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Development proposal for Velocity of Sound (VOS) marbling probe (Proof of concept)

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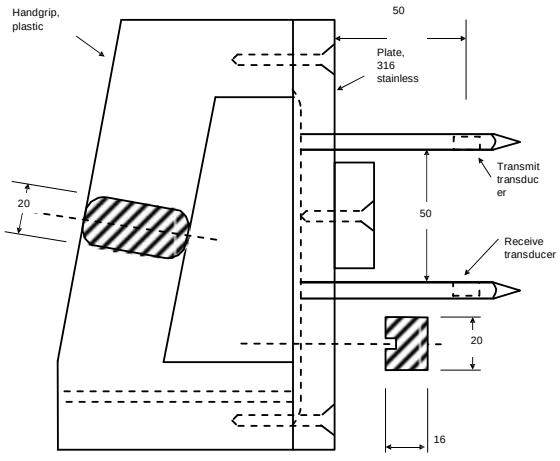
Abstract

There is increasing emphasis to measure and grade the hot carcass. Whilst marbling can be measured using both subjective and objective methodologies on the cold carcass, measurement on the hot carcass provides a challenge as the fat has not solidified and is not visible.

The technique known as velocity of sound (VOS) provides a possible technique by which to measure marbling objectively on both the cold and hot carcass. A hand-held ultrasound penetration probe was constructed for VOS testing of beef samples in laboratory conditions. VOS measurements at 30□C predicted IMF with a residual standard deviation of 2.4% fat (r=0.85). The predictive value of VOS was better at 30□C that the two lower temperatures tested (15□C and 2□C).

The measuring equipment for VOS consisted of an adjustable, U-shaped calipers like device, the free extremities of which house a transmitting and a receiving transducer opposite each other and directly in line (see Fig 1 below. The precision of alignment and the rigidity of the clamp are critical for the accuracy of measurements. Upon initiation, the electronic system automatically measures the time that a pulse of ultrasound takes to travel through the carcass from one transducer to the other and determines the inter-transducer distance. It then computes and displays the speed of transmission.

This research proposes to develop and evaluate a prototype unit for measuring meat quality traits including marbling using Velocity of Sound Technology. The proof-of-concept prototype VOS device now could be developed to the next stage, incorporating multiple transducers, a temperature sensor and real-time processing/display of the result. VOS therefore provides a possible tool to objectively measure marbling in both the cold and hot carcase.



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1 Background

There is increasing emphasis to measure and grade the hot carcass. Whilst marbling can be measured using both subjective (marble score) or objective (video image analysis) methodologies on the cold carcass, measurement on the hot carcass provides a challenge as the fat has not solidified and is not visible.

The technique known as *Velocity of Sound* (VOS) provides a possible technique by which to measure marbling objectively on both the cold and hot carcass. The VOS for muscle is different to fat. An electronic system automatically measures the time that a pulse of ultrasound takes to travel through the material from one transducer to the other. Using the inter-transducer distance, it then computes the speed of transmission and then the fat content as an indication of marbling.

Previous research shows that measurements of the speed of ultrasound transmission through the soft tissues of beef sides are good predictors of per cent lean meat (Miles, et al. 1990). The velocity of sound method has also been used for determination of fish lipid content (Shannon et al. 2004). The speed of ultrasound is a function of the temperature of the medium being measured and whilst this poses a potential problem for development of the technique, if it can be accurately recorded at the time of measurement appropriate correction factors may be calculated.

Park et al. (1994) examined the accuracy of VOS to predict intramuscular fat % and marbling scores in beef. They only tested product at room temperature but showed that VOS predicted intramuscular fat with 90% accuracy in samples with more than 8% fat and 76% accuracy in samples with less than 8% fat. Correlations between intramuscular fat % and visual marbling scores were lower than the VOS.

There is increasing emphasis to measure and grade the hot carcass. Whilst marbling can be measured using both subjective or objective methodologies on the cold carcass, measurement on the hot carcass provides a challenge as the fat has not solidified and is not visible.

The technique known as velocity of sound (VOS) provides a possible technique by which to measure marbling objectively on both the cold and hot carcass. The use of VOS was pioneered for use on meat animals by Miles and Fursery (Miles and Fursey 1974). The measuring equipment for VOS consisted of an adjustable, U-shaped calipers like device, the free extremities of which house a transmitting and a receiving transducer opposite each other and directly in line. The precision of alignment and the rigidity of the clamp are critical for the accuracy of measurements. Upon initiation, the electronic system automatically measures the time that a pulse of ultrasound takes to travel through the carcass from one transducer to the other and determines the inter-transducer distance. It then computes and displays the speed of transmission (Miles et al. 1987).

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2 Project Objectives

To develop and test the performance of an ultrasonic velocity of sound (VOS) penetration probe to operate under laboratory conditions. The probe is to predict the intramuscular fat of beef longissimus dorsi muscles as an objective indicator of marbling.

3 Methodology

A hand-held ultrasound penetration probe and the associated electronics was constructed. Measurement data was collected on a laptop computer for post-processing and statistical analysis.

One very lean cube roll sample was tested at various temperatures in order to estimate the VOS-temperature correction for muscle. Similarly, one sample of “Supafry” blended animal fat was tested to estimate the correction for fat.

A total of 22 striploin samples were collected from striploins collected from medium to long fed cattle slaughtered at John Dee Pty Ltd. The cattle were finished in feedlots at Rangers Valley and Yarrenbrook. Prior to collecting samples the sides were assessed for their marbling grade. The stripoins were vacuum packed and transported chilled to Armidale on the day of boning. These samples were stored at 0□C and tested the following day to minimise any changes in muscle structure and subsequent ultrasound properties with ageing.

Each striploin was cut into three portions, which were then placed in a plastic bag and allocated for testing at one of three different temperatures. The portions were placed in a corresponding water bath at 2□C, 15□C or 30□C to equilibrate. After at least 2 hours in the water bath, portions were removed and the probe stabbed into the meat for a VOS reading.

The ultrasound probe was calibrated with a measurement in the water bath prior to testing. VOS measurements were made in a medial-lateral direction penetrating from the superficial surface. Three measurement locations were made at ca. 20 mm spacing and a 3 penetration depths (30, 40 and 50 mm) ie a total of 9 measurements per sample. The deep tissue temperature was measured with a thermocouple probe. A 50x50 mm section of tissue was then cut out between the probe penetration marks with a depth range of 20 to 60 mm and minced and sampled for chemical fat determination.

Percentage of intramuscular fat in the meat was determined by solvent extraction of the fat from freeze dried samples of known weight (ca. 10g). The solvent used was chloroform, with an extraction time of ca. 48 hours (24 to 26 refluxes). Percent fat was calculated from the difference in initial and final sample weight, expressed as a percentage of pre-extraction wet weight (pre-extraction dry weight multiplied by moisture proportion of initial freeze-dried sample).

4 Results

4.1 VOS vs temperature in lean muscle

The measured VOS on 1 muscle (lean cube roll) sample progressively heated from 5□C is shown in Figure 1. VOS was found to increase with temperature. This quadratic best fit relationship was used to correct for temperature in the following striploin VOS measurements.

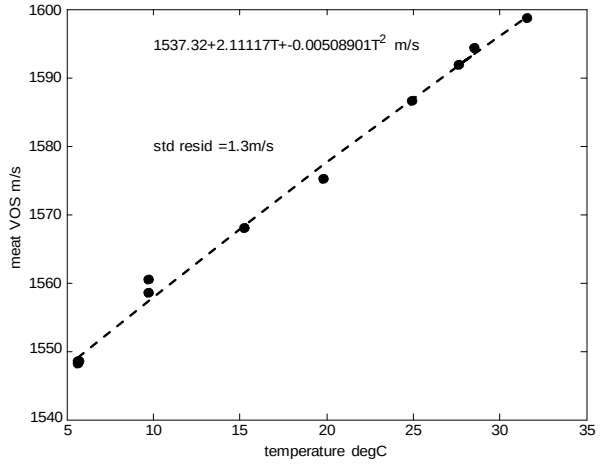

Figure 1 Measured VOS in muscle sample (dots) with quadratic best fit (dashed)

4.2 VOS vs temperature in fat (Supafry)

Measured VOS in "Supafry" from 2□C to 50□C is shown in Figure 2. VOS was found to decrease with temperature (which is opposite to muscle). Less than 20□C where the fat was solid there was little relationship between temperature and VOS. Between 22 and 30□C the fat was seen to be partly solid and partly liquid, while it was fully melted above 30□C. The VOS was found to be significantly lower for liquid. The attenuation of the ultrasound signal passing through the fat sample was found to vary greatly with temperature.

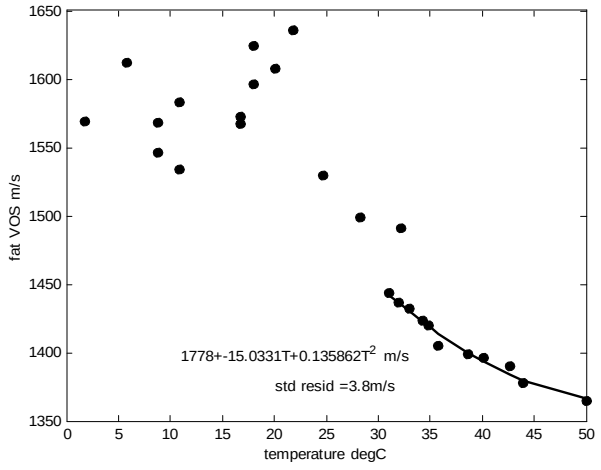

Figure 2 Measured VOS in fat (dots) with quadratic best fit (line) to the "liquid fat" data points

Indeed, the attenuation below 22□C was more than 500 times that at 40□C and was so great that no reliable ultrasound measurements could be made with the equipment.
The ultrasound signal needs to be above ca. 0.3mV to be measurable with the equipment used. Higher amplitude signals are measured more precisely. Figure 3 shows the ultrasound signal level is below the equipment's minimum sensitivity of 0.3mV at lower temperatures. A quadratic best fit based on data above 30□C was used to correct for temperature in the following striploin VOS measurements.

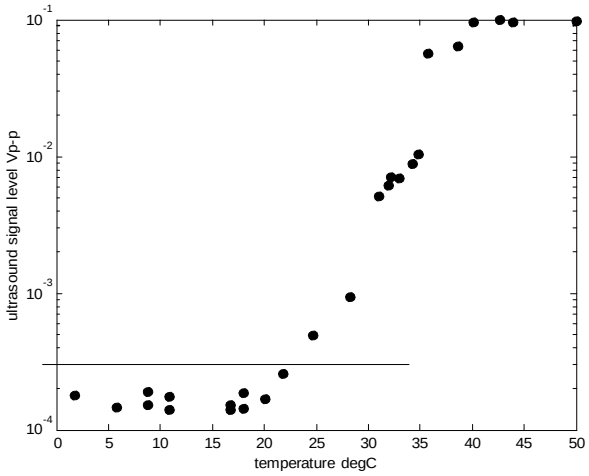

Figure 3 Ultrasound signal level (volts) at the receiving transducer for fat at various temperatures. Signal levels below the line are too low for VOS.

4.3 VOS *vs* intramuscular fat in striploins

The 9 VOS measurements made on each portion (3 depths x 3 locations) were averaged. The averaging was weighted by the received ultrasound signal level. A linear regression between the VOS and the intramuscular fat (IMF) content from chemical extraction was preformed to find the prediction equation.

4.3.1 Summary statistics

	mean	sd	range
IM Fat %	10.5	4.0	4.0 — 19.3
Marbling score (1 to 12)	3.3	1.6	0.5 — 6.0

Intramuscular fat content showed a 5 fold range in the 22 striploins sampled.

4.3.2 Prediction of IMFAT% using VOS in striploins at 30□C

Result for samples tested at 30□C are shown in Figure 4. The correlation was r=0.85. The residual standard deviation of the predicted fat content was 2.4 percentage points, ie 66% of the data lay within + or – 2.4% units of the true value.

At the 30□C temperature treatment there was a small variation in sample temperature (25 to 30°C), although when temperature was included in the prediction equation it did not significantly improve prediction accuracy

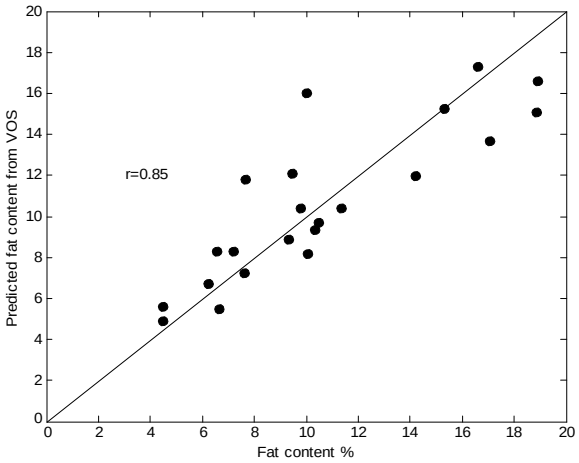

Figure 4 Predicted fat content from averaged VOS data at 30□C *vs* IMF. n=22

4.3.3 Prediction of IMFAT% using VOS in striploins at 15□C

At 15□C the correlation between VOS and intramuscular fat % was very poor: (r=0.14 Figure 5). The VOS technique relies on there being a difference in ultrasound velocity between muscle and fat. Figure 1 and Figure 2 show that, while there is a difference at 30□C, the difference diminishes to zero around 15-20□C. Consequently, VOS could not predict intramuscular fat content at this temperature.

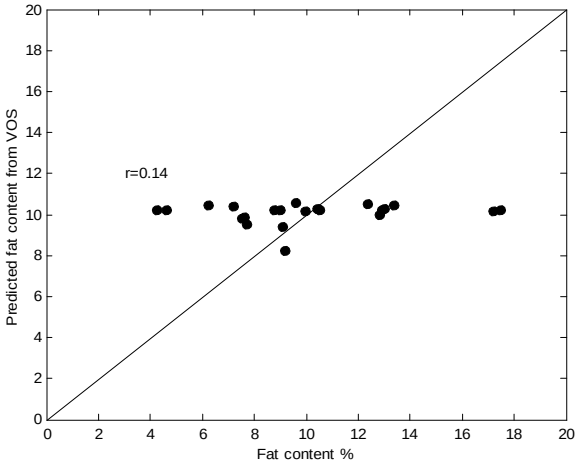

Figure 5 Predicted fat content from averaged VOS data at 15□C *vs* IMF. n=22

4.3.4 Prediction of IMFAT% using VOS in striploins at 2□C

At 2□C the correlation between VOS and intramuscular fat % was higher than at 15°C but not as high as at 30°C (r=0.69 Figure 6). There appeared to be a significant difference in VOS between muscle and fat at this temperature so VOS had some predictive value for fat content. Attenuation of the ultrasound signal was higher at this temperature and the measurements were noisier. VOS appeared to work better at 30□□than at either of the lower temperatures tested.

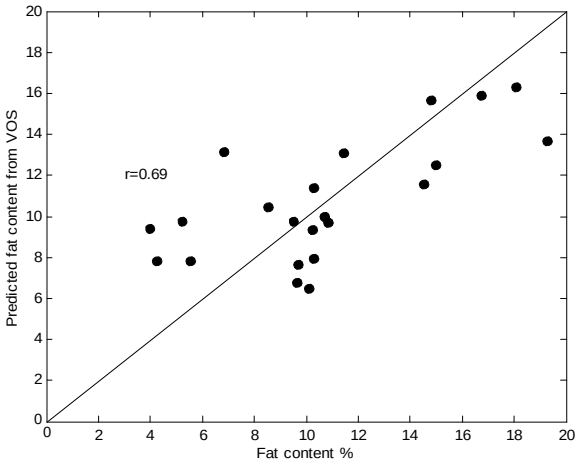

Figure 6 Predicted fat content from averaged VOS data at 2□C *vs* IMF. n=22

4.4 Marbling *vs* intramuscular fat in striploins

The relationship between the assessor's marbling score and IMF is shown in Figure 7. Each sample was assessed once for marbling prior to being divided into 3 portions for testing. Consequently there are 3 IMF results for each marbling score. The correlation was r=0.86 similar to that schieved using the VOS probe. The three repeated IMF measurements within the a sample had a standard deviation of 1.2 percentage points. This indicated the degree of inherent variation in the fat distribution through the striploin samples.

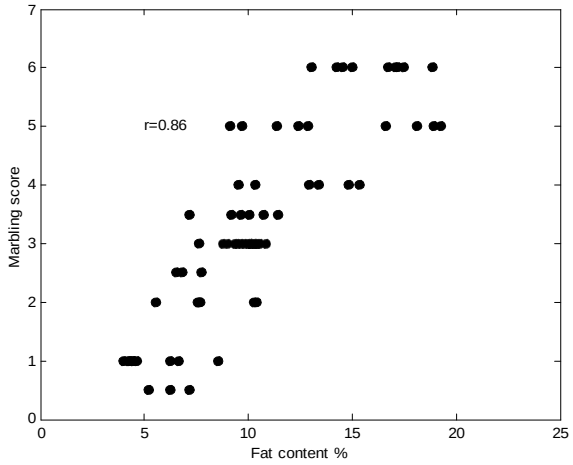

Figure 7 Marbling score *vs* IMF.

5 Discussion

5.1 Prediction of Intramuscular fat

The prototype VOS probe was found to have a high relationship with intramuscular fat when measured at a meat temperature of ca. 30□C. If VOS was to be further developed for assessment in a meatworks, it should be applied to the hot carcass on the production line.

5.2 Coupling

It was found that no coupling liquid was required as there was enough free liquid in the meat to provide coupling. It is common practice to apply some type of liquid to ultrasound transducers to improve the ultrasound coupling into the material being tested but this was not needed which rather simplifies the design and avoids concerns about contamination of the meat by a coupling liquid.

5.3 Probe Scaling

The size of the probe spikes used in the prototype (9x6mm cross-section stainless steel) was a compromise which turned out to be satisfactory. The spikes needs to be large enough to house the transducers and remain straight when forced into the meat but, if they were too large, they would damage the meat and require too much hand force. The size was mainly dictated by the transducers used (which were custom-made to be smaller than those generally available). The amount of hand force required to push the probe into the meat samples seemed reasonable.

5.4 Sample Volume

A single VOS measurement was clearly inadequate. In this experiment each sample portion was measured for VOS 9 times. The individual measurements showed a high degree of variation as seen in Figure 8. There appeared to be two sources of variation: sampling and instrument effects. Intramuscular fat was not uniformly distributed through the portion and the VOS probe measurements were confined to a relatively small sample between the transducer faces (effectively a cylinder of meat 50mm long and 5mm diameter).

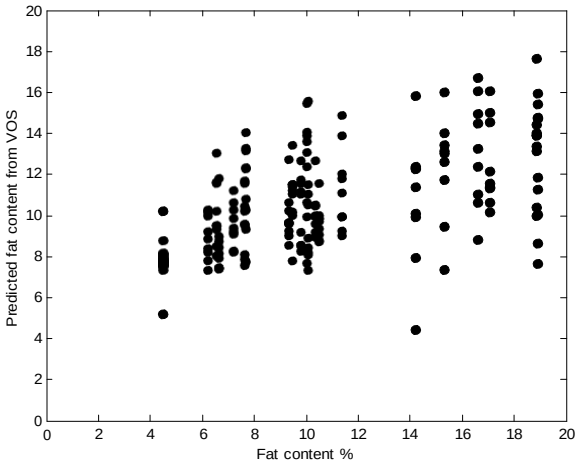

Figure 8 Predicted fat content from VOS data at 30□C (without averaging) *vs* the fat content from chemical extraction

Clearly sampling is an issue that needs to be addressed in developing the VOS probe as the amount of fat will vary significantly as the probe is moved. Secondly, the VOS instrument has some measurement variation, the largest source being estimating the arrival time of the ultrasound.

These results indicate that averaging a number of VOS readings over a volume is essential for a representative reading and averaging more than the 9 used in this experiment is now advised. Each VOS reading took 0.32 sec (and this could be reduced with little effort). If the technology was to be further developed the question of both filtering the data for abnormally low signals and the number of repeated measurements to reduce sampling error needs to be addressed.

It is interesting to speculate as to the reason for variability in the quality of the ultrasound signal over an above the issue of variation in intramuscular fat within the muscle sample. For every insertion there were some poor signals collected. Signal quality was not simply addressed by slightly moving the probe or twisting it to improve contact, rather if the initial quality of the signal was poor it generally improved as the probe was inserted further into the muscle. This suggests that the poor quality of the VOS signal may be a function of muscle structure, perhaps fibrous tissue at various locations in the muscle.

This suggests that a commercial probe may use a combination of filtering and multiple measurements to improve signal quality.

It is possible that insertion and twisting of the probe as it is inserted in the meat may cause deflection of the ultrasound signal and contribute to the signal noise. However the probe was constructed in stainless steel and so this was an unlikely source of error.

5.5 Measurement Direction

VOS in muscle is known to be different when measured parallel vs. perpendicular to the fibre direction so the measurement angle can be a source of error. VOS measurements in this study were made in a medial-lateral direction so that the ultrasound beam should be perpendicular to the fibre direction (which generally lie in a sagittal plane). No effort was made to control or verify this on each sample so the experiment simulated realistic conditions with a carcass.

6 Industry Impact of this Research

Accurate measurement of marbling is critical to accurate classification of beef product. Incorrectly grading product could result in significant downgrading of product and significantly affects a meat processing business's profitability. Marbling classification is currently conducted by trained carcase graders, and the set point of fat of 7 degrees Celsius and below is a requirement to ensure the marbling has solidified and permitting accurate grading. We know that marbling is easier to grade the colder the meat is. An objective method, such as VOS marbling probe, may assist the meat grader in accurately classifying carcases and product. When a successful device can be developed, more accurate classification of product (irrespective of temperature) will provide more versatility for when carcase grading and measurement can occur. Carcase evaluations including MSA evaluations will benefit from such objective measures. Therefore, VOS technology provides a possible tool to objectively measure marbling in both the cold and hot carcass.

7 Conclusions

- VOS predicted the intramuscular fat content of beef striploins with a correlation of r=0.85 and rsd=2.4 percentage points of fat. This correlation was similar to that between marbling score and IMF (r=0.86).
- The rsd was higher than the target for this stage of the project which was ±1.0 % intramuscular fat.
- VOS measurements should be made above 30□C (so that the fat is liquid). The accuracy will be degraded if the fat has solidified.
- At least 9 repeated VOS measurements are required.
- VOS measurements should be made in a medial-lateral direction.
- The existing prototype VOS probe can test about 10 samples per hour. That number could be increased threefold if the probe housed a number of transducers along the two shafts thereby testing a range of depths simultaneously. If the transducers were closely spaced, the sampling volume could be increased which should improve accuracy.
- Meat temperature has to be measured for VOS. It is likely that either a thermocouple or an infrared thermometer integrated into the ultrasound probe would be both fast and accurate enough.
- A real-time “signal level” indication would assist the operator obtain reliable measurements.

8 Recommendations

- The proof-of-concept prototype VOS device may be developed to the next stage incorporating multiple transducers, a temperature sensor and real-time processing/display of the result.
- The new version VOS probe be tested and verified in laboratory conditions using striploins.
- The new version VOS prove be tested under controlled conditions in a meatworks.

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Appendices

10 Appendix 1 - Ultrasound Probe

A1.1 Probe Specification

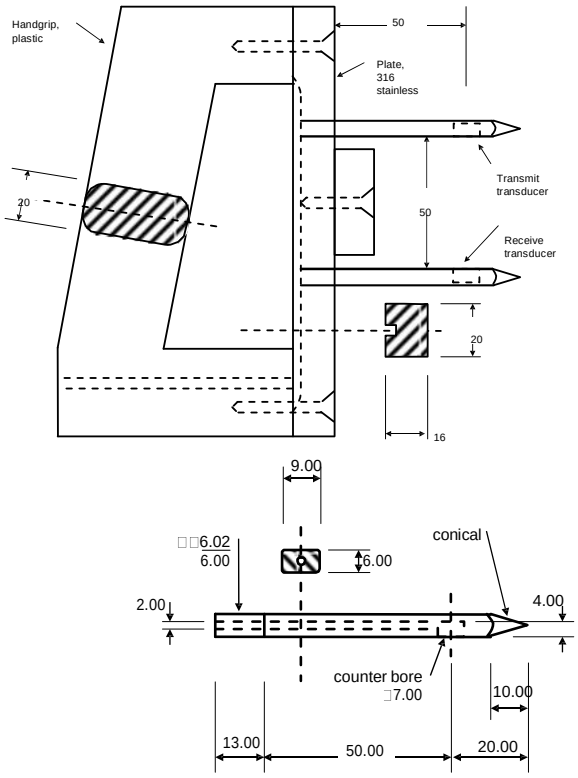

Figure 9 VOS Probe Details

A1.2 Probe Measurements

Transducer spacing	49.8 mm	nominally 50 mm
Mechanical Compliance	100 kN/m	between transducer faces

A1.3 Ultrasound Transducer Specification

Ultrasound transducer type	SAHT-5.0-5-P-DRL.1	Piezo Technologies
Vibration mode	Compression	
Active element diameter	5.0mm	
Housing diameter	6.0 – 7.0mm	
Focal Zone	0 – 60mm	
Ultrasound centre frequency	5 MHz	

A1.4 Ultrasound Transducer Measurements

Housing diameter	7.0mm	
Transmitter pulse amplitude	-150 volts	
Transmitter pulse width	120 ns	
Ultrasound centre frequency	5 MHz	

A1.5 Versions

Oscilloscope	Tektronix TDS310	SN B031188
Matlab	Ver 6.0.0.88	Release 12
VOS Matlab software	Ver 2.0	
Pulse driver design	Ver 1.1	
Logic design firmware	Ver 2.0	

11 Appendix A2 - How VOS works

A2.1 Overview

The velocity of sound (VOS) equipment measures the volume fraction of fat in the sample between two ultrasound transducers. An ultrasound pulse travels faster in lean muscle that in fat. In a mixture, the velocity will be somewhere in between these limits depending on the volume fraction of fat and muscle.

A2.2 VOS vs Fat

The velocity in the sample v_s is related to the velocity in fat v_f, in muscle v_m and the volume concentration of fat □:

$$v^{-1} = \square_s v_f^{-1} + (1-\square_m) v^{-1}$$

The mass concentration of fat □□is related to □□and the densities by:

$$\square\square = \frac{\square\square_f}{(1-\square\square\square_m)\square\square\square_f}$$

A2.3 VOS measurement

If the geometric path length between the transducers is x then the time and velocity are related by

$$v = \frac{x}{t}$$

The measured time consists of the time taken for the ultrasound to travel from one transducer to the other plus additional time associated with propagation in the cables, in acoustic impedance matching layers, in the transducers themselves and in the processing electronics and triggering the recording oscilloscope. Grouping all of these factors together as a "time offset" t_o, then for the sample being measured at a temperature T_s:

$$v_s(T_s) = \frac{x}{t_s - t_o}$$

For calibration, we place the probe in water for which:

$$v_w(T_w) = \frac{x}{t_w - t_o}$$

The ultrasound velocity in water varies with temperature T[□C] as follows [Bilaniuk 1993]

$$v_w(T) = 1.40238742 \times 10^{3} + 5.03821344\,T - 5.80539349 \times 10^{-2}\,T^{2} + 3.32000870 \times 10^{-4}\,T^{3} - 1.44537900 \times 10^{-6}\,T^{4} + 2.99402365 \times 10^{-9}\,T^{5}$$

At 20□C this evaluates to 1482.364 m.s^{-1} or 0.674598 □s/mm

Putting these together we have the velocity in the sample

$$v_s^{-1} \square T_s \quad \square t \quad \square T_w \square$$

$$\square\square\square \quad \frac{1}{x} \square\square v_w$$

wher
e

$$\square t \ \square\square t_s \square T_s$$

$$\square\square\square\square t_w \square T_w \square$$

Therefore we measure the change in arrival time for the ultrasound pulse when passing through the sample as compared to a water path.

The problem is to determine the arrival time of a pulse 4□s long to an accuracy of 0.02□s even when the shape of the pulse is distorted. The distortion arises from the ultrasound signal passing through multiple parallel paths in the meat. The signal analysis must be robust under these circumstances. Five methods were trialled:

- phase shift
- time of centroid of the signal energy
- time of the first cross over a threshold
- time of the peak
- time of the peak of the analytic signal

Of these, the first 3 were found to be better than the others but all gave rise to some outlying VOS results. The simple average of the first 3 methods was finally used.

A2.4 Empirical Equations

The temperature correction for VOS in lean muscle from a quadratic best fit was found to be

$$v_m = 1537 + 2.111T - 0.005089T^2$$

and for fat

$$v_f = 1778 - 15.0331T + 0.135862T^2$$

The relationship between the concentration of fat □□from VOS and IMF was found to be

$$IMF = 6.8 + 0.293\square$$

Units are:

T	□C
v_m v_f	m/s
□, IMF	% by mass

A2.5 Equipment description

Electrical pulses produced by the Pulse Generator are fed to the ultrasound probe handpiece transmitting transducer. The Pulse Generator consists of an Altera UP2 development board programmed in VHDL (Figure 13) and a custom high voltage pulse generator (Figure 12). The transducer emits an ultrasound pulse that passes through the sample being tested to the receiving

transducer where it produces an electrical voltage. The voltage is amplified and digitised by an oscilloscope and the resulting waveform data transferred to a PC for logging and post processing. The oscilloscope sampling is synchronised by a trigger pulse from the pulse generator. A thermocouple probe measures the sample's temperature. Custom control software (in MATLAB)

allowed the user to capture the ultrasound waveforms along with the body number, marbling score and test temperature.

Further custom software (also in MATLAB) was used to post-process the acquired data to obtain the VOS values and correlate them with intramuscular fat.

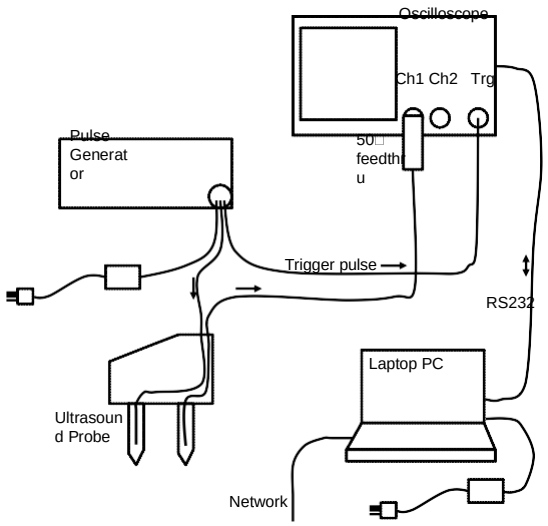

Figure 10 Test set up wiring diagram

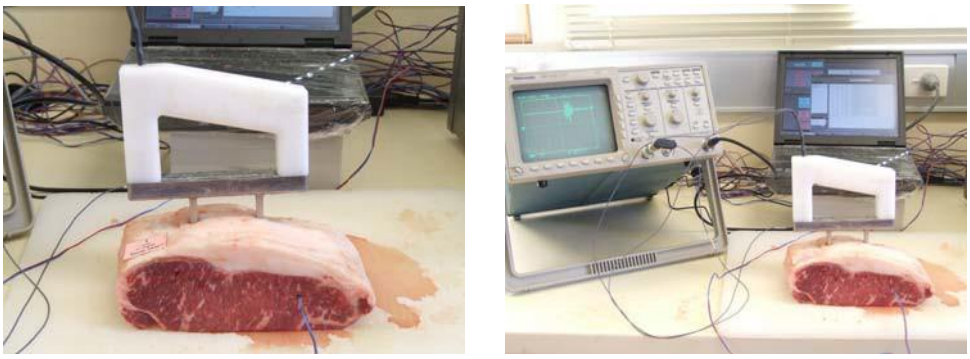

Figure 11 Test set up

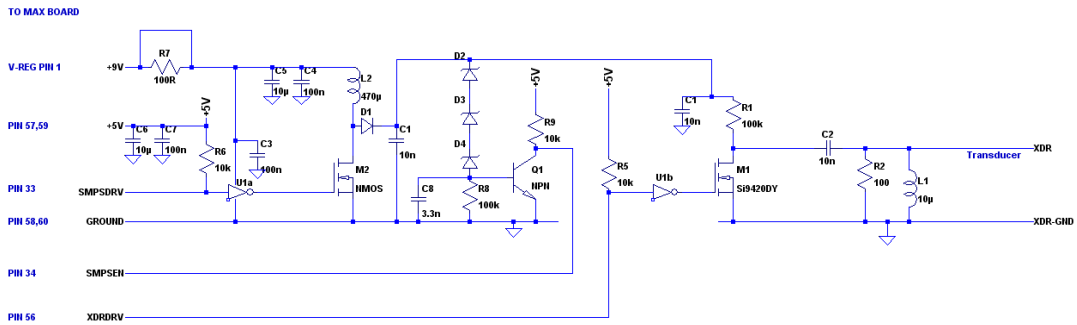

Figure 12 High voltage pulse generator circuit diagram

```
-- VOS pulse generator for Altera UP2 board
-- (c) Ron Bradbury 2006
--
-- clocked from 25.175MHz osc on board
-- 1 tick = 39.722ns
-- divides freq by 251750 = 100.00Hz
-- and has delayed output to trigger scope
-- pulsedrv pulse width is trimmed to match transducer centre freq

-- tell compiler to read some definitions from these files
LIBRARY IEEE;
USE IEEE.STD_LOGIC_1164.all;
USE IEEE.STD_LOGIC_ARITH.all;
USE IEEE.STD_LOGIC_UNSIGNED.all;

-- define inputs and outputs
ENTITY pulse IS
	PORT
	(
		xtalosc:    IN STD_LOGIC; -- on-board xtal oscillator, PGT
		scopetrig:  OUT STD_LOGIC;		-- scope trigger pulse, PGT
		pulsedrv:   OUT STD_LOGIC;		-- drive pulse for transmitting transducer, active '0'
		smpsenable: IN STD_LOGIC;		-- enable switching power supply, active '1'
		smpsdrv:    OUT STD_LOGIC;		-- drive pulse for dv dc switching power supply, active '0'

		dig1sega: OUT STD_LOGIC;
		dig1segb: OUT STD_LOGIC;
		dig1segc: OUT STD_LOGIC;
		dig1segd: OUT STD_LOGIC;
		dig1sege: OUT STD_LOGIC;
		dig1segf: OUT STD_LOGIC;
		dig1segg: OUT STD_LOGIC;
		dig1segp: OUT STD_LOGIC;
		dig2sega: OUT STD_LOGIC;
		dig2segb: OUT STD_LOGIC;
		dig2segc: OUT STD_LOGIC;
		dig2segd: OUT STD_LOGIC;
		dig2sege: OUT STD_LOGIC;
		dig2segf: OUT STD_LOGIC;
		dig2segg: OUT STD_LOGIC;
		dig2segp: OUT STD_LOGIC
	);
END pulse;

ARCHITECTURE pulse_a OF pulse IS
	-- a 18-bit counter is enough for about 10.41ms cycle timing
	SIGNAL count: STD_LOGIC_VECTOR(17 DOWNTO 0);
	SIGNAL smpsenlatch: STD_LOGIC;

BEGIN
	-- turn 7-seg displays off
	dig1sega <= '1';
	dig1segb <= '1';
	dig1segc <= '1';
	dig1segd <= '1';
	dig1sege <= '1';
	dig1segf <= '1';
	dig1segg <= '1';
	dig1segp <= '1';
	dig2sega <= '1';
	dig2segb <= '1';
	dig2segc <= '1';
	dig2segd <= '1';
```

```
		dig2sege <= '1';
		dig2segf <= '1';
		dig2segg <= '1';
		dig2segp <= '1';

		PROCESS(xtalosc)
		BEGIN
			-- on rising edge of clock
			IF xtalosc'EVENT AND xtalosc = '1' THEN
				-- increment the count and wrap to zero each 10 msec
				-- 251750 pulses = 10 msec
				IF count < 251749 THEN
					count <= count + 1;
				ELSE
					count <= "0000000000000000";
				END IF;

				IF count < 3 THEN		-- PW is about 40ns x number
					pulsedrv <= '0';
				ELSE
					pulsedrv <= '1';
				END IF;

				IF count >= 512 AND count < 2048 THEN
					scopetrig <= '1';
				ELSE
					scopetrig <= '0';
				END IF;

				IF count(7 downto 0) = "11111111" THEN
					smpsenlatch <= smpsenable;
				END IF;

				IF count >= 2048 AND count < (251750-2048) AND smpsenlatch = '1' THEN
					smpsdrv <= count(7);
				ELSE
					smpsdrv <= '1';
				END IF;

			END IF;
		END PROCESS;

END pulse_a;
```

Figure 13 Altera UP2 development board VHDL programming

A2.6 Ultrasound Measurement Equipment Set up

Sample rate	50 Msamples/s	
Sample interval	20 ns	
Sample signal length	20 □s	
Waveforms averaged	32	
Sampling resolution (before averaging)	0.08mV	at highest sensitivity

A2.7 Example waveforms

The waveform of the ultrasound pulse after passing through 50mm of water is shown in Figure 14. The pulse extends for about 4 □s and each cycle is about 0.2 □s. VOS in water is determined from the arrival time of the ultrasound pulse, the time from the transmission of the pulse to the start of the recording and the distance between the transducer faces.

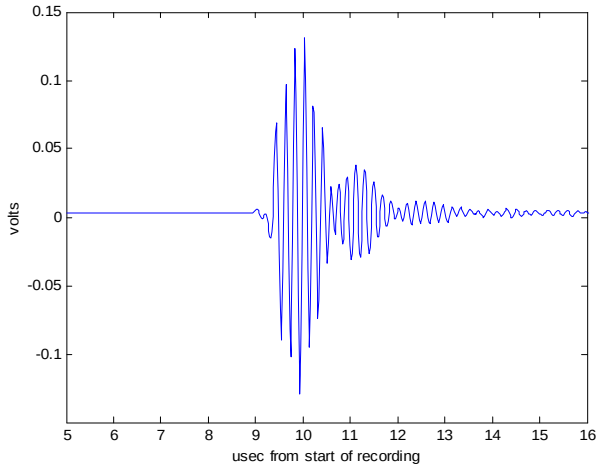

Figure 14 Typical ultrasound pulse waveform for water

The waveform after passing through 50mm meat sample is shown in Figure 15. The pulse is shifted to the left because the ultrasound propagation velocity is higher on meat than water so the pulse arrives earlier. It is also attenuated in amplitude and distorted in shape. VOS in meat is determined by measuring the shift in arrival time compared to the corresponding water-path measurement.

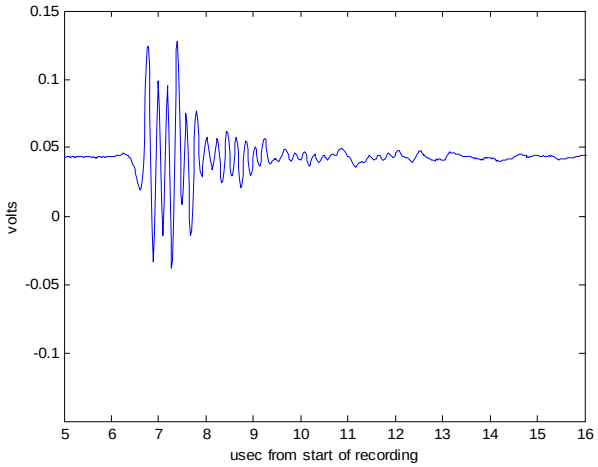

Figure 15 Typical ultrasound pulse waveform for meat