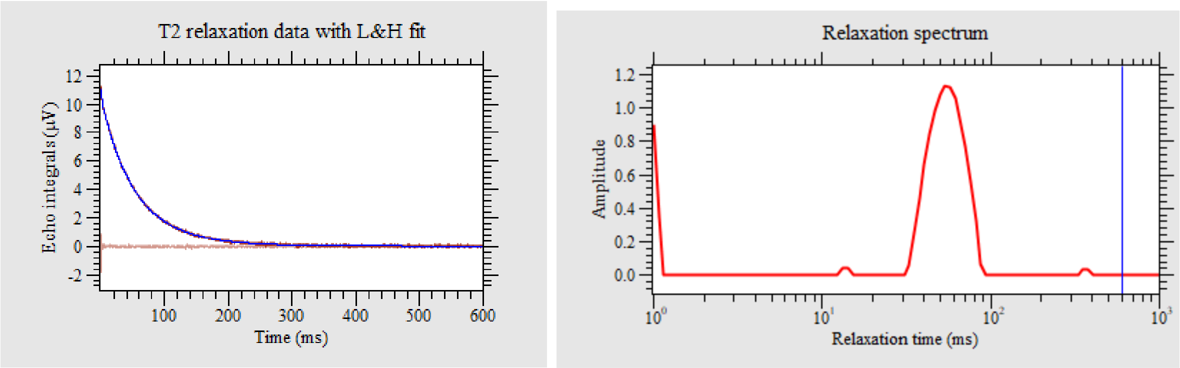
4.3 Test

4.3.1 Workshop

Our first NMR measurements of meat occurred within 24 hours of completing the build, so the progression to measuring meat was very simple and direct due to the prior design and testing work.

Our NMR measurement optimisation work was limited to a store purchased sample of cryovac-packaged loins. Fig. 7 is an example of a relaxation measurement (left) and it's inverse Laplace Transform (right) showing the characteristic peaks for meat at 12, 50, and 300ms. The relaxation spectrum typically has 2-4 peaks that represent fat and water in different local environments at the molecular level. Peaks in the left of the spectrum have fast relaxation rates and to the right have slower relaxation rates. These peaks are discussed further in the following sections. The data was acquired using a CPMG[2] pulse sequence and the SNR was about 340.

Figure 7. CPMG decay acquired from a packaged lamb tenderloin (left) and inverse Laplace transform (right). Data from MARBL™.



From this work we ascertained measurement parameters used for testing.

4.3.2 On-site

The equipment was checked using a chilled saddle and we confirmed measurement of IMF on site; Fig. 8 (left).

The carcases weighed between 16.2 and 24.2 kg and measurements were taken within 30 minutes of being slaughtered, and typically 17-19 mins post slaughter; Fig. 8 (right). We successfully measured 10 carcases, however, the number of carcases measured was curtailed by damage to the RF cable during set up.

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[2] CPMG: Carr-Purcell-Meiboom-Gill pulse train is a fundamental component of pulse sequences used in NMR

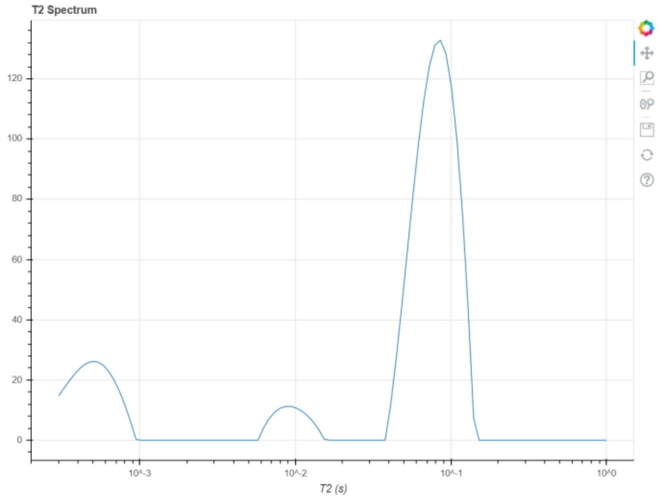
Figure 8. Equipment set up at the end of the slaughter floor. Chilled saddle sample (left photo) and hot carcase (right photo)

The performance of the prototype equipment on its first use was regarded as a success in that we successfully measured IMF on a limited number of carcases. Items specific to operating the equipment on site were identified for further work.

Fig. 9 shows a typical relaxation spectra for the saddle. This shows the following 3 peaks:

- Left hand peak: Often represents solids, however in this magnet geometry it is also related to an artefact associated with signal observed from the sample outside the sweet spot [Hurlimann MD and Griffin PP, 2000].
- Middle: buried water and fat, [Anderson and McCarney (2021); Bertram et al. (2002)]. This is the peak of interest to measuring IMF. This peak does include some variation in buried water content, however, from our observations this variation is less than the range of heterogeneity of fat within a meat sample.
- Right (slowest relaxation): represents water interacting with myofibrils.

Figure 9. Typical transverse relaxation spectrum of the cold saddle.



Similar spectra were obtained for hot carcases. The spectra highlighted that hot carcases have a more easily acquired fat peak.

4.3.3 MLA Resource Flock – UNE, Australia

Key goals of the testing in Australia at UNE of the MLA Resource Flock were to:

- improve sample handling,
- improve our measurement methodologies through dealing with >200 samples, and
- access to independent measurement of IMF%[3]

Results and learnings on each of these matters are covered in the following sections.

Fit of lamb samples into MARBL™

During the first (partial) day of testing at UNE we noticed that the packaged saddles were flattened a bit by the cryovac process. In addition, many carcase backs were rather flat and with a decreasing radius of curvature as the distance from the spine is increased. This resulted in a poor fit of the saddles within the enclosure, which was designed with a constant radius in mind (Fig. 10). Removing the enclosure so that the saddle could rest on the coil and magnet block resulted in a good fit that curved around a single loin muscle and also accommodated the lack of curvature across the back. This is a consideration specific to packaged samples and not of real significance when the end application for this work is non-destructively measuring carcases rather than packaged cuts.

Figure 10. The saddle fit was not as expected from the radius data because a constant radius was assumed.

MARBL™ was used both with and without the red spacer (see Fig 10), lowering of the RF coil by 5 mm. Lowering the coil increased the depth of penetration of the NMR signal to manage contribution from the fat cap. While the fat cap is usually much less than 15 or even the original 11mm, the cold samples did not mould to the surface of the coil and often had a gap of several mm between the coil and the sample. Other adjustments made during measurements included alignment with the RF coil, so measurements were being recorded as close as possible to the cut end.

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[3] UNE freeze dried samples of the lamb loin and then measured IMF with infrared spectroscopy.

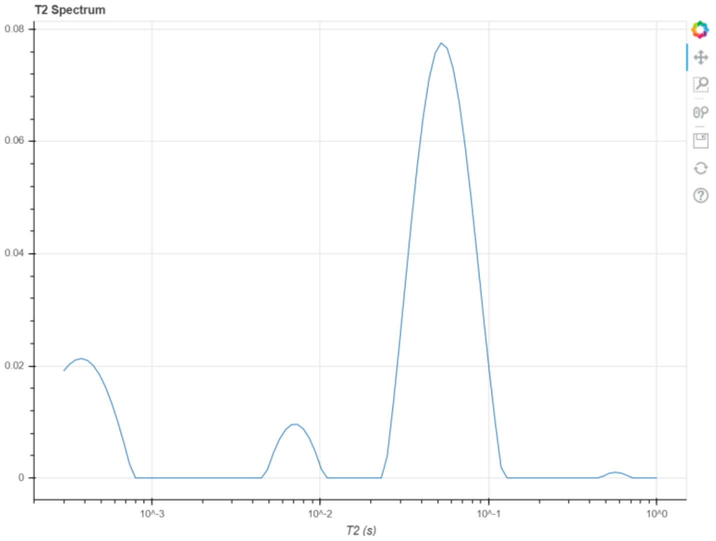
Full carcases were aligned in the same manner as the saddles, however, it was necessary to raise the sensor off the bench with cutting boards because the neck did not allow for the sample to lay flat against the coil (Fig. 11).

Figure 11. The carcase was positioned to collect data on the same portion of loin muscle measured in the racks. The sensor was raise using a stack of cutting boards to allow the carcase to lay flush against the NMR coil.

Representative NMR data

NMR data of the saddle samples was conducted on cold samples. A typical transverse relaxation spectrum is shown in Fig. 12. The data collected on the loin from body 181 (L181) contains 4 peaks.

Figure 12. Transverse relaxation spectrum of lamb loin L181.



Statistical analysis of IMF measurements

Statistical analysis was performed to assess the NMR results from the Resource Flock. The descriptive statistics of the NIR reference measurements (Table 1) and the NMR fit parameters were conducted. The table includes the full data set of 213 samples, excluding the carcase measurements and three handling errors, and a subset that selects the thickest loins. By dropping the RF coil and increasing our depth, we were worried that we were measuring through the longissimus dorsi muscle and into bone and connective tissue. We therefore created a subset of 55 loins that had a sum of c-site fat and eye muscle depth of greater than 40mm.

Table 1. Descriptive statistics (mean, standard deviation, minimum, and maximum) for the NIR reference IMF measurements and the NMR fit parameters across the complete data set and a subset with a total sample depth of greater than 40mm (c-site fat plus eye muscle depth)

Measurement	Mean	Standard deviation	Minimum	Maximum
NIR-IMF (n=55)	3.66	0.95	1.92	5.67
(n=213)	3.45	0.88	1.72	6.61

The samples from this kill had a limited variation in IMF compared to earlier work where the maximum and minimum IMF in the plots were between 3.5% and 8.5% respectively with good variation across that range [Pooke D & McCarney, 2019]. The decreased range of IMF in 2021 challenges making correlations with NMR.

Prior and parallel work has shown excellent correlations between NMR and NIR measurements In recent studies using MARBL™ to measure IMF in beef shortloins (with fat cap trimmed), MARBL™ gave correlations with r^2>0.86 for both MSA marbling and NIR IMF% [McCarney E & Webster B, 2021].

In addition there is further work to do on the prototype, see Section 6.

5. Conclusion

5.1 Key findings

- A prototype single-sided NMR sensor has been designed, built and tested for use in non-destructive IMF measurements in lamb.
- The sensor has been shown to be able to predict IMF.
- In other work, the system has been proven to accurately measure IMF in beef with correlations for hot and cold applications. From this work it was not possible to expand on the known correlation of NMR with NIR as the samples had a low variation in IMF.
- We have learnt that hot carcases will be easier and more accurate to measure than chilled carcases.
- There is further work required for the application to lamb (see Section 6).

5.2 Benefits to industry

The industry seeks objective measurement of IMF% in lamb to define eating quality traits and thus value to the meat. MARBL™ is a non-destructive tool based on NMR that permits direct measurement of meat below the surface of a carcase at a nominated grading site. The design of the sensor is robust, does not require repeated calibration and it has the potential for measurement speeds that align with line speeds. Further, it has been shown that measurements can be conducted on hot carcases, permitting grading or sorting information to be available before carcases are chilled.

6. Future research and recommendations

The following areas of further work have been identified:

v) Sensor – test alternate pulse sequences and magnet design for improved application to lamb measurement.

vi) Sample -
  - understand the industry needs of the measurement site.
  - work with the Resource Flock and industry to build the knowledge base of the NMR measurement method.

vii) System – there is an opportunity to automate tuning (in this work it was a manual step) and to decouple the sample and sensor.

viii) Site - Measurement time alignment with line speed. We did not set a measurement rate goal for this project, but we are aware this is important for implementation within a meat processing plant. We can make the required measurements within 3 seconds when extraneous noise is managed and signal to noise is optimised.

The natural progression of the proof of the sensor prototype work conducted here is to integrate an improved sensor into a production prototype unit. In parallel, the knowledge base could be built by having sensors in use with early adopters.

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8. References

Anderssen KE and McCarney ER (2021). Mechanisms of Transverse Relaxation of Water in Fish and Meat. [Manuscript submitted].

Bertram HC, Purslow PP, and Andersen HJ. (2002) Relationship between Meat Structure, Water Mobility, and Distribution: A Low-Field NMR Study. *J. Agric. Food Chem.* 50, 4, 824-9.

Casanova, F and Perlo, J (2011) NMR in Inhomogeneous Fields. *Single-Sided NMR. 11-56.*

Craigie CR et al,2017, Intramuscular fat content of New Zealand lamb M. longissimus lumborum, Proceedings of the New Zealand Society of Animal Production, Vol 77, p 189-193.

Devine, C et al (2006), Feasibility of using low field nuclear magnetic resonance (LF-NMR) to measure meat properties on-line, P.PSH.0265, MLA Report.

Hoult, D.I., Richards, R.E., 1976. The signal-to-noise ratio of the nuclear magnetic resonance experiment. J. Magn. Reson. 1969 24, 71–85.

Hürlimann MD and Griffin DD. (2000) Spin Dynamics of Carr–Purcell–Meiboom–Gill-like Sequences in Grossly Inhomogeneous B_0 and B_1 Fields and Application to NMR Well Logging. *J. Magn. Reson*. 143 (1), 120-135.

McCarney E and Webster B (2021), Bovine IMF Measurement Production Prototype (Stage 1), AMPC report 2021-1128, June.

McGilchrist P, Presentation to MSA, “Hogget Phenotyping & Eating Quality”, Copy provided by Dr P McGilchrist

North, M et al (2006), Develop on-line VSA/NIR & NMR measurement technologies for beef and sheep meat, P.PSH.0229, MLA Report.

North, M et al (2008a), Industry consultation and cost/benefit analysis of Low Field Nuclear Magnetic Resonance (LF-NMR) for on-line measurement of meat quality attributes, P.PSH.0324, MLA Report.

North, M et al (2008b), Develop on-line NMR measurement technologies for beef and sheep meat, P.PSH.0324, MLA Report.

Perry, D., Shorthose, W.R., Ferguson, D.M., Thompson, J.M., 2001. Methods used in the CRC program for the determination of carcass yield and beef quality. *Aust. J. Exp. Agric*. 41, 953

Pearce K et al (2007), Preliminary study of a Magritek low field nuclear magnetic resonance device to measure meat attributes, A.MQT.0035, AMPC Report.

Pooke, D and McCarney, ER (2019) NMR Measurement of Intra-Muscular Fat, MLA Report, V.RDP.2110, September.

Reis, MM; Rosenvold, K, and North M (2011) Preliminary study of a Magritek Halbach NMR instrument as a device for shear force and drop loss measurement in meat.

Realini, C et al, Does intramuscular fat level affect the eating quality of New Zealand lamb? Meat Innovation Workshop 2020,
https://www.youtube.com/watch?v=43VUaknOayI&list=PLCLuDSotcmhI-s-t1IlnDpeOFQJnDKi0v&index=9

Stewart S.M., Pethick D.W. and Gardner G.E. (2020). The distribution of chemical Intramuscular fat percentage within M. Longissimus Dorsi in Australian beef carcasses. An Advanced measurement technologies for globally competitive Australian meat Project. June.

Strong J (2020) Chiller Room Secrets: the stories behind the Australian meat industry's quest for perfection | Podcast on Spotify
https://open.spotify.com/episode/6p4nCaZ0qzbjqwdKyFFguc?si=nEkixkYCSSWJchW4V4x3Kw&nd=1

Other -Website articles

https://www.stuff.co.nz/business/farming/87236538/lambs-with-low-fat-and-high-breeding-values-make-for-poor-eating

https://www.nzsap.org/proceedings/intramuscular-fat-content-new-zealand-lamb-m-longissimus-lumborum

https://www.youtube.com/watch?v=43VUaknOayI&t=606s

https://www.alliance.co.nz/news/2020/10/handpicked-lamb-announcement/

https://www.mpi.govt.nz/funding-rural-support/primary-growth-partnerships-pgps/current-pgp-programmes/omega-lamb/

https://www.stockjournal.com.au/story/6419668/huge-opportunity-to-breed-wagyu-of-sheep/

https://www.foodbeast.com/news/wagyu-beef-lamb-trying-save-environment/