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The potential of using very fast chilling systems for processing red meat [150.11D]

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1 Executive Summary

A study was done to investigate the potential of using "very fast chilling" (VFC) to process red meat in Australia. This study consisted of two components; a literature review and a pilot experiment using a tunnel system currently in commercial use for chilling grapes.

1.1 Literature review

- VFC is defined broadly in the literature as the core temperature of meat reaching a temperature in the range of -2 to 0^{o}C within 5h of slaughter. This can be achieved using either liquid immersion or air chilling systems but requires meat thickness to be less than 8cm. Hence VFC can be done in the carcase form for lamb and not for beef unless hot boned.

- Optimal refrigeration settings for VFC are a balance between energy costs, carcass shrink and eating quality. Evidence in the literature suggests that air temperature should be less than -10^{o}C, humidity about 90%, air speed 1.5 m/s, and duration less than 3 h, for an optimal air chill VFC system. For immersion systems the immersion medium should have a temperature of less than -2^{o}C and duration 5-8h.

- An identified benefit of VFC is a reduction in carcass shrink (from 2% to 1%). However it was not clear that this benefit would necessarily translate in to an increase in meat yield hence greater financial value once the carcase has been processed further.

- Economic analyses have shown that VFC increases energy and capital requirements compared to conventional chilling (CC) but these costs are generally outweighed by the financial value of an increased carcass weight due to VFC. Reductions in processing time (from 48h to 24h) and chiller space are potential benefits but were less clearly quantified.

- Eating quality studies have focussed on the effect of VFC on tenderness and less information was available on other quality issues. VFC results in a rate of pH by temperature decline that is well outside of the range considered optimal under CC conditions. Colour stability and shelf life is a proven benefit of VFC with horticultural produce and probably for meat as well.

- Different studies have demonstrated that meat from VFC can be as tender as meat from CC. However a lack of consistency in results remains a concern and may account in part for VFC not being adopted by the European red meat industry. The two tenderness mechanisms that research has focussed on are prevention of cold shortening and accelerated proteolysis.

- Cold shortening appears to be a certain outcome with VFC unless some intervention to control sarcomere length is implemented. Surface freezing has been proposed as a restraint method to prevent cold shortening, and proof exists that this can be effective. However the effect of sarcomere shortening on tenderness was found by different authors to be variable and perhaps overstated.

- An increase in the rate of proteolysis early in the post-mortem period (accelerated proteolysis) has been attributed to high pH and high calcium concentrations induced by VFC early in the chilling period. However results have been inconsistent and further understanding is required to manipulate this effect predictably. Optimal management of animal selection, cuts, boning,

conditioning time, and marketing to be used in conjunction with VFC remains a large area of uncertainty. These factors contribute to variation in eating quality for VFC as they do with CC.

- The conclusion was made that VFC presents an opportunity to reduce shrink loss, processing time and ageing time hence the cost of processing quality red meat in Australia.

- The potential value of using VFC to improve eating quality and or shelf life is not proven in a commercial sense but remains of central interest. Accelerated proteolysis combined with control of shortening could potentially produce a tenderer product from VFC than from CC. Maintaining eating quality in the range expected from CC should at least be a part of any future research into using VFC to reduce costs because of the potential for severe cold shortening.

- Further research and development is recommended before commercialisation of VFC is considered. There was evidence in the literature that VFC can potentially be used to reduce processing time and at the same time improve or at least maintain meat eating quality. However the method to do this predictably under various market scenarios was not clearly described in the literature. Elucidating such a method presents an on opportunity for further research in VFC.

1.2 Pilot Experiment

- A pilot experiment was conducted using the Pandura Tunnel Chiller (PTC). The temperature profile of 6 lamb carcases was recorded for several hours post slaughter. As well as temperature various eating quality measurements were made immediately after VFC and again later after conditioning at 1.7^{o}C.

- Muscle temperature monitoring confirmed that VFC was possible for lamb carcases cooled with this air based cooling tunnel. The VFC rate, i.e. 0^{o}C in 5 hours, was achieved in deep muscle across the carcase in the loin, leg and shoulder, albeit at slightly different rates in each of these regions.

- Several observations were made in relation to eating quality. However further experimentation is required to confirm these observations given the limited nature of the pilot experiment.

- The pH of meat was relatively high (>6) at the end of the VFC period, although fell to levels expected for ultimate pH at 24h post slaughter. High pH in combination with high calcium concentration induced by low temperature early in the post-mortem period is thought to favour accelerated tenderisation. High pH when temperature is low also raises questions about how to estimate the time of rigor after VFC prior to deboning.

- Sarcomere shortening occurred but was not severe. A novel finding was that in two carcases sarcomere length of loin meat appeared to increase following VFC. Again this raises questions about the biochemical processes that accelerate tenderisation as well as the timing of rigor in relation to pH and temperature profiles that occur with VFC.

- The PTC was able to produce meat of acceptable eating quality but the refrigeration settings required to replicate good results needs further investigation. Taste panellists noted that the meat was very juicy, a character that is particularly important for lamb.

- In agreement with the taste panel assessment, shear force measurements indicated the unit was able to produce meat of acceptable tenderness after a minimal ageing period. Further improvement is likely with a longer ageing period.

- Consistent with the findings of other VFC studies the meat was slightly dark in colour having a value just below the target acceptable to consumers.

1.3 Future Research

Key areas identified for further research include:

- The potential use of VFC to reduce processing time (including ageing) and energy costs under different market scenarios (domestic vs export)

- The physical nature of carcass shrink loss and the effect of VFC on meat yield under different deboning scenarios.

- Further definition of the optimal rate of pH and temperature decline needed to induce accelerated tenderisation under VFC.

- Definition of the conditioning period including its role, length of duration, temperature and humidity that is complimentary to a VFC regime.

- The role of electrical stimulation with VFC in relation to the optimal rate of pH decline to prevent cold shortening and to optimise protease activity

- The expected changes with time in key biochemical (calcium concentration, osmotic pressure, pH, calpain activity, caspase activity) and biophysical (rigor, shortening) parameters for the purpose of optimising tenderness under VFC for different muscle groups and boning systems.

- Identification of commercial scenarios where the value of VFC benefits such as tenderness and shelf life are transparent to consumers.

- Animal, muscle and other sources of variation for the post-mortem activity of protease enzymes in response to VFC

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2 Background

Very fast chilling (VFC) is a relatively new method of processing meat and is defined in broad terms as reducing the temperature of muscle to -1^{o}C by 5h post-mortem (Joseph, 1996). A large concerted research effort sponsored by the European Union has shown that VFC using blast freezers can be a viable commercial alternative to conventional slow chilling. The comparative benefits of VFC include reductions in carcass shrinkage due to reduced evaporative loss, reductions in holding times and decreased chiller space requirements (Troy & Joseph, 2001).

Controlling the rate of pH post-mortem is generally considered mandatory to avoid cold shortening in red meat (Simmons *et al.*, 2006). Electronically controlled medium voltage systems are an effective way of controlling the rate of pH decline, and have been shown to reduce the variability in tenderness of lamb meat under commercial conditions in Australia (Toohey *et al.*, 2006).

Paradoxically VFC does not cause cold shortening when done correctly and a degree of super tenderisation may even occur (Sheridan, 1990; Joseph, 1996; Aalhus *et al.*, 2002; McGeehin *et al.*, 2002). Calcium release, protease activity, surface freezing and interaction with actin myosin cross bridging have been proposed as possible explanations of the mechanism for tenderisation under conditions of fast chilling (Koohmarie, 1996).

Despite positive research findings (Troy & Joseph, 2001), there is little evidence that VFC has been adopted by the red meat processing industry in either Europe or New Zealand where research has also taken place. Further investigation is therefore required to assess the potential value of VFC to the Australasian red meat industry.

Recent developments have made the evaluation of very fast chilling regimes for red meat more feasible under local conditions in Australia. Pandura Farms have developed a cooling tunnel that can chill food materials rapidly, using an air temperature of 2^{o}C rather than -30^{o}C used in the case of blast chillers. This enables rapid cooling without surface freezing and is being used commercially to process high quality table grapes in South Australia.

3 Objectives

3.1 Project aims

1. Prepare a review of the international scientific literature pertaining to VFC

2. Summarise quantitative technical findings from the literature under VFC conditions pertinent to Australasian red meat processing.

3. Conduct a preliminary investigation in to the use of the Pandura Farms tunnel chiller (PTC).

3.2 Specific aims of the Pandura tunnel pilot experiment

1. To determine whether the Pandura Tunnel Chiller system (PTC) can provide a chilling profile in lamb meat carcasses consistent with a very fast chilling regime (-1^{o}C by 5 hours).

2. To make some preliminary meat quality assessments of lamb meat chilled with the Pandura Tunnel.

4 Methods

4.1 Literature review

The worldwide scientific meat science and food engineering literature was searched. The series of three books produced by the Concerted European Action CT94-1881 formed a starting point for the literature search and provided a substantial amount of reference material.

4.2 Pandura tunnel pilot experiment

This experiment was conducted at Pandura Farms, River Rd., Merbein, Victoria.

4.2.1 Animals

Six lambs were slaughtered on site on April 11th, 2007. The lambs were of a crossbred genotype (Merino X Poll Dorset) obtained from a local producer. On April 10th, the lambs were transported for a period of 45 minutes from the farm of origin to Pandura at approximately 1600h. From arrival at 1600h until slaughter the next day, the lambs were held in a covered yard and fasted with access to water via a single water trough located in the corner of the yard.

4.2.2 Slaughter

Lambs were slaughtered and dressed one at a time (Table 1) with no electrical inputs of any type during the slaughter process. The first 5 lambs were chilled as carcases whilst for the last lamb the carcase was cut into 2 forelegs, 2 back straps and 2 hind legs immediately after dressing prior to chilling (hot boned).

4.2.3 Chilling details

The PTC consists of 6 different compartments. Under the commercial operating procedure for grapes all 6 compartments are used and grapes pass between compartments on a conveyor roller system (Henriod, 2004). However in our experiment only 3 of the 6 chiller compartments were used. Cooling began in compartment 1 and was completed in compartment 2. Compartment 3 was used as a storage cool room after the carcases were removed from compartment 2.

Another difference was that carcases were moved from one compartment to another via the viewing doors and not directly between compartments via the conveyor system. This was necessary due to the dimensions of the carcases that made direct movement difficult without modification of the tunnel. The cooling process used was therefore not entirely indicative of the grape cooling process and was not optimal in that sense.

Various configurations for carcase orientation and chiller settings were tried in the course of the experiment. The time that each carcase spent in each compartment varied (see Figures 5-20 Appendices) as did total chilling time (Table 1). Chiller settings and times varied between different carcases also. Refrigeration settings and air speed were increased from carcases 4 to 6. Carcase orientation in relation to air flow varied. Carcase 1 was placed in the PTC in a dorso-ventral orientation with the sternum resting on the chiller rollers. Carcase 2, 3, and 4 were secured to a wooden pallet. Carcass 2 was inverted when changed from compartment 1 to compartment 2 from a dorso ventral to a ventro-dorsal orientation. This was done to improve the air flow to the chest cavity and was not done for the other carcases. Carcases 3 and 4 were kept in a ventro-dorsal orientation (the back facing the pallet and floor of the PTC) for the entire chilling process. Carcase 5 was placed a ventro-dorsal orientation but with a wood rod placed inside the chest to open the chest

cavity. Grapes (6 trays) were loaded in the chiller with carcase 5 and 6 but not with carcases 1-4. This was done 10 minutes after carcase 5 had been placed into compartment 1. Temperature monitoring began after this period so the starting temperatures of carcase 5 are relatively lower as a result of this change. Carcase 5 was not attached to a pallet but a wooden rod was place in the chest cavity to keep this open (Figure 21). For carcase 6 the *m. longissimus dorsi* (LD) muscle was placed on the pallet without any physical restraint.

The PTC switched off whilst carcase 1 and 2 were being chilled presumably because the heat load from a single carcase was insufficient for the refrigeration unit to run. This was noticed at 1120h (120 minutes and 40 minutes after chilling began for carcase 1 and 2 respectively) but the actual time that switching occurred could have been some time before this.

At the end of day 1 carcases 3, 4, 5 and 6 were transferred to a cool room kept at a temperature of 1.7^{o}C

Table 1 Kill time, length of dressing period, chiller entry time and length of chilling period

Lamb	Kill time (hhmm)	Length of dressing period (mins)	Chiller entry time (hhmm)	Length of chiller period (mins)
1	0830	0:47	0917	200
2	0944	0:55	1039	220
3	1153	0:58	1251	300
4	1403	0:47	1450	230
5	1515	0:45	1600	180
6	1543	1:10	1653	120

4.2.4 Measurements

Rectal temperature was measured in the live animal with a Surgipack digital thermometer (Vega Technologies Inc China). Live weight was measured with an Avery 50kg clock face scale. Carcase weight was measured with an electronic platform scale.

Thermocouples inserted into stainless steel probes were used to measure muscle temperature. Each thermocouple was attached to a DataTaker DT500, Data Electronics, Rowville (Vic), Australia and real time temperature was recorded via a laptop computer using DeTerminal for Windows. Each thermocouple was calibrated before and after the experiment using a high accuracy certified quartz thermometer (*Quat 100*, Heraeus, Hanau, Germany) in an insulated water bath over a range of 5 to 40°C.

Two temperature probes were placed in the shoulder, loin and leg of each lamb except for carcase 6. At each muscle location one probe was located deep and one probe was located superficially. The deep probes were placed perpendicular to the muscle surface at a depth of 25-30mm. The superficial probes were inserted parallel to the muscle surface at a depth less than 5 mm. Plans to use a deeper probe (50mm) were abandoned because it was thought to be too long particularly for

the loin. For carcase 6 there were insufficient probes available to do all muscles and locations because the timing of carcase 6 overlapped with carcase 4 and 5. The probes were removed and replaced during the transfer process between compartments 1 and 2. Probes were removed and relocated when carcases were moved from one compartment to another. During these short periods of time carcase temperature was not recorded, evidence of which this can be seen in the raw data presented in Figures 5 to 20.

The pH of the LD, *m. semimembranosus* (SM) and *m. semitendinosus* (ST) was measured before and after entry to PTC and the next day (24h approximately). Muscle pH was measured using a TPS WP-80 Waterproof pH-mV-Temperature Meter (TPS Pty Ltd, 4 Jamberoo St, Springwood Brisbane, 4127, Australia). with a (Mettler Mettler-Toledo Ltd., 220 Turner Street, PO Box 173 Port Melbourne, VIC, 3207 Australia) electrode attached. Meat colour was measured with a Minolta chromometer.

Loin samples were taken after PTC and the next day for sarcomere and tenderness measurements. These samples were frozen at -10^{o}C within an hour of collection and transported to the laboratory in dry ice. Sarcomere length was measured by NSW DPI Cowra using a laser diffraction technique. Tenderness measurements were done with a MIRINZ Tenderometer at Murdoch University. Meat samples were cooked from frozen to an internal temperature of 75^{o}C prior to tenderness measurement.

An informal taste panel was performed using 10 DAFWA employees for short loin from carcases 3, 4, 5, and 6. Loins were divided into 2cm thick slices that were cooked for 2m15s on a Silex grill set at 200^{o}C. Portions were randomised before being offered to panellists. Panellists were offered 4 samples and asked to rate each sequentially for strength of odour , liking of odour, tenderness, juiciness, strength of flavour, liking of flavour, residual feel, overall liking and eating quality rating. To score each character, panellists were asked to put a mark on a scale that was 10cm in length, from very weak for 0 to very strong for 100. The length of the scale where the mark appeared was the score for each character.

4.2.5 Statistical analyses

Regression analysis was used to fit an exponential line of best fit to the combined temperature data of carcases 1, 2, 3, and 4. Data from carcase 5 and 6 were excluded because of the settings being very different to those for the first 4 carcases. Generalised analysis of variance (ANOVA) was used to compare consumer panel scores for eating quality and sarcomere lengths for different carcases. Genstat ninth edition was used to perform all statistical analyses.

5 Literature review

5.1 Background

Very fast chilling (VFC) has been the subject of research for some time and was the focus of an EU concerted action during the 1990's. Evidence was found that VFC has been tried in Australia but no specific Australian publications were found to support this. Bowater (1997) presented data in England from work done by the Riverstone Meat Company, Sydney in 1980. An anecdotal account of work in Western Australia in the 1980's was uncovered but no report.

Studies reviewed include those done to investigate VFC as a commercial outcome and others that had a more fundamental focus on the effects of very low temperature on muscle metabolism. Some of the latter were done independently of a VFC outcome but were cited when relevant to this review.

The exact origin of the VFC definition is difficult to find. It may have evolved in the process of finding ways to reduce carcass shrink losses. For example Bowater (1988-1989) alludes to removal of all of the heat from the carcass being practical within 5 hours, using an air temperature of -10^{o}C and an air speed of 2m/s. In this scenario loin temperature of a beef carcass reached 0^{o}C in about 5 hours. Such a practicality may have been a simple basis for the VFC definition.

A link to eating quality is less obvious because the temperature at which muscles enter rigor is likely to be much lower for VFC than with conventional chilling (CC), the basis of which has been influenced by standards for eating quality. McGeehin (2002) cites the work of Jamie *et al* (1992) as being pivotal in relation to the potential for VFC to produce a tender product.

The effects reported for VFC on meat eating quality are variable and in some cases extreme. Although progress has been made, the understanding of the variability in eating quality attained with VFC appears to be incomplete at this stage. There could be different reasons for this apparent lack of consistency including the definition itself.

Whilst temperature and time parameters are clearly stated, the VFC definition allows for variations in the refrigeration method used to attain VFC and boning methods done in conjunction. This is clearly evident from the summary of cooling techniques in the studies published (Table 3). Notably a prescription for the conditioning period after VFC does not appear to be part of the VFC definition despite this having ramifications for carcass shrink and eating quality. Temperatures reported during the conditioning period vary from the same regime used for conventional chilling (CC) to no refrigeration until the temperature returns to conventional chilling levels. Under experimental conditions a conditioning period allows for real time comparisons between VFC and CC that takes 24 h to complete.

Virtually all of the experimental work cited was done with meat rather than a meat substitute. James *et al* (2005) investigated the use of Karlsruhe test substance (tylose) for the purpose of testing the effect of salt concentration on the freezing point of cured meats. This may have some application for testing refrigeration settings in future VFC research. Davey and Pham (1996) alluded to methyl cellulose being used as well. These materials may be suitable for evaluating new refrigeration systems for the purpose of VFC.

In summary, considerable research has been done to prove the potential benefits of VFC. However biochemical and biophysical guidelines are less clearly available in the literature for VFC compared to CC. Development of such guidelines is a potential focus for new research in this area.

5.1.1 Definition of VFC

A commonly cited definition for VFC is that core muscle temperature should reach 0^{o}C within 5 hours post mortem Van Moeseke *et al* (2001). The time length in this definition is similar to Bendall's original recommendation that muscle should not be cooled below 11^{o}C in less than 5h or until muscle pH has fallen below 6.2 (McGeehin *et al.*, 2002). Bowling *et al* (1987a) defines a temperature range of -2 to 0^{o}C, rather than just an upper limit, for the core muscle temperature to be reached within 5 hours post mortem. As can be seen later in this review, changes in the rates of chemical reactions occur at very low temperatures close to freezing point, so specification of a lower limit is likely to be preferable to having just an upper limit.

Freezing of meat commences just below 0^{O}C and at -2^{O}C about 50% of the water in meat is present as ice (Dransfield, 1998). However the location of ice depends on temperature as well. Rahelic *et al* (1985) examined meat frozen at -10, -22, 33, -78 and -115^{o}C using electron microscopy. They found that ice crystals were present between cells only at -10^{o}C and began to form within cells at -22^{o}C. Ice crystals formed firstly in the region of the I band, that contains hydrophobic actin molecules, and then later in the A band. So while VFC involves temperatures close to the freezing point of meat, the water within muscle cells can be expected to remain in the liquid phase during the entire VFC process.

Further to Bendall's recommendations various guidelines have evolved for optimal eating quality based on rates of temperature and pH decline post-mortem and include 10^{o}C at 10h, pH 6.2 at16^{o}C, and pH 6 to occur in the range 18-25^{o}C (Thompson *et al.*, 2005). The rate of cooling with VFC clearly goes beyond these guidelines.

The time for completion of VFC occurs very soon in the post-mortem period compared to CC. The timing of biochemical and biophysical events that occur post mortem, such as glycolysis, shortening, rigor and tenderisation, are all potentially different for VFC compared to CC. Comparing the expected sequence and timing of these events under VFC and CC was attempted in this review to gain an understanding of the optimal management of VFC to improve eating quality.

5.2 VFC systems

Considerable engineering and modelling work has been done to construct VFC systems. This review does not go into any of this research in detail but models such as Beefchill (Haughey & McKenna, 1998) could be available for manufacturers wanting to explore this area. In Australasia, Davey and Pham (1997) produced a model to predict heat load and weight loss during beef chilling. Automation systems around the refrigeration unit are a consideration as well particularly for immersion systems. Drumm *et al* (1992) investigated a tunnel chilling system although VFC did not appear to be part of this work

5.2.1 Cooling techniques

VFC is not synonymous with any particular cooling system and a number of different cooling techniques have been used to achieve VFC. The most obvious and major difference between systems used is between air and liquid immersion systems.

The range of chilling techniques used in the reviewed papers is detailed in table 3. In both experimental and commercial contexts the different systems have different advantages. Immersion chilling is commonly used in the UK and the USA to process poultry (Brown *et al.*, 1988) and has been trialled in New Zealand for beef. Some of the differences between immersion and air chilling are discussed in this review. However it was difficult to make a practical comparison because

neither of these types of systems is yet to be commercialised in a VFC application for red meat. An optimal system in any particular situation may depend on a number of different aspects such as species, energy costs and market requirements as well as the meat quality outcome.

A fundamental difference between air and liquid immersion is the difference in the rate of heat loss from the surface. The difference in temperature between an object and the environment and the rate of heat transfer, characterised by the “heat transfer coefficient”, influences the rate of heat loss from a surface (Table 2). In an air cooling scenario the heat transfer coefficient can be influenced by humidity and air speed. Heat loss by convection and evaporation are both influenced by the temperature difference between the carcass and air. Heat loss due to evaporation is influenced by vapour pressure differences between the meat surface and the air as well.

The chilling rate of a carcase can therefore be increased either by decreasing ambient temperature, or by changing the heat transfer coefficient in some way. Different methods have been used to increase the heat transfer coefficient of carcass meat. These include; increasing air speed, using liquids with low freezing points such as brine, oil and propylene glycol, and agitation of immersion solutions.

The importance of the heat transfer coefficient was demonstrated by Van Moeseke *et al* (2001). They demonstrated a faster rate of temperature decline in beef *m. semitendinosus* (ST) cooled in a brine solution kept at -2^{o}C compared to those cooled in a freezer with an air temperature of -20^{o}C and an air speed of 3m/s.

Table 2 The effect of cooling method on heat transfer coefficient of meat (adapted from Van Moeseke (2001)

Method	Air speed (m/s)	Transfer coefficient (W/m^2 K)
Slow air chilling	1.5	5
Fast air chilling	3	50
Immersion		850
Spray chilling		850

5.2.2 Boning techniques

The mass and thickness of a body are fundamentally important to the rate of cooling and this explains why hot boning can facilitate the rapid rate of chilling needed for VFC. Furthermore the opportunity exists to bone earlier with VFC than with CC in a cold boning scenario. The EU hygiene requirement of meat being at a temperature of 7^{o}C or lower before boning is likely to be no restriction with VFC although other hygiene requirements may be important. Australian Quarantine Inspection Service have a temperature model for hot boned meat that drives a temperature monitoring protocol for boxed meat (Murray, 2001).

Cooling of an object generally consists of two phases. Firstly a period of inertia where there is no change in core temperature and secondly a period where core temperature declines at a uniform rate. Both phases of this cooling process are influenced by mass and the difference between the ambient and core temperatures as determined by Newtons law of cooling (Henssge, 1988). Large masses exhibit a prolonged inertia period and a slow rate of decline in temperature subsequently. Mass therefore is a fundamental issue in relation to the rate an object cools under any refrigeration scenario, particularly in the case of meat that has a low conductivity coefficient of 0.49W/m^{o}C (Van Moeseke *et al.*, 2001). This conductivity coefficient for meat is on a par with wood.

5.2.2.1 Carcass size

Hot boning is effectively a way of reducing the mass and thickness of the meat prior to chilling and is considered by some researchers to be mandatory to achieve VFC in beef. Aalhus *et al* (2002) found that deep carcass tissue in the hip region never approached VFC or even the cold shortening window when chilled as a carcass. This was the case when carcasses were subjected to an ambient temperature of -35^{o}C for 10 hours.

Van Moeseke *et al* (2001) found that the limit for meat sample diameter to achieve VFC was 8cm when two different methods were used, immersion in a brine solution at -2^{o}C and blast chilling at -20^{o}C. With this limitation hot boning may not be necessary for lamb carcasses although measures to reduce carcass size could still be advantageous for cooling rate in lambs. Redmond *et al* (2001a) reported an improvement in the rate of cooling when lamb carcasses were split into sides. This improved the air flow around the carcasses as well as reducing mass.

5.2.2.2 Temperature variation between cuts

Variation in the rate of temperature change occurs between muscles when meat is cooled in carcass form. This was demonstrated in a study by Stolowski *et al* (2006) who compared the rate of temperature decline for seven major muscles for beef carcasses chilled under a conventional chilling regime. Under this regime carcasses were exposed to an ambient temperature of 2^{o}C for 48 h. For the rate of temperature decline post mortem, the *m. longisimus dorsi* (LD) was the most rapid, the *m. semimembranosus* (SM), *m. semitendinosus* (ST), *m. vastus lateralis* (VL) and *m. triceps brachii* (TB) were intermediate and the *m. biceps femoris* (BF) and *m. gluteus medius* (GM) were the slowest respectively. Optimising the rates of temperature decline post mortem is therefore difficult to achieve across a carcass unless the carcass is reduced in size prior to chilling. The LD having the most rapid rate of cooling is a significant finding as this rate will probably guide the rate of chilling in carcass form under a practical scenario. In this case the slow cooling muscles in a carcass may not achieve a cooling rate consistent with a VFC regime. A system that cools carcases more uniformly known as differentiated chilling using a pad system is underway in Denmark (Damgaard & Borup, 2007).

5.2.2.3 Temperature variation within a cut

Variation in temperature occurs from the surface to the depth of a muscle. The effect of a temperature gradient on metabolic rate was demonstrated by Tarrant (1977). In this study it was found that the rate of glycolysis in SM depended on depth from 1.5 to 8 cm when the muscle was left on the carcass in the case of beef. However when the muscle was hot boned a more uniform rate of glycolysis was seen throughout the muscle. Samuel *et al* (2002) found that a difference in chill rate between inside and outside of SM in beef led to a two tone of colour and a difference in colour stability. More precise temperature control within a cut could be an advantage of VFC in terms of the colour and appearance of meat.

5.2.2.4 Boning summary

Reducing the mass and thickness of a meat by hot boning can improve the rate of heat loss, reduce the variation between cuts within a carcass and reduce the variation within a muscle due to depth. However hot boning removes skeletal restraint before muscles enter rigor and therefore predisposes meat to cold shortening. For example King *et al* (2003) caused cold shortening by immersing hot boned *m. longissimus thoracis et lumborum* (LT) and *m. triceps brachii* (TB) in an ice bath. The rate of temperature decline described in this study was not quite within the VFC range as LT at 4h was 3.7^{o}C and 0^{o}C was reached at 8 h.

If hot boning is combined with VFC, as is likely to be needed with beef, then virtually all processing is complete by the end of the VFC period. Integrating hot boning with VFC successfully in a commercial application is likely to require a greater research and development effort than would be required with VFC alone. For this reason application of VFC may be easier to achieve with lamb than beef in the short term. On the other hand further development of VFC may enable the benefits of hot boning to be realised more easily. Interactions with hygiene requirements is an important issue but is not represented in any depth in this review.

Table 3 Cooling techniques used in different experiments cited from the literature

Cooling medium	Boning method	Species	Ambient temp (^{o}C)	Air speed (m/s)	Reference

Air	Carcase	Lamb	-20		(Redmond *et al.*, 2001b)
Air	Hot boned	Beef	-20	2	(Neto *et al.*, 2002)
Air	Carcase	Beef	-70		(Bowling *et al.*, 1987a)
Air	Hot boned	Beef	-20/25	3	(Van Moeseke *et al.*, 2001)
Air	Hot boned	Beef	-20/25		(Trevisani *et al.*, 1998)
Air	Carcase	Beef	-20 & -35	2.32	(Aalhus *et al.*, 2002)
Air	Hot boned	Beef	-28		(Mahoney *et al.*, 1998)
Air	Carcase	Lamb	-10, -20, -25	0.5, 1.5	(McGeehin *et al.*, 2002)
Air	Hot boned	Beef			(Salm *et al.*, 1983)
Air	Hot boned	Beef	-70	0	(Roncales & Beltran, 1998)
Brine	Hot boned	Pork	0		(Brown *et al.*, 1988)
Brine (13% NaCl)	Hot boned	Beef	-7		(White *et al.*, 1998)
Brine (3.4% NaCl)	Hot boned	Beef	-2		(Van Moeseke *et al.*, 2001)
Carbon dioxide	Hot boned	Beef	-78.5		(Swain *et al.*, 1999)
Oil	Hot boned	Beef	1		(Taylor *et al.*, 1998)
Water	Hot boned	Beef	0		(King *et al.*, 2003)
Water	Hot boned	Lamb	0, 4, 10, 20, 36		(Jamie *et al.*, 1992)
Water	Hot boned	Beef	0, 5, 10, 15, 20, 25		(White *et al.*, 2006a)

5.3 Biochemical effects of VFC

Biochemical events affected by VFC include glycolytic rate, calcium release, protease activity, osmotic pressure, and colour stability.

5.3.1 Glycolytic rate

5.3.1.1 Effect of temperature on glycolytic rate

The relationship between glycolytic rate, indicated by the rate of pH decline, and temperature is complex and changes as different mechanisms come in to play over the temperature range encountered during the chilling of meat. Primarily the effect of temperature is to double enzyme activity for every 10^{o}C increase until the enzyme is denatured at high temperatures. This has a predominant influence on glycolytic rate for temperatures above 20^{o}C such that the rate of pH decline decreases at a constant rate until temperature reaches this point.

Below 20^{o}C the nature of this relationship begins to change as the cold shortening range is approached. In fact at very low temperatures the rate of pH decline increases. Dransfield (1998) states that the rate of pH decline in pre-rigor meat reaches a minimum when the temperatures is about 5^{O}C and then increases until the temperature reaches -3^{O}C. He further states that the rate of pH decline at -3^{O}C is unusually fast, being equivalent to that at about 25^{O}C.

The mechanism responsible for this phenomenon is believed to be utilisation of adenosine triphosphate (ATP) due to cold shortening (Dransfield, 1998) . Honikel and Hamm (1978) found an increased rate of breakdown of ATP between 6^{o}C and -1^{o}C in minced muscle. Newbold and Scopes (1967) proposed that the rate of glycolysis post-mortem was governed principally by the activity of phosphofructokinase and phosphorylase *b* both of which are activated by adenosine monophosphate (AMP). AMP was found to increase at low temperatures due to a stimulation of total adenosine phosphatase activity. Evidence of cold shortening appears in many of the VFC reports and could account for higher than expected rates of pH decline when this occurs.

Further to the effect of cold shortening, the “freeze concentration effect” may also have an influence at temperatures below -1^{O}C (Dransfield, 1998). This occurs when pure water freezes out of solution in the form of pure ice crystals. This increases the concentration of the remaining solution and causes the freezing temperature to drop as well as the viscosity to increase. Enzyme and substrate concentrations will therefore rise and potentially lead to an increase in glycolytic rate. However Rahelic *et al* (1985) found that ice does not form inside muscle cells until temperature falls below -10^{o}C. Glycolysis ceases at -25^{O}C (Dransfield, 1998) and ATP concentration remains unchanged when meat is kept at a temperature of -20^{o}C.

5.3.1.2 Rate of pH decline with VFC

Utilising low temperature might appear to be an alternative to methods such as electrical stimulation for increasing glycolytic rate post mortem. However because a rapid pH decline at low temperatures is a result of cold shortening it obviously cannot be used to prevent cold shortening. The practicalities of using the “freeze effect” in the absence of cold shortening are not clear at this stage but may warrant further investigation.

Results for the effect of VFC on the rate of pH decline have in fact varied from an increase, no change to a decrease in the rate of pH decline. Mahoney *et al* (1998) found that a VFC regime resulted in a lower pH 3 hours post-mortem compared to CC. By contrast Redmond (2001b) and Taylor *et al* (1998) both found no difference in the rate of pH decline between VFC and conventionally chilled lamb and beef respectively. Redmond attributed this result to the explanation of Dransfield (1998) that the relationship between the rate of glycolysis and temperature is U shaped between 20^{o}C and -3^{o}C. This could effectively make the rate of pH decline for CC and VFC to be similar over the course of the post mortem period. Similarly White *et al* (2006b) found no difference

between treatments in the range of 5-20^{O}C and an increase in rate of pH decline at higher temperatures.

Seeking a higher pH during chilling has attracted interest because of the effect of pH on enzyme activity. In the study by Jamie (1992) the LD muscle shortened by about 30% in muscle kept at both 0^{o}C and 4^{o}C yet pH was higher in the 0^{o}C treatment. Presumably the difference between treatments here for pH was the effect of low temperature decreasing enzyme activity as shortening occurred to the same extent in both treatments. Guignot *et a*l (1993) also found a relationship between the rate of pH decline and myofilament spacing, and this may have relevance to meat colour.

5.3.2 Ultimate pH

Some studies have shown a slight increase in ultimate pH (pHu) in response to VFC (Jamie *et al.*, 1992; McGeehin *et al.*, 2002). This potentially could influence colour and tenderness. The reason for this is not clear but it might suggest that measurement of pHu should be delayed when glycolytic rate is depressed by low temperatures. It could also be speculated that ATP concentrations are higher at the time of pHu with VFC due to a different relationship between ATP and rigor onset at low temperatures.

5.3.3 Calcium release

An increased rate of calcium release early in the post-mortem period has been reported in several VFC studies. Jamie *et al* (1992) reported this in lamb loins , van Moeseke *et al* (2001) in bovine semitendinosus muscle and Roncales and Beltran (1998) in bovine sternomandibularis muscle. Generally the finding has been that calcium concentration is higher compared to conventionally chilled muscles early in the post mortem period (5h). This effect is transitory because ageing causes an increase in calcium concentration from 24h in conventionally chilled meat (Jamie *et al.*, 1992; Roncales & Beltran, 1998; Van Moeseke *et al.*, 2001).

Calcium release causes cold shortening and activation of calcium dependent proteases. There is also a school of thought that calcium has a non enzymatic weakening effect on myofibrilla structures. Takahashi (1992) proposed that calcium ions cause a non enzymatic weakening of myofibrilla proteins when present at the concentration of 0.1mM. These effects included weakening of the Z disk, weakening of rigor linkages between actin and myosin due to activation of paratropomysin, and splitting of α connectin (titin). Yamanoue and Takahashi (1988) provided evidence of paratropomyosin causing a reduction in rigor tension and an increase in sarcomere length of passively stretched muscle. This was in support of a number of other studies. Hattori and Takahashi 1988 (1988) suggested that translocation of paratropomyosin from the A-I junction region onto thin filaments during the post-mortem period can be induced with a calcium ion concentration of 10^{-4} M.

By comparison the calcium concentrations measured by Jamie *et al* (1992) were a lot lower than 0.1mM being 0.015mM in VFC and 0.007mM in CC respectively. However this may not preclude calcium concentration being higher in specific locations within the cell.

5.3.4 Protease activity

5.3.4.1 Mechanism

Several studies investigating protease activity under different chilling scenarios have ascertained this to be a complex issue. Not only protease activity but the roles of different myofibrilla proteins for meat tenderness remain an area of active research. Both direct and indirect effects of temperature and pH may be important for protease activity. Jamie *et al* (1992) found an increase in proteolytic activity early in the pre-rigor period with loins immersed in water at 0^{o}C. They associated this

observation with induction of μ calpain activity due to a release of calcium when pH was relatively high. The influence of pH on μ calpain activity was confirmed by Carlin *et al* (2006) who found that activity was highest at pH 6.5 for desmin degradation in porcine myofibrils. Marsh *et al* (1981) also put the view that proteolysis can begin before rigor and is facilitated by high pH in the pre-rigor period. Dransfield *et al* (1992) found an effect of temperature on the rate of tenderisation when pH fell below 6.1 but not when pH was greater than 6.4. Roncales and Beltran (1998) found evidence of an increase in μ calpain activity and a decrease in calpastatin activity 24h post-mortem.

5.3.4.2 VFC results

With the level of complexity involved it perhaps is not surprising that attempts to repeat the effects of VFC on proteolysis have not always been successful. Redmond *et al* (2001b) found no difference in tenderness and no difference in calpain and calpastatin activities between CC and VFC lamb. In fact they concluded that lamb processed with VFC may require a longer ageing period of 9 days to prevent toughness compared to a period of 5 days for CC. Van Moeseke *et al* (2001) found no effect of VFC on proteolysis despite an increase in calcium concentration. However the increase in calcium concentration reported in this study was small in comparison to that reported by Jamie *et al* (1992). King *et al* (2003) found a reduction in desmin degradation due to VFC in beef.

The role of other proteases such as caspases and proteosome 20 in relation to VFC remains uncertain. Ouali *et al* (2006) proposed that the process of apoptosis may be an alternative mechanism for proteolysis early in the post mortem period through an enzyme group known as caspases. Whilst caspases require calcium for activation their sensitivity to pH is less well known. Caspases and the process of apoptosis could be an area to investigate in future VFC studies.

5.3.5 Osmotic pressure

Intracellular osmotic pressure increases post-mortem primarily due to lactate production by glycolysis. Ouali (1992) proposed that high osmotic pressure post-mortem could increase the susceptibility of myofibrils to proteolysis or have a direct weakening effect on myofibril structures. Tenderisation occurs most rapidly in white fibres (Pospiech *et al.*, 2003) and this may be explained by differences in glycolytic rate and osmotic pressure changes (Ouali, 1992).

The effect of VFC on glycolytic rate might conceivably affect the rate of change of osmotic pressure post mortem. There was no specific reference found that described osmotic pressure changes that might occur under the low temperatures experienced with VFC. Ionic strength in combination with low pH may in turn decrease the activity of glycolytic enzymes and the rate of ATP production (Honikel & Hamm, 1978).

5.3.6 Biochemistry summary

VFC appears to reduce the rate of pH decline, increase calcium concentration early in the post-mortem period and accelerate protease activity. The latter is a potential benefit of VFC but is unpredictable at this stage and requires further development. The optimum rate of pH decline post mortem does not appear to have been defined for VFC in the way that it has for CC.

5.4 Biophysical effects of VFC

The biochemical changes associated with VFC lead to biophysical changes in relation to timing of shortening, rigor and others. These changes are important for boning management and ultimately eating quality.

5.4.1 Temperature induced shortening

5.4.1.1 Cause of shortening

The relationships between sarcomere length and temperature of incubation during the pre-rigor period have been described by different authors. Rigor shortening is said to occur above 20^{o}C and cold shortening below 15^{o}C. Rigor or heat shortening occurs because of the pH dependence of the sarcoplasmic reticulum membrane Ca^{2+} uptake system, being optimal at pH 6.3 and decreasing rapidly when pH drops below 6 (Honikel & Hamm, 1978). Cold shortening is thought to be due to release of calcium from mitochondria and the sarcoplasmic reticulum, when ATP concentration is not limiting (>3.5µM), due to anoxic and cold conditions (below 15^{o}C) causing inactivation of the ATP driven calcium pump (Honikel & Hamm, 1978).

Henderson *et al* (2005) found that the temperatures and pH values at which shortening occurs depends on the species of animal and muscle type. Heat shortening may be more severe than cold shortening in pigs for example and the reverse is the case for cattle (Table 1). Sarcomere shortening was maximal at 2^{o}C ,minimal in the range 16-25^{o}C and high again at 37^{o}C in beef (Henderson *et al.*, 2005). Unfortunately there was no similar data to compare for sheep in this paper. Similarly Honikel *et al* (1986) found that sarcomeres in excised unrestrained bovine *M. sternomandibularis* incubated in a water bath shortened by 70% below 6^{o}C, by less than 10% between 6^{o}C and 18^{o}C and by 40% between 20^{o}C and 38^{o}C.

Table 4 The effect of temperature on sarcomere length in 3 species (Henderson *et al.*, 2005)

Species	Cold shortening		Minimal shortening		Heat shortening	
	Temperature (^{o}C)	Sarcomere Length (µ)	Temperature (^{o}C)	Sarcomere Length (µ)	Temperature (^{o}C)	Sarcomere Length (µ)
Bovine ST	2	1.3	16-25	1.8	25-37	1.6
Porcine LD	2	1.6	25	1.8	37	1.5

5.4.1.2 Timing of shortening

Different studies have examined the timing of shortening in relation to other post mortem events. Henderson (2005) described a relationship between time and sarcomere shortening for bovine muscle maintained at a constant temperature during the pre-rigor period. Heat shortening occurred between 4 and 8 hours post-mortem and cold shortening occurred between 8 and 24 hours post mortem in bovine loin.

Other studies suggest cold shortening occurs faster than this and well within the 5 hour time frame for VFC. Honikel (1983) found that shortening occurred as a staged event whilst Mahoney *et al* (1998) found that bovine *m. sternomandibularis* (SB) shortened by 50% within 5 hours of being chilled at -32^{o}C.

Jamie *et al* (1992) found that sarcomeres were 30% shorter at the time of rigor than 1 hour post mortem prior to chilling although the time that rigor occurred in relation to VFC was not reported. In the study of Van Moeseke (2001) the timing of sarcomere shortening varied between animals beginning at 1 hour and being 40% lower by 5 hours after chilling at -20^{o}C for one individual.

5.4.1.3 Sarcomere length and tenderness

It may be possible to achieve good eating quality from VFC meat irrespective of shortening. Sarcomere length is related to tenderness, but the relationship is neither linear nor systematic (Puolanne & Ruusunen, 1998). Shortening from 0-20% causes little or no toughening while shortening up to 40 % toughens the meat remarkably (May *et al.*, 1992; Redmond *et al.*, 2001b). Shortening beyond 50% can result in tender meat again (Troy & Joseph, 2001).

White *et al* (2006b) found that meat with long sarcomeres at day 14 was consistently tender but meat with short sarcomeres was not consistently tough. They concluded that sarcomere length cannot be used as a sole indicator to predict tenderness when sarcomere lengths are short.

5.4.1.4 Shortening results with VFC

Whist there is some variation between experiments the general consensus appears to be that VFC will cause sarcomere shortening unless some restraint is imposed. Van Moeseke *et al* (2001) found shortening to be profound (45%) in bovine semitendinosus muscle subjected to -20^{o}C blast chilling for 5 hours as did White *et al* (1998) for beef LD immersed in a brine solution at -10^{o}C. Up to 68% shortening (super shortening) has been observed (Troy & Joseph, 2001).

Extremely low ambient temperatures will cause a superficial layer of tissue to freeze. Aalhus *et al* (2002) found this with beef carcasses blast chilled with air at -20 and -35^{o}C. Surface freezing imposes a degree of restraint on the muscle and has been promoted as a technique to prevent cold shortening. Chilling by immersion has been shown to produce tough meat due to shortening caused by VFC in the absence of surface freezing (Trevisani *et al.*, 1998). Bowling *et al* (1987a) found that chilling at -76^{o}C for 5 hours increased sarcomere length of loin relative to carcasses chilled at -7^{o}C. In this experiment restraint was in two forms; surface freezing and skeletal attachment.

Extreme or “super shortening” has been associated with improved tenderness due to damage to the Z disk. In the experiment of Taylor *et al* (1998) there was little difference in shear force of VFC and CC for beef *m. sternomandibularis* in which the length had reduced by 60% and sarcomere length was less than 1.1µm. However “super shortening” does not appear to have been of central interest in VFC research and details on how to produce super shortening predictably were not found. Part of the reluctance to use super shortening appears to be the extreme toughness of meat with 40% shortening in the event that super shortening process was not completely successful (Troy & Joseph, 2001).

5.4.2 Rigor

Rigor is defined as the cessation of muscle extensibility, follows shortening, and is due to cross linking between actin and myosin proteins after ATP depletion. Honikel *et al* (1983) studied rigor by measuring extensibility of *m. sternomandibularis* and *m. mastoideus* after immersion in water baths of different temperatures between -1^{o}C and -38^{o}C post slaughter.

They found that low temperature induced a faster rate of ATP depletion in relation to the rate of pH fall due to the utilisation of ATP by cold shortening. Rigor began sooner and at a higher pH for low temperatures compared to high temperatures. In this case shortening was extreme (67% at -1^{o}C). ATP concentration depended on temperature at the onset of rigor but not at the time of rigor completion (Table 5).

Table 5 The effect of incubation temperature on pH and ATP concentration at the onset of rigor (adapted from (Honikel *et al.*, 1983)

Incubation temperature (°C)	pH		ATP concentration (μM)	
	Rigor onset	Rigor completion	Rigor onset	Rigor completion
38	6.25	5.5-5.6	2	0.5
15	5.75	5.5-5.6	1	0.5
0	6.11-6.2	5.9-6.0	1.8-2	0.5

The ability of muscles to resynthesise ATP quickly enough may be impaired at low temperature. In a similar way inhibition of glycolysis by iodacetate hastens rigor (Jeacocke, 1984).

These results suggest that rigor can occur very rapidly at low temperatures and may be complete by the end of the VFC period. However the relationship between ATP concentration, pH and rigor might be different again when surface freezing prevents cold shortening. If rigor was not complete by the end of the VFC period, then shortening might continue during the conditioning period after restraint from surface freezing has diminished due to thawing. The rate of pH decline during VFC therefore requires further investigation to gain an understanding of the relationship between pH and rigor in relation to eating quality.

5.4.3 Water holding capacity

Shortening causes water to move from the intracellular space to the extracellular space due to the shrinkage of filamental spacing (Honikel *et al.*, 1986). Bowling *et al* (1978) found evidence that VFC reduced water holding capacity as did Aalhus (1991). Different studies have demonstrated that VFC will increase cooking loss (King *et al.*, 2003).

5.4.4 Condensation

Reduced condensation on chiller surfaces may occur as a result of rapid chilling (Bowater, 1997) and this has benefits in terms of preventing bacterial growth and meeting hygiene standards. This effect could involve a sublimation process where ice evaporates to water in one process.

5.4.5 Product shape

Cold shortening will cause muscle to be shorter in length and wider in diameter (Taylor *et al.*, 1998). For this reason product shape may change and influence consumer acceptance of the resulting product. For immersion chilling this may be exacerbated in brine solutions in which the product floats. In a New Zealand study (unpublished), immersion chilling was found to cause distortion of the shape of strip loins, cube rolls, and rumps. This problem was particularly evident in rumps.

5.4.6 Biophysical summary

VFC causes shortening, reduces water holding capacity and probably accelerates the time of rigor. These changes have important connotations for eating quality and product shape.

5.5 Meat quality results from VFC

5.5.1 Tenderness

The effect of VFC on meat tenderness varies between different reports in the literature. When VFC has produced tender meat it appears to have been due to acceleration of proteolysis during the ageing period (Marsh *et al.*, 1981). When proteolysis does not occur, tough meat might be expected because of the propensity for cold shortening. This was the experience of Van Moeseke *et al* (2001) who found that despite pH and calcium concentrations being higher 5h post-mortem, accelerated proteolysis did not occur in the VFC treatment. However this may have been an animal genotype effect as Belgian Blue bulls were used for this experiment.

In the past there has been some controversy in relation to ageing of cold shortened meat. Jamie (1992) stated that tenderisation occurs independently to shortening and that cold shortened muscles can tenderise with ageing. Olssen *et al* (1994) found that the ability to age depended on the degree of shortening. They suggest that ageing can occur when muscle is shortened but not when shortening is greater than 40%. Whilst a tender product might be achievable; a reliance on ageing over a 9 day period as reported by Redmond *et al* (2001b) could have an influence on the economic viability of VFC. Jeacocke (Jeacocke, 1984) proposed the existence of two different types of rigor cross bridges according to calcium concentration that differ in strength. However this does not appear to have been supported by other workers and different rates of tenderisation appear to be the favoured explanation as already discussed.

A more desirable research outcome would be to find a way of inducing accelerated ageing predictably with the goal of producing tender meat within 24h at least for the domestic market. For long shipping export markets tenderness may not be the major issue particularly if VFC was to improve carcass weight and shelf life on arrival.

5.5.2 Muscle colour and colour stability

Reports suggest that VFC causes meat to be darker (Aalhus *et al.*, 2002) and for marbling scores to be improved in the case of beef. The explanation for this is not entirely clear but may be due to pH being higher 24h post slaughter. New Zealand work suggests that colour stability can be improved with VFC. However relatively little data was found in relation to colour stability as the main focus for quality has been on tenderness. There is also potential for colour to be confounded by hot boning which can make meat darker in colour. Redmond *et al* (2001a) found that VFC caused no visual concerns for lamb meat in the eyes of French buyers.

5.5.3 Eating quality variation

5.5.3.1 Animal factors

In an introductory review of the Concerted action research program, Roncales (1998) stated that variability of results regarding tenderness was a problem still to be overcome before VFC could be successful. White *et al* (2006a) confirmed this opinion and suggested that the problem caused by cold shortening was not so much an increase in toughness rather an increase in the variability of tenderness. Speed of proteolysis may depend on gene expression (Pospiech *et al.*, 2003). In the study of (Van Moeseke *et al.*, 2001) the failure of proteolysis under conditions of accelerated calcium release and high pH may have been due to the genotype being Belgian Blue. Variation also occurs between consignments and carcasses in relation to speed of onset of rigor development (Dransfield, 1998). As well as genotype differences nutrition may play a role. Rowe *et al* (2004) found evidence that vitamin E intake influenced the activity of μ calpain and calpastatin in beef strip loins by changing the oxidation status post-mortem.

5.5.3.2 Muscle differences

The potential for differences between muscles could be an important consideration for commercial application of VFC and could account for some of the variation reported in the literature in relation to VFC. Various muscles have been used to study the effects of VFC including the *m. infraspinatus, m. supraspinatus, m. triceps brachii, m. semimembranosus, m. semitendinosus, m. longissimus dorsi* and *m. sternomandibularis*. Some muscles, *m. semitendinosus* and *m. sternomandibularis* for example, appear to have been favoured because they're size and shape facilitates rapid chilling once removed from the carcass. As well as being extreme in an anatomical sense these muscles are obviously different in a biochemical sense in terms of fibre type and connective tissue content to other muscles. Potential for interaction with cooling treatment and muscle type means that results from individual muscles will not be valid across the whole carcass.

The degree of shortening in response to low temperature depends on the muscle type. Olsson *et al* (1994) found that shortening was greater in the LD than the SM. Across the temperature range from 1 – 10^{o}C the LD shortened more and quicker than the SM although both muscles shortened. They attributed this effect to the SM containing a greater percentage of white fibre types that contain less mitochondrion and have a more effective sarcoplasmic reticulum than do red fibre types. Stolowski (2006) found ST to be susceptible to shortening. Interactions may also occur with treatments designed to prevent shortening. White *et al* (2006a) found that electrical stimulation reduced the amount of cold shortening in the SM but not the LD and concluded that different muscles exhibit different pre-rigor behaviour

Olsson *et al* (1994) also found that tenderisation due to ageing varied between the muscles. They found that tenderisation over a 15 day period after slaughter due to ageing was greater in the LD than the SM for meat kept at 1-10^{o}C during the pre-rigor period. This was confirmed by Stolowski *et al* (2006) who categorised muscles according to response to aging for beef chilled as a side at 2^{o}C (Table 6). However just how much of the differences between muscles might have been due to differences in the rate of cooling post mortem was not clear from this study.

Table 6 Ageing categories adapted from Stolowski et al (2006)

Aging category	Muscle
Tender slow aging up to 42 days	GM, LD
Slightly tender aging up to 14 days	SM, TB
Slightly tough with slow aging response after 28d	ST VL
No aging	BF

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5.5.3.3 Electrical stimulation

A number of studies have examined the eating quality effects of electrical stimulation with VFC. McGeeehin *et al* (1999) found that electrical stimulation reduced shear force at 1 day but not at 5 days post slaughter for both VFC and CC lamb LD. The main benefit was to reduce the number of very tough animals hence the variability of eating quality and this effect was more evident in the VFC than the CC treatment. In this study VFC (-20^{o}C) reduced the rate of pH decline after stimulation compared to CC (4^{o}C). Sheridan (1990) found that electrical stimulation had no effect on tenderness for CC and VFC lamb.

A study by Salm *et al* (1983) investigated the interaction between electrical stimulation and chilling temperate. Unfortunately the lowest temperature attained in this study was 3^{o}C, so this study was not really compliant with the VFC definition. They found that electrical stimulation decreased the effect of rapid chilling on shortening and that this effect was greater for rapidly chilled than CC bot honed LD muscle. However the shortening in the electrically stimulated muscles was still in the range expected to cause a decrease in tenderness, and an effect on tenderness was confirmed by panel and shear force assessments. White *et al* (2006a) also compared the effects of electrical stimulation in fast and slow chilled meat but not within the VFC range.

Causing a rapid pH decline by using electrical stimulation prior to VFC could be counterproductive if proteolysis is favoured by high pH. Salm *et al* (1983) found that the effect of electrical stimulation on proteolysis was influenced by the temperature regime used. With CC electrical stimulation increased proteolysis but with rapid chilling there was no effect. They concluded that electrical stimulation would not alleviate toughening in rapidly chilled meat.

Electrical stimulation could potentially be used either to prevent cold shortening by accelerating the rate of ATP utilisation prior to chilling or to enhance proteolysis. Securing the value of electrical stimulation in a VFC scenario will depend on a clear purpose for electrical stimulation being defined in relation to sarcomere shortening and proteolysis. Further work is desirable in this area before a recommendation can be made.

5.5.4 Eating quality summary

Tenderness has been the major focus of eating quality research for VFC. Whilst VFC can produce tender meat, variation in eating quality is still a concern for VFC. Colour stability is a potential benefit of VFC although relatively few papers presented data on this aspect.

5.6 Carcass shrink

5.6.1 Background

A reduction in carcass shrink and the resultant potential for economic gain is a major part of the interest in VFC and has been described in a number of papers. Gigiel and Collett (1989) found a weight loss of between 1.1 and 2% after 24h and between in 1.5 and 2.3% after 48h in a study of 14 commercial beef chillers in the UK. Whilst the effect of VFC is usually to reduce shrink loss some reports have shown either no effect or an increase in shrink loss. For example, Redmond *et al* (2001a) found that chilling at -4 and -10^{o}C in air did not change carcass weight relative to CC. This suggests that some attention needs to be paid to the refrigeration method to secure the maximum benefit for carcass shrink.

5.6.2 Mechanisms

5.6.2.1 Immersion systems

Liquid immersion systems increase the rate of heat transfer without increasing loss of heat due to evaporation so have benefits for reducing carcass shrink. Redmond *et al* (2001a) compared shrink from air chilling to immersion chilling in propylene glycol over a temperature range of -14 to 4^{o}C. They found that immersion chilling produced consistently lower shrink loss across this range although attributed this partly to a need to wrap the meat in plastic prior to immersion.

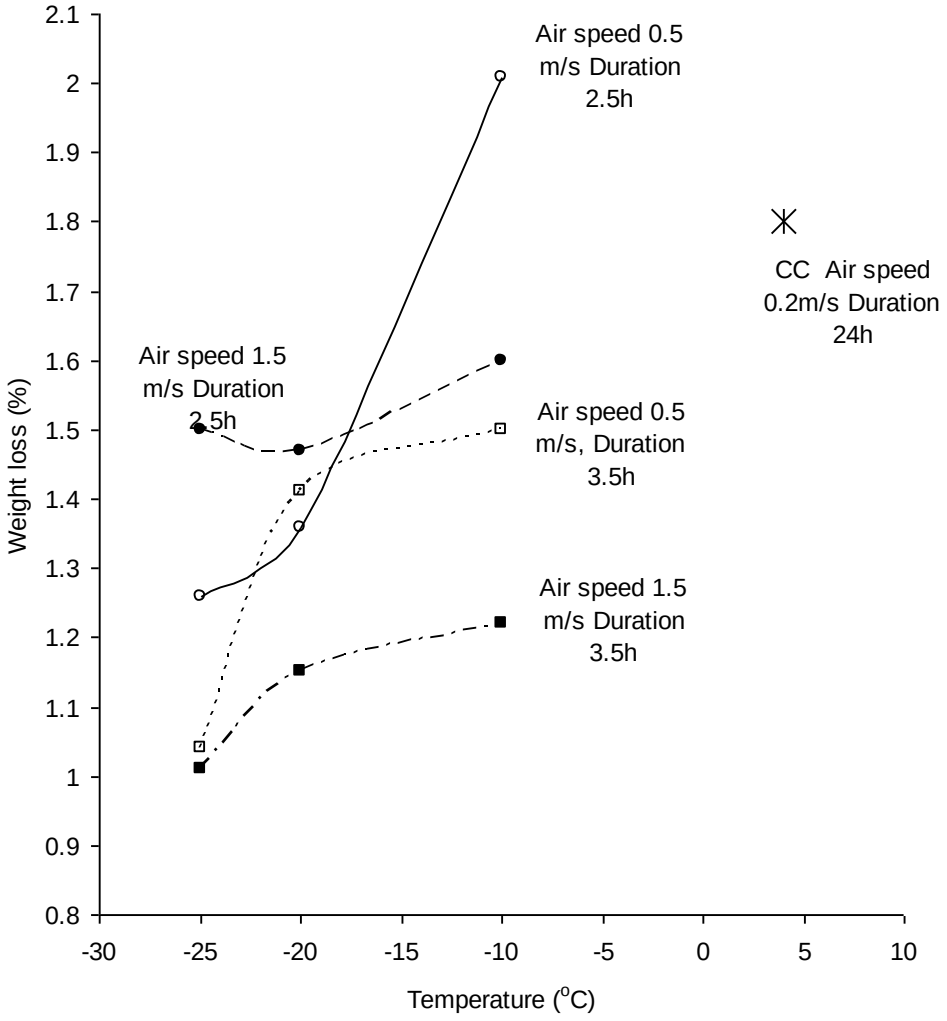
5.6.2.2 Air chill systems

The reason for the improvement in carcass shrink for air based VFC systems is intriguing. Generally speaking shrink loss decreases with increasing rate of chilling (Bowater, 1997). This is despite heat transfer due to evaporation causing carcass weight loss. In fact weight loss can be calculated from the amount of heat loss due to evaporation (Levy, 1978) and vice versa. Davey and Pham (1996) used a load cell mounted on a rail to measure weight change over time to estimate latent heat loss due to evaporation.

The mitigating factor for VFC appears to be condensation and absorption of moisture during the conditioning period. Aalhus *et al* (2002) demonstrated a relationship between time of exposure to VFC and ambient temperature to carcass shrink. Carcass weight loss measured 24h post mortem decreased with increasing time in VFC conditions, by 0.8 g/kg/h to 1.6g/kg/h for -20^{o}C and -35^{o}C chilling regimes respectively, compared to a CC regime of 2^{o}C. For the -35^{o}C regime, shrink fell to 0% when carcasses were held under these conditions for 7 hours. Carcasses held for longer than 7h increased in weight. This effect was attributed to condensation and moisture freezing on the carcass at low carcass temperature. McGeehin *et al* (2002) found less carcass shrink when the VFC period was 3.5 h compared to 2.5h and stated that greater moisture condensation during the temperature equilibration phase was responsible. Carcass weight loss decreased with increasing air speed and or decreasing ambient air temperature (Figure 1). Drumm *et al* (1992) measured this effect with a load cell mounted on the rail.

The colder the carcass at the end of the VFC period the greater is the reduction in shrink. Similar carcass weight results can be obtained with different refrigeration and air speed settings. Ambient conditions during the conditioning period could also possibly influence this outcome. Redmond *et al* (2001a) recommended that humidity should be high during VFC (90%) and high but not too high during conditioning. If too high during conditioning the carcass may appear wet. More importantly the timing of deboning and the temperature during the subsequent conditioning period could clearly interact with the effect of VFC on carcase yield and this needs further investigation.

Figure 1 Effect of temperature on carcass weight loss at 24h for different air speeds and VFC duration CC = conventional chill (adapted from McGeehin *et al* (2002))



5.6.2.3 Persistence of the shrink effect

The reduction in carcass weight shrink appears to persist for some time. Brown *et al* (1988) showed the effect to be of similar magnitude 15 days after storage as that at 24 hours for pork chilled as primal cuts in a brine solution. Bowling *et al* (1987b) demonstrated the magnitude of improvement in shrink due to VFC was unchanged 144h after death. A simple explanation for this effect might be that weight loss tends to decrease over time as the surface dries out and the temperature difference compared to the environment decreases (Levy, 1986).

In contrast Bowling *et al* (1978) found that VFC reduced shrink in lamb carcasses at 24h but not at 72h compared to holding lambs at higher temperatures (16°C) for conditioning prior to chilling. In this study the shrink levels were quite high with the best result being 2.1% for lambs exposed to a

temperature of -32^{o}C and an air speed of 1.3m/s for 2h prior to a CC regime of -1 to 1^{o}C. They concluded that chilling method changed the timing rather than the amount of carcass shrink.

5.6.3 Other factors

While the rates of carcass weight loss documented by Aalhus (2002) demonstrate how to minimise carcass shrink, achieving a balance with eating quality outcomes and energy requirements may also be important. McGeehin *et al* (2002) found that the best chilling regime for weight loss was not the same as for eating quality. In their study a 2.5h chill duration produced the best tenderness result whilst a chill duration of 3.5h produced the least weight loss. The relationship between fan speed and energy requirements is cubic hence a doubling of fan speed leads to an eight fold increase in energy usage (Bowater, 1997) .

Sheridan (1990) compared weight loss in washed and unwashed carcasses and found that washing influenced carcass weight for CC but the difference was not significant for VFC. Weight loss was reduced from 1.60 to 0.82% for washed and from 1.83 to 0.96% for unwashed lamb carcasses exposed to an air chilling regime of -20^{o}C, air speed of 1.5 m/s for a 3.5h duration..

5.6.4 Carcass shrink summary

A positive effect of VFC on carcass shrink has been well established. However any future work with new or different refrigeration systems should clearly include carcass shrink validation work. Yield at the retail cut level does not seem to have been investigated in detail and so further work could be useful in this area. Meat yield in a hot boning VFC scenario could also be worth exploring further.

5.7 Economic analyses

5.7.1 Overview

Relative economic benefits are going to depend on many variables such as chilling method, chill duration, energy costs, plant size, automated loading equipment, and carcass weight saving. Economic analyses tend to favour VFC compared to CC on the basis of decreased shrink, reduced processing time and a smaller footprint for chilling facilities.

5.7.1.1 Energy costs

Increased energy costs could be a greater issue now than was the case previously given current energy costs and greenhouse gas concerns. Ramirez (2006) unveiled a disturbing trend whereby efficiency of energy utilisation for meat processing in European countries has decreased during recent years due to the demands imposed by higher hygiene standards . In this study beef, veal and sheep required 1390MJ/t carcass weight to process compared to 3096 MJ/t for poultry and 2097 MJ/t for pork. Cooling was found to have the largest need for electricity being 45-70% of electricity requirements for slaughtering cattle. However reports suggest that VFC will likely increase rather than decrease energy costs.

5.7.1.2 Eating quality

In none of the economic analyses found was there any financial benefit attributed to a change in eating quality, either positive or negative, due to VFC. This implies that eating quality was assumed to be roughly equivalent in value for VFC and CC meat. This assumption might be due to studies being focussed on tenderness and could underestimate the potential benefits to product quality. In the grape industry a VFC system has been found to increase shelf life from 12 to 27 days and improvements in shelf life has been a major reason for the increase in value due to this application

(Henriod, 2004). Further investigation into the use of VFC to extend shelf life in both domestic and export markets may be warranted.

5.7.1.3 Shrink

Another important point is that the financial value of less shrink is realised only if the weight advantage is retained at the time of sale. This might seem obvious but could be an important consideration if VFC meat had to be aged for longer than CC meat in order to produce a product that is of acceptable tenderness to the consumer. This advantage might also be lost if meat is converted into a processed product (Bowater, 1988-1989).

5.7.2 Economic analysis examples

Two economic analyses were found published in the literature (Bowater, 1997), (Redmond *et al.*, 2001a) and one unpublished report from New Zealand. Bowater (1997) states that fast chilling increases the capital and running costs of chilling with higher fan speeds and lower refrigeration temperatures required. Increased capital costs were due to a need to increase evaporator surface area from 9.5m^2 to 28m^2 per carcass for a beef plant. In the New Zealand study there was no difference in running costs between immersion chilling and blast chilling when the time the product had to remain in the immersion chiller was increased from 5 to 8 hours. This demonstrates the effect of changing various variables on running costs. Bowater (1997) compared 3 different chilling options (Table 7).

Table 7 Air speed, temperature and weight loss for 3 options assessed by Bowater

Parameter	Option1 (48h)	Option 2 (24h)	Option 3 (fast)
Air speed (m/sec)	0.2	1	2
Temperature (^{o}C)	4	-1	-10
Weight loss (%)	2.5	1.2	0.6

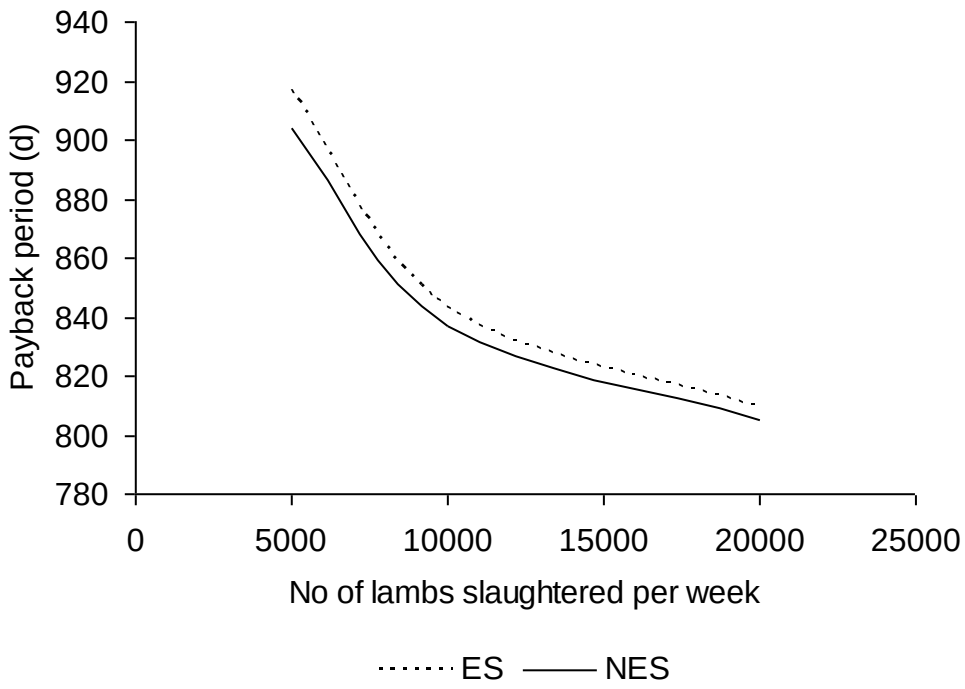
Table 8 Production costs ($ per head) of beef for different chilling systems- taken from Bowater (1997)-currency exchange rate (£ to $) of 0.60 assumed

Item	Option1 (48h)	Option 2 (24h)	Option 3 (fast)
Electricity cost	$0.38	$0.50	$1.10
Working capital	$1.50	$0.75	$0.75
Capital cost	$5.33	$3.80	$7.25
Weight loss	$37.50	$18.00	$9.00
Total cost	$44.70	$23.05	$18.10
Cost saving relative to option 1	$0.00	$21.65	$26.60
Lamb equivalent cost saving relative to option 1*	$0.00	$2.17	$2.66

*Assuming that 10 lambs are equivalent to 1 beast

The Bowater (1997) analyses demonstrates that savings could be substantial compared to a slow chilling scenario (Table 8) due to savings in carcase weight loss. Increased capital and energy costs were a feature as was the case in the study by Redmond (2001a) who attributed this to higher capacity refrigeration units and a humidifier. They used a pay back period approach to evaluate the net cost of VFC and found that the payback period was less for larger installations (Figure 2). This association between pay back period and size of plant could suggest that VFC would be more attractive to larger plants, although the rate of improvement due to plant capacity was reduced after a plant capacity of 10000 lambs per week was reached.

Figure 2 The effect of plant size on payback period (adapted from Redmond et al (2001a)



Comparison of the benefits and costs for the entire period between slaughter and retail sale may require further work. Whilst thorough in relation to the VFC period, details about the times for conditioning and ageing were not elucidated in the economic studies cited. The value of changing the lengths of these different components to reduce energy costs was therefore not clear hence this could warrant further investigation.

5.7.3 Economic summary

VFC economic analyses have highlighted an improvement in processing efficiency due to reduced carcass shrink in the absence of any change in product value. This improvement in efficiency requires greater capital and energy costs but leads to a positive financial benefit due to the savings in shrink loss.

5.8 The potential value of VFC to the Australian red meat industry

5.8.1 Quantification of VFC effects

The direction of the effect of VFC is given below (Table 9) for the range of parameters it has been reported to influence.

Table 9 List of claimed effects for VFC

Characteristic	Usual Effect	Magnitude
Marbling	Increase	
Lightness	Decrease	Up to 6 units of L value
Proteolysis	Increase	Effect is early in post mortem period
Calcium concentration	Increase	100X
Rate of pH decline	Decrease	
Tenderness	Variable	
Sarcomere length	Decrease	0-60%
Carcass shrink	Decrease	0-50%
Fat measurement	Decrease	
Eye muscle area	Increased width, decreased depth	
Water holding capacity	Decrease	
Drip loss	Increase	Double
Processing time	Decrease	
Energy costs	Increase	
Capital costs	Increase	

An objective of this study was to quantify likely changes due to VFC. However with the variation found in the literature both in the methods used and the relevant responses, it is difficult to be prescriptive about the magnitude of the effects seen. Therefore the effect has been quantified

(Table 9) only when the magnitude was clearly indicated in the literature, otherwise the direction only is given.

5.8.2 Commercial application of VFC

Despite a large research effort there is little evidence of commercial adoption of VFC for red meat across the world. Currently there is a Norwegian initiative to use super chilling to improve the keeping quality of fish and pork. However rapid freezing technologies are becoming available commercially such as the Supachill® system.

5.8.3 Future directions for research

The following is a list of knowledge gaps apparent in the literature that could warrant further investigation for the benefit of the Australian red meat industry.

- The potential use of VFC to reduce processing time (including ageing) and energy costs under different market scenarios (domestic vs export)
- The physical nature of carcass shrink loss and the effect of VFC on meat yield under different deboning scenarios.
- Further definition of the optimal rate of pH and temperature decline needed to induce accelerated tenderisation under VFC.
- Definition of the conditioning period including its role, length of duration, temperature and humidity that is complimentary to a VFC regime.
- The role of electrical stimulation with VFC in relation to the optimal rate of pH decline to prevent cold shortening and to optimise protease activity
- The expected changes with time in key biochemical (calcium concentration, osmotic pressure, pH, calpain activity, caspase activity) and biophysical (rigor, shortening) parameters for the purpose of optimising tenderness under VFC for different muscle groups and boning systems.
- Identification of commercial scenarios where the value of VFC benefits such as tenderness and shelf life are transparent to consumers.
- Animal, muscle and other sources of variation for the post-mortem activity of protease enzymes in response to VFC

6 Pandura Pilot experiment- Results and Discussion

6.1 Lamb description and practical considerations

Table 10 Lamb liveweight, rectal temperature, hot carcass weight (HCW) and dressing percentage (DP)

Lamb	Liveweight (kg)	Rectal temperature (^{o}C)	HCW (kg)	DP (%)
1		38.8	21.8	
2	45.8	38.8	23.2	50.7
3	42.4	39.0	21.1	49.9
4	38.8	39.3	19.2	49.6
5	39.6	39.1	19.8	49.9
6			18.7	
Mean	41.7	39.0	20.6	50.0

The lambs used were representative in liveweight and carcase weight of lambs commonly marketed in Australia (Table10). Chilling conditions varied between carcases as indicated by the length of chilling time (Table 11). This and other technical considerations would likely have impacted on eating quality. However the aim of this exercise was to conduct a pilot experiment and the experience gained in this process will be valuable for future development work. Some of the limitations of the pilot experiment are discussed below.

6.1.1 Carcass movements through the chiller

The dimensions of the carcass prevented them from being moved between the different cooling chambers in a continuous way as happens now with grapes. This necessitated moving each carcass from one compartment to the next via the chiller doors. This exposed the carcasses to ambient air temperature at the change point and interrupted the chilling profile compared to what could be expected with a continuous flow system.

6.1.2 Carcass orientation

Again because of physical dimensions the carcasses had to lay laterally and not vertically as is the case with commercial slaughtering. This made it difficult to attach and view temperature probes during operation. Airflow to the different parts of the carcass was likely to be influenced by this orientation also.

6.1.3 Central temperature data logging

The temperature probes used were chosen because they offered greater precision in placement and measurement than other remote sensing devices. However the use of a central data logger proved to be cumbersome in this situation because of the need to move carcasses from one compartment to another via the doors. This meant the probes had to be removed and reattached in the process of movement. For future work using the same probes with a dedicated data logger for each carcass is likely to overcome this problem.

6.1.4 Settings

The PTC was available for just one day due to seasonal commitments. This prevented any preliminary work on air flow and refrigeration settings as well as measurement methodology prior to the experiment. A number of variables were changed between carcasses including the air flow and refrigeration settings, carcass position and chiller load (grapes plus carcass). Some of these changes were made intentionally whilst others were necessitated by practical limitations imposed by the system being designed for grapes. This means it is somewhat difficult to gain a consistent interpretation of the results in relation to settings.

6.1.5 Refrigeration "cut out switch"

Superficial temperature increased coincidentally with the PTC switching itself off for carcasses 1 and 2. This may also have been the case with carcass 3 and 4 as the problem recurred but not to the same extent. Interestingly there was no evidence of this from the loin and shoulder plots from carcass 5. Therefore the theory that the surface temperature increases during cooling due to heat moving from deeper regions can not be corroborated at this stage.

6.2 Carcass shrink

The carcass shrink data (Table 11) was variable and clearly influenced by some of the practical difficulties encountered. For this reason it may be premature to make conclusions in relation to carcass shrink.

Carcass 3 had the greatest carcass weight loss and was kept in the PTC for the longest period of time (5 h vs 3h). This was done to confirm that the deep leg temperature would reach 0^{o}C within 5 hours. Carcass 1 and 2 had low carcass weight losses but for these carcasses the PTC malfunctioned for part of the time so the cooling regime was the least severe for these carcasses. The back strap from carcass 6 did not change weight (0.56 kg) during the PTC or conditioning period.

A further observation was that carcass shrink during VFC was faster than during the post VFC conditioning period. Carcasses 3, 4 and 5 probably represent the best opportunity to estimate carcass weight loss as the PTC malfunctioned for carcass 1 and 2. Carcasses 3, 4, and 5 were weighed at 1100h and 1600h on day 2 (April 12) to estimate weight loss during the conditioning period post PTC.

During PTC the mean rate of weight loss for these carcasses was 70g/h whereas during the post PTC cool room period the mean rate of weight loss was 8 g/h. Assuming that PTC time was 3 hours the predicted carcass weight loss at 24 hours would have been 2.2%. By comparison Redmond *et al* (2001a) found a shrink rate of 1.86% or 15 grams per hour over a 24 hour period for conventionally chilled lamb and a lower rate for VFC lamb. In developing the PTC for meat a better understanding of the effect of the various refrigeration and fan settings on carcase shrink will be needed.

Table 11 Carcass weight (CW) change during PTC

Carcase	Hot carcase weight	Carcase weight post PTC	Shrink (kg)	Shrink (%)	Shrink (g/kg/h)

1	21.8	21.72	0.08	0.37	1.1
2	23.2	23.06	0.14	0.60	1.6
3	21.14	20.7	0.44	2.08	4.2
4	19.24	19.04	0.2	1.04	2.7
5	19.78	19.56	0.22	1.11	3.7
Mean	21.0±0.70	20.8±0.73	0.22±0.06	1.03±0.003	2.7±0.5

Values are means ± sem.

6.3 Carcase temperature

Predictions for temperature are shown in Figures 3 and 4. The raw temperature data and the timing of the changes between the compartments are presented in the appendices. For the latter unedited plots data capture errors associated with the technical difficulties encountered in this pilot project. In particular the effect of moving carcases between compartments can clearly be seen from the raw plots.

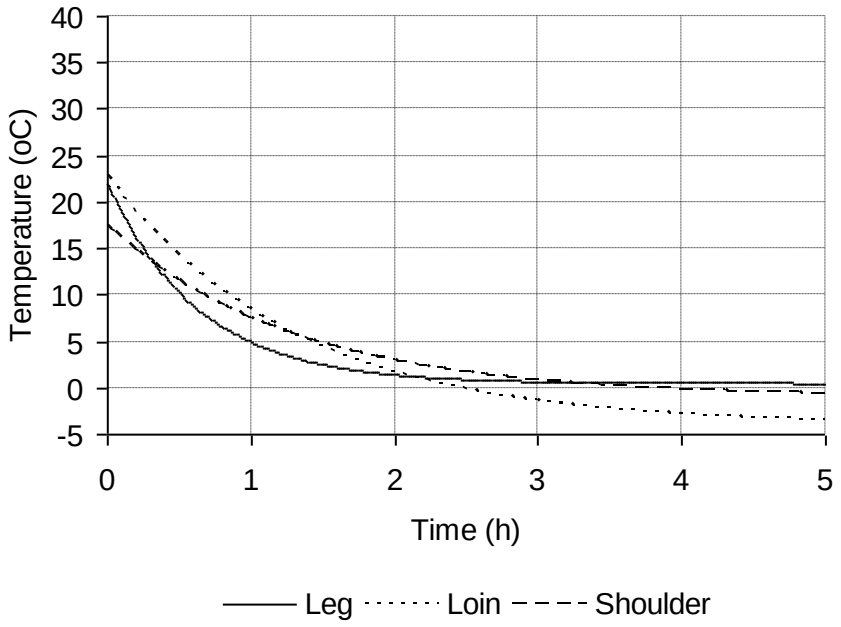
6.3.1 Relationship between temperature and time

There were significant correlations ($P<0.01$) between temperature and time of chilling for both superficial and deep probes (Figures 3 and 4). Furthermore there was a clear effect of probe depth on the rate of temperature decline. The temperature of superficial probes declined more quickly than the temperature recorded by deep probes.

Table 12 Percentage variance accounted for by temperature prediction models for superficial and deep probes in the leg, loin and shoulder

Cut	Variance accounted for (%)	
	Superficial probes	Deep probes
Leg	75.4	91.9
Loin	76.2	97.5
Shoulder	41.0	95.6

Figure 3 Predicted superficial (<5mm) muscle temperature for leg, loin and shoulder (data from carcases 1-4)



Prediction equations superficial temperature

y= temperature and x= time

Superficial loin

$y = -4.053+26.8551*0.987187^{X}$

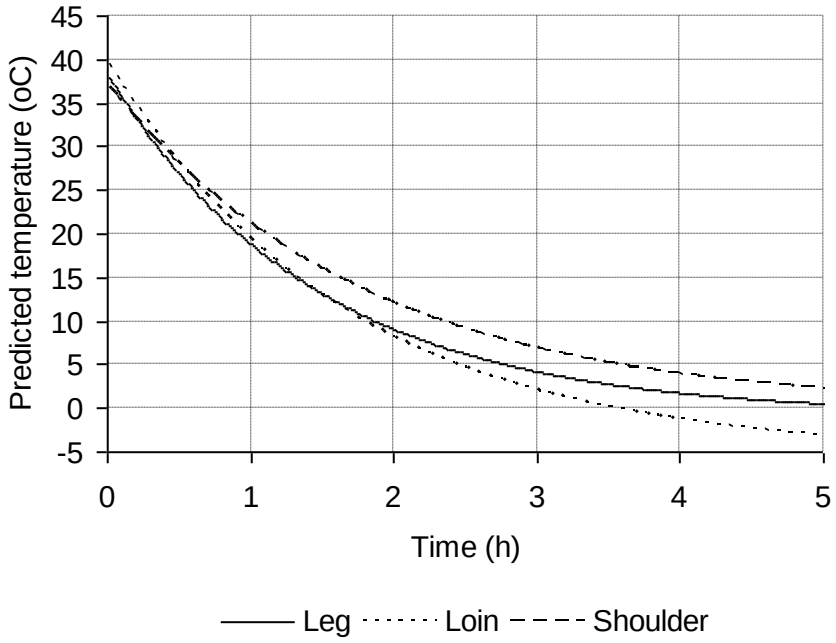
Superficial leg

$y = 0.479+21.511*0.974^{X}$

Superficial shoulder

$y = -1.033+18.409*0.98722^{X}$

Figure 4 Predicted deep (25-30 mm) muscle temperature for leg, loin and shoulder (data from carcases 1-4)



Prediction equations deep probes temperature

y= temperature and x= time

Deep loin
$Y = -5.442+44.907*0.990029^X$

Deep leg
$Y = -0.705+38.533*0.988543^X$

Deep shoulder
$Y = -0.066+36.876*0.990675^X$

6.3.2 VFC criteria

The predicted results for carcases 1-4 suggest that a VFC regime is achievable with the PTC. This was evident from the raw data plots as well as deep leg temperature for carcase 3 that reached 0^oC within 300 minutes. In the case of carcase 5 deep loin temperature reached 0^oC after just 180 minutes of cooling.

6.3.3 Muscle variations

As expected from other studies (Stolowski *et al.*, 2006), there was evidence of variation between muscles for the rate of cooling. For example, the temperature was about 5^oC in deep loin compared to 20^OC in deep leg temperature, for carcase 5 one hour after cooling had commenced.

6.3.4 Cut size

The data from the loin of carcase 6 demonstrates that chilling rate can be extremely fast if muscles are hot boned. However this rapid rate was not seen when muscles were left as primal cuts in the case of leg and shoulder for carcase 6. This may have been because cutting into primal cuts effectively changed the thickness of the loin but not the leg. Other studies have shown relationships between muscle thickness and rate of cooling with 8cms being cited as the maximum depth if meat is to be cooled rapidly (Van Moeseke *et al.*, 2001). The shoulder appeared to be the most difficult region to cool.

6.3.5 Carcase orientation

There was evidence that carcase orientation affected temperature dramatically. Carcase 2 was inverted when moved to the second chamber. When data capture recommenced the leg surface temperature was seen to increase markedly such that the lines do not coincide at the point of change (120 mins). In carcase 5 there were large apparent differences between the temperature on the surface of the shoulder and loin. Without air speed measurements the reasons for this remains unclear but it may simply have been differences in airflow due to carcase orientation in both of these cases.

6.3.6 Surface freezing

The rapid rate of cooling in carcase 5 and 6 caused temperatures at the surface of the loin to approach freezing temperatures. Surface freezing appears to be possible with the PTC if settings result in fast rates of temperature fall.

6.3.7 Probe depth

Temperature change obviously occurs much more quickly at the surface than deep in a muscle. Superficial temperature was close to ambient air temperature by the start of the PTC period. Data from the superficial probes was more variable than those from deep probes with less of the variance being accounted for by the prediction models (Table 12). As superficial temperature records were more responsive to changes in ambient air temperature they may be useful to monitor technical difficulties. Superficial temperature increased coincidentally with the PTC switching itself off for carcases 1 and 2. Interestingly there was no evidence of temperature rise in the plots for carcase 5. Therefore the perception that the surface temperature might increase during cooling, due to heat moving from deeper regions, can not be corroborated at this stage.

Achieving an even more precise depth of probe (within a millimetre) may also be worthwhile. Additional measurements such as infra red measurement of surface temperature, air temperature, and air flow measurements may be useful in future development work.

6.4 Meat quality measurements

6.4.1 Meat pH

The pH results (Table 13) were relatively high at the end of the VFC period compared to the pH values expected at the end of a CC process. This result is similar to the findings of Bowling *et al* (1987a) and Jamie *et al* (1992) and suggests the rate of temperature fall in relation to the pH decline is very rapid for VFC.

Table 13 Muscle pH at various times

Muscle	pH before PTC	pH after PTC	pH 24h post slaughter
LD	6.49±0.13	6.15±0.04	5.73±0.07
SM	6.43±0.11	6.21±0.03	5.75±0.04
ST	6.11±0.08	6.07±0.10	5.74±0.07

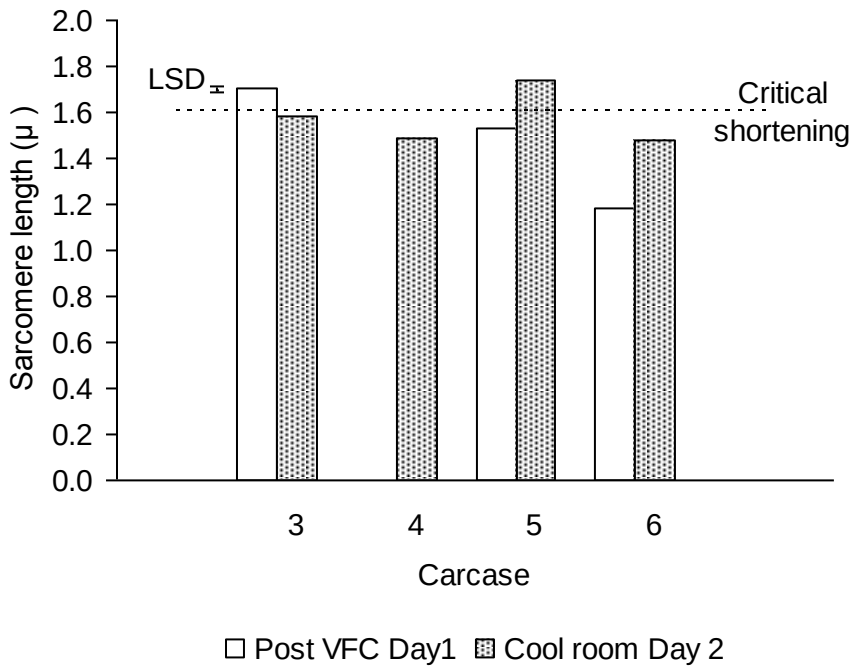
Values are means ± sem.

6.4.2 Sarcomere length

Shortening occurred in all carcases and was greatest for carcase 6 (Figure 5). The sarcomere length measurements are consistent with the pH by temperature rate of decline being sufficiently slow to cause cold shortening. However the back straps taken out of carcass 6 hot did not change length (46cms) during the cooling process including the subsequent period of 24 hours during which they were kept in a cool room with a temperature setting of 1.7^{o}C.

Measurement of the gross length of back straps may therefore not be an effective way of judging sarcomere shortening. An unexpected finding was that sarcomere lengths apparently increased after PTC in carcases 5 and 6. The reasons for this are uncertain and such a finding needs further validation to determine if it was in fact a real effect.

Figure 5 Sarcomere lengths of loin for carcases 3, 4, 5, and 6



Values are means for each carcase. Sample from day 1 for carcase 4 was subject to visual distortion and could not be read by the laser diffraction method.

6.4.3 Shear force values

Table 14 Shear force values for the loin

Carcass	Shear force (kgF)	
	Day 0	Day 1
1	12.0	*
2	8.8	*
3	14.1	9.5
4	13.5	7.7
5	5.8	*
6	24.2	17.6
Mean	13.0	11.6

* Sample not available for testing

Shear force (Table 14) was below the consumer benchmark of 11 KgF in 2 of the 6 carcases immediately after VFC. Shear force reduced for all of the 3 carcases in which the shear force was measured on both days. This suggests that significant tenderisation occurred in the first 24 hours post slaughter.

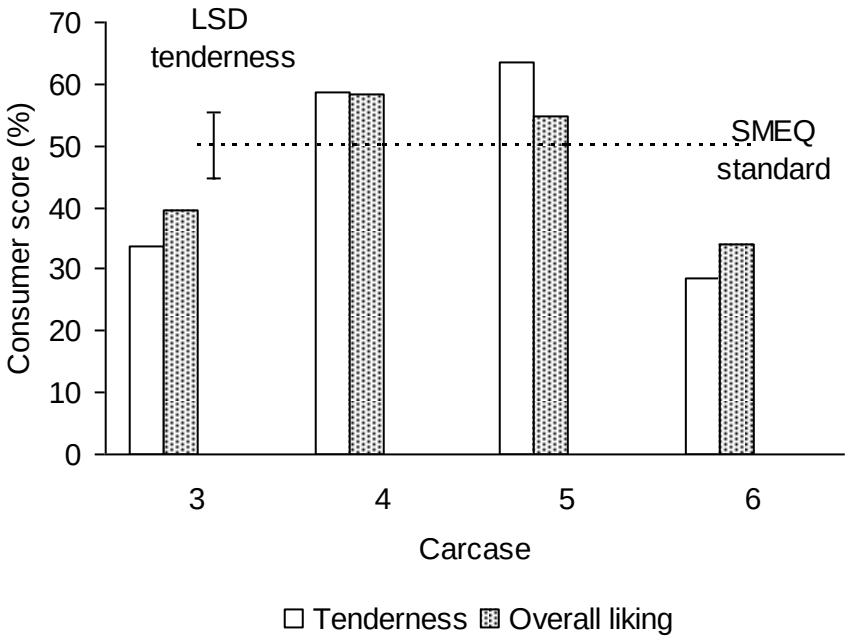
6.4.4 Taste panel assessment

Table 15 Odour, juiciness and flavour scores for loin from carcases 3, 4, 5, and 6

Parameter	Carcase				SED	P value
	3	4	5	6		
Odour strength	57.8	63.7	53.3	61.5	7.79	0.57
Odour liking	50.0	49.5	49.7	57.2	15.60	0.76
Juiciness	57.9	54.4	56.0	47.6	13.60	0.76
Flavour strength	52.6	51.4	52.2	51.7	14.00	1
Flavour liking	53.0	60.3	63.7	47.7	14.00	0.17
Residual feel	34.2	38.6	32	46.2	10.90	0.13

There was no significant difference ($P>0.05$) between carcases for consumer assessment of odour, juiciness, flavour and residual mouth feel (Table 15). However there was a significant ($P<0.05$) difference between carcases for tenderness and overall liking (Figure 6).

Figure 6 Tenderness and overall liking scores for carcases 3, 4, 5 and 6



SMEQ = Sheep Meat Eating Quality

Meat from lambs 1 and 2 were excluded from the taste panel because of the difficulties associated with the chilling of these bodies. However meat from these carcases was barbecued on the evening of April 11th. This meat was judged to be variable by a number of people with some pieces appearing tough and others tender. The comment was made that the meat was very juicy.

The controlled taste panel were done with loins from carcases 3, 4, 5 and 6 (Table 15, Figure 6). The results from this exercise suggest that meat of acceptable eating quality is possible with a minimal ageing period from meat subjected to VFC in the PTC. Carcase 5 had the highest tenderness rating and the highest sarcomere length on day 2; conversely carcase 6 had the lowest tenderness score and lowest sarcomere length. The tenderness ratings reflected the shear force values (Table 6). The reason for carcase 3 being tough is not clear. The explanation is not likely to be related to sarcomere length because the sarcomere length was similar for carcases 3 and 5. McGeehin *et al* (2002) found that extending the VFC period reduced eating quality so perhaps this effect may have been related to chilling time in some way. Again comments were made by members of the taste panel that the meat in general was very juicy.

6.5 Meat colour

The meat was slightly dark in colour having a L value below the accepted target of 36 (Hopkins, 1996). However the meat was also very red in colour due to very low b values (Table 16). This was consistent with other studies that have found that VFC causes meat to be darker in colour.

Table 16 Meat colour 24h post PTC

Colour parameter	Muscle	
	LD	SM
L (lightness)	34.9±1.18	33.7±1.39
A (red/green)	19.4±1.03	20.1±1.53
B (blue/yellow)	4.4±0.86	4.3±1.1
Chroma (intensity)	20.0±0.86	20.6±1.23
Hue (shade)	12.0±0.36	11.9±0.49

7 Conclusions

7.1 Literature review

A considerable amount of literature is available on very fast chilling. The most consistent economic benefit of VFC appears to be reduced carcase shrink loss although it was not clear how this might translate to an increase in lean meat yield. The results for eating quality have been variable and further work is required to understand this variation. The source of variation in tenderness may be similar for both VFC and CC, and the influence of sarcomere shortening may simply “amplify” this variation in a VFC scenario. A better understanding of post mortem proteolysis could lead to a tender product from VFC. There was evidence in the literature that VFC can potentially be used to reduce processing time and at the same time improve or at least maintain meat eating quality. However the method to do this predictably under various market scenarios was not clearly described in the literature. Elucidating such a method presents an on opportunity for further research in VFC.

7.2 Pandura Pilot Experiment

A chilling rate consistent with VFC was achieved for lamb carcases with the PTC. Encouraging results were obtained for eating quality although a larger experiment would be required to evaluate the eating quality of meat chilled using the PTC system. A prototype based on the PTC system could be suitable for further evaluation of VFC in Australia on a larger scale than was possible in the pilot experiment.

8 Appendices

The following graphs present the raw temperature data for each carcase. Annotations are provided to describe the timing of various interventions, such as movement from one compartment to another.

8.1 Temperature by time plots for each carcase

Figure 7 Carcass 1 loin

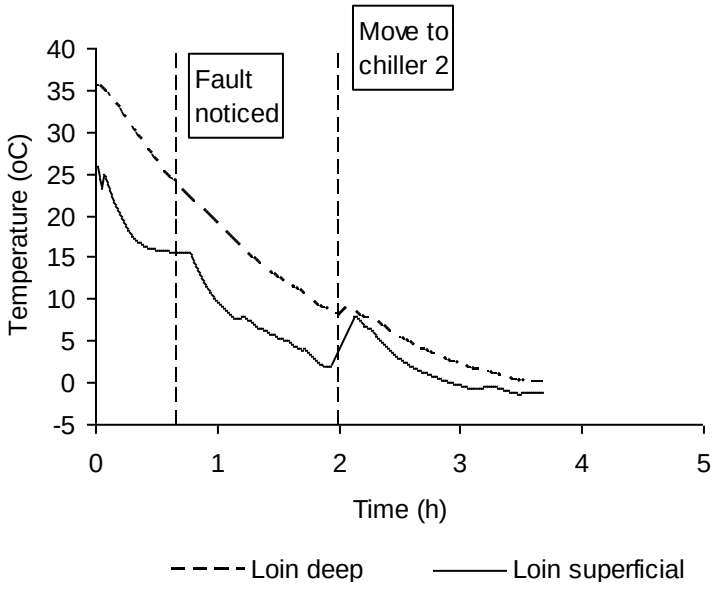


Figure 8 Carcass 1 leg

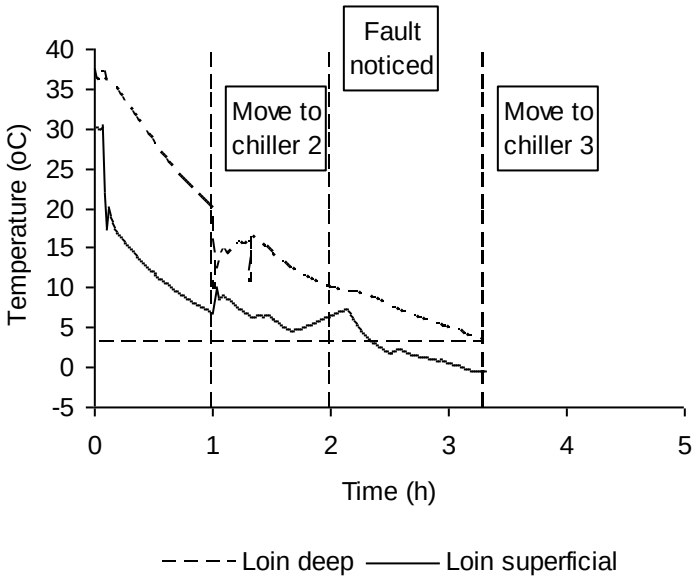


Figure 9 Carcass 1 shoulder

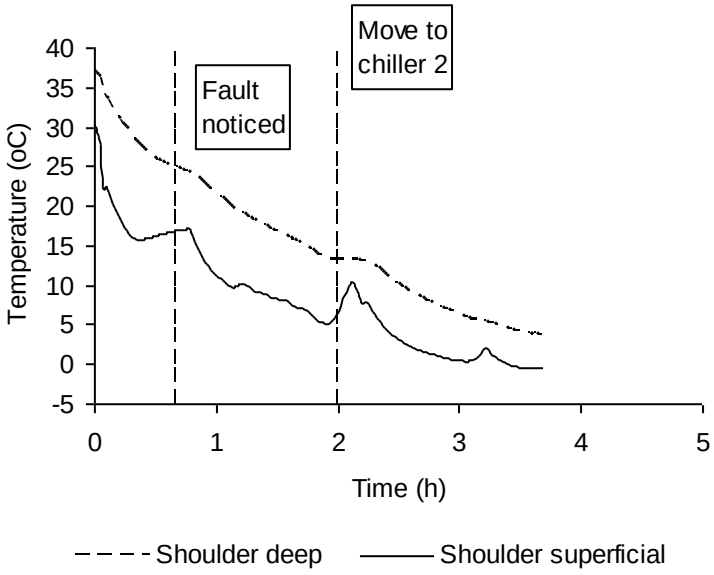


Figure 10 Carcass 2 loin

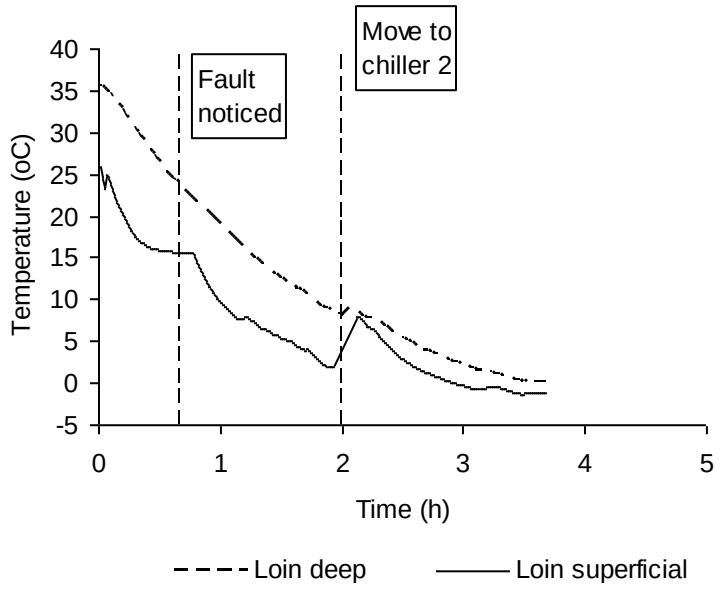


Figure 11 Carcase 2 leg

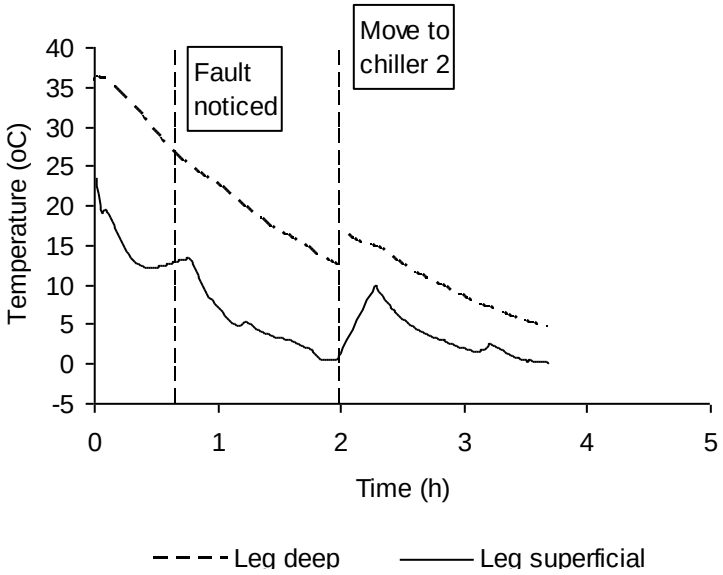


Figure 12 Carcass 2 shoulder

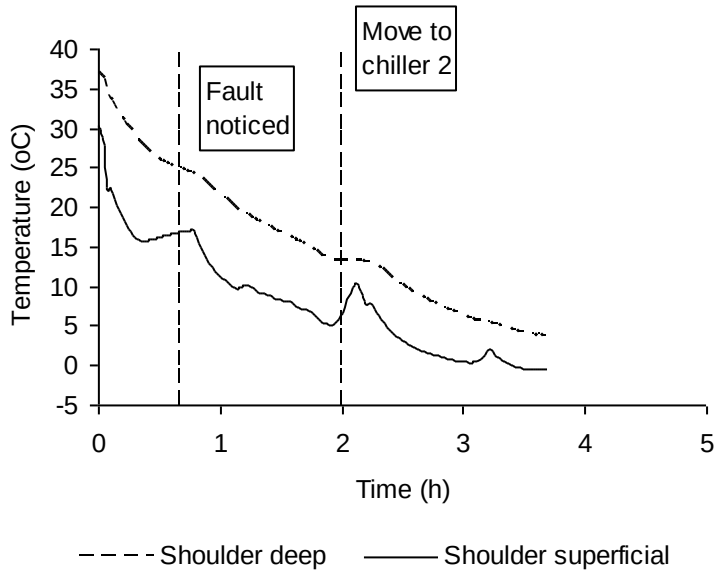


Figure 13 Carcass 3 loin

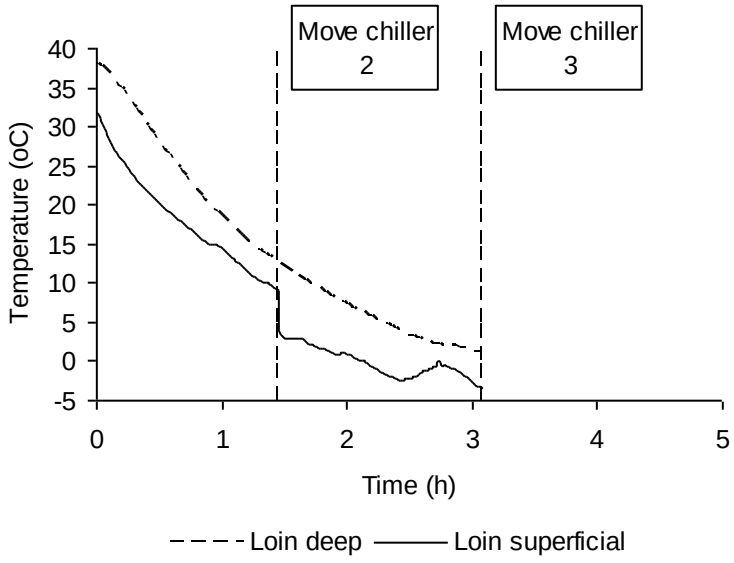


Figure 14 Carcass 3 leg

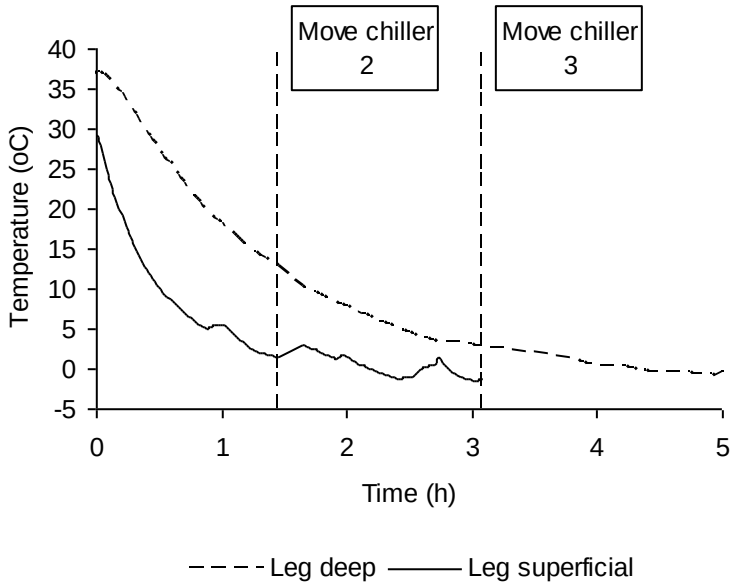


Figure 15 Carcass 3 shoulder

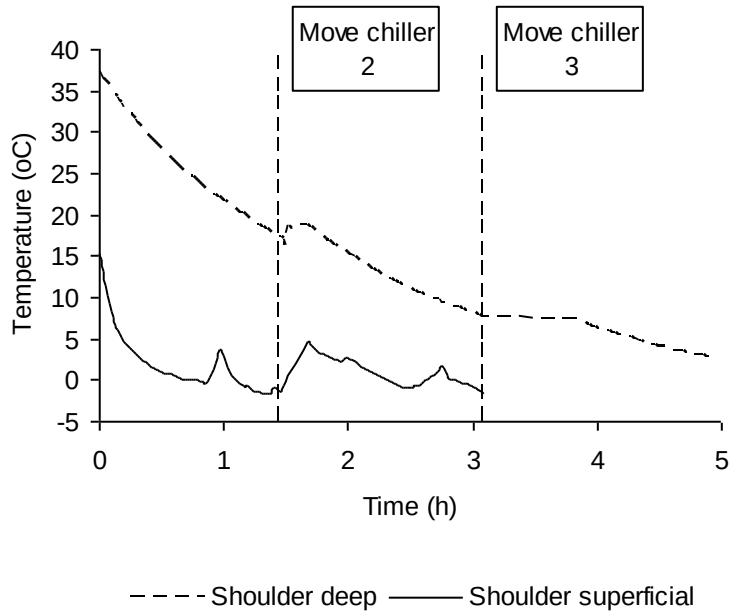


Figure 16 Carcass 4 Loin

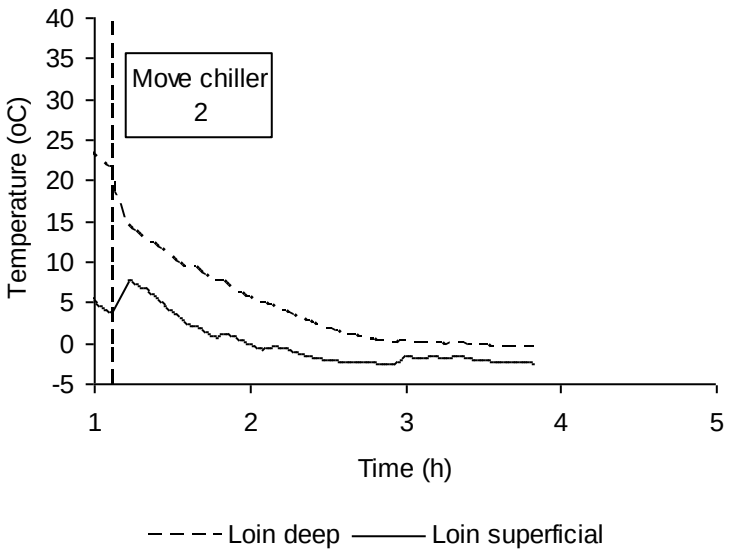


Figure 17 Carcass 4 leg

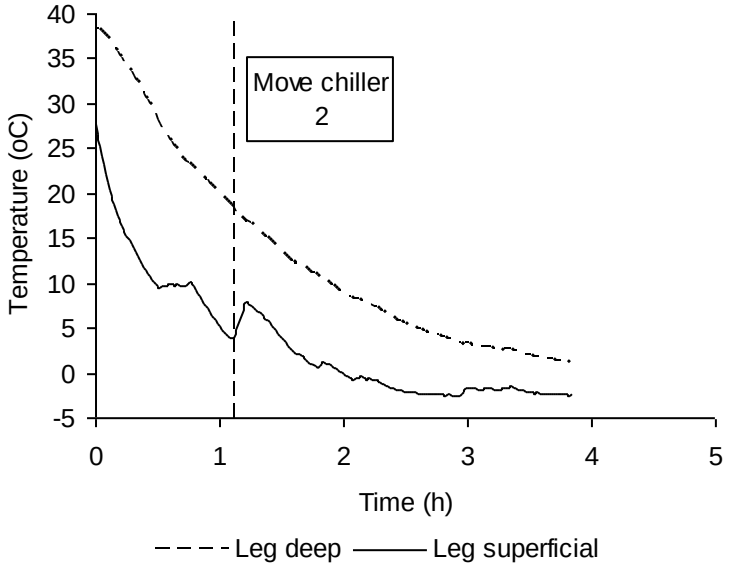


Figure 18 Carcass 4 shoulder

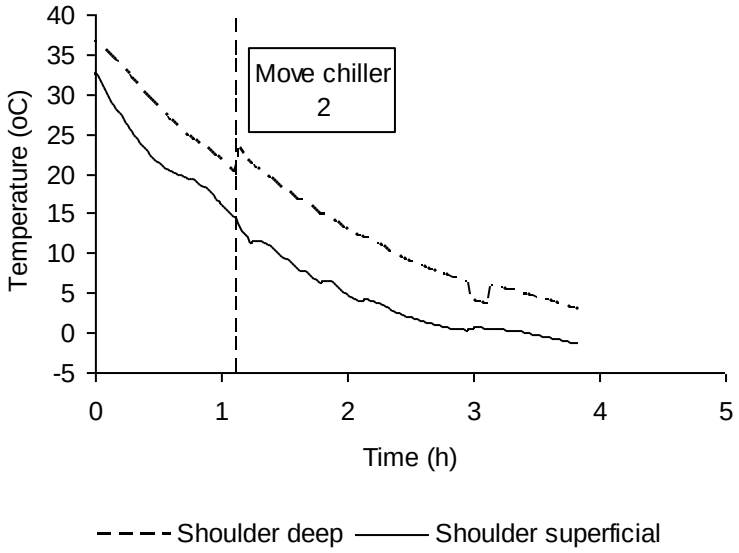


Figure 19 Carcass 5 loin

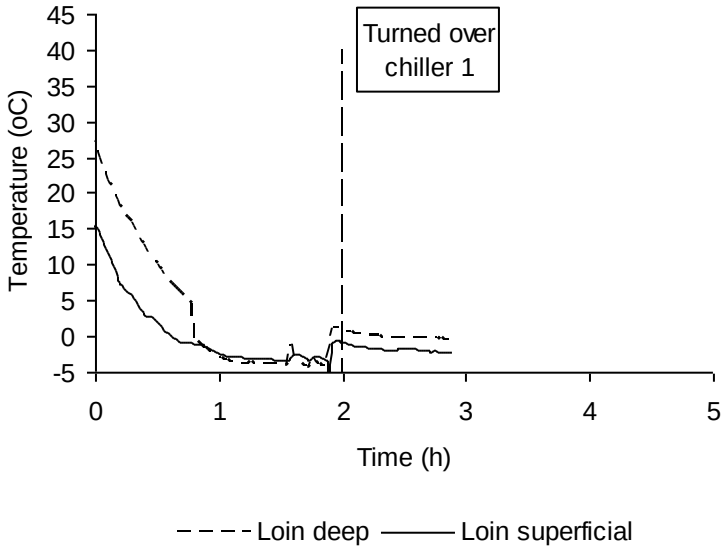


Figure 20 Carcass 5 leg

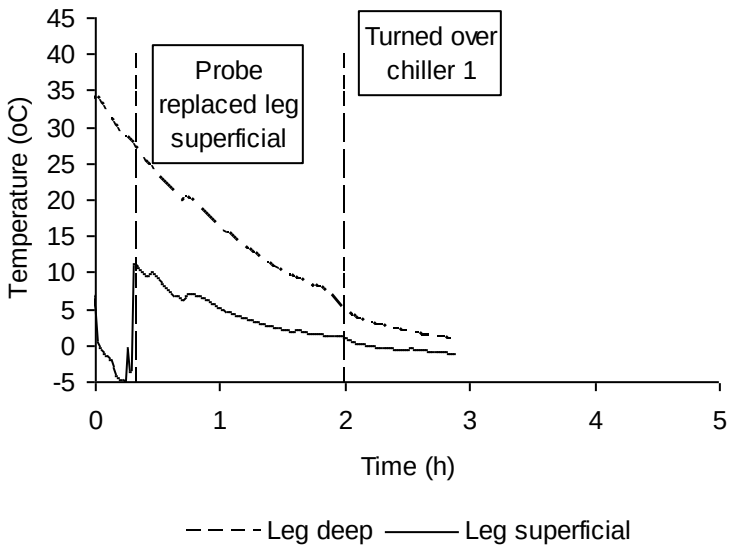


Figure 21 Carcass 5 shoulder

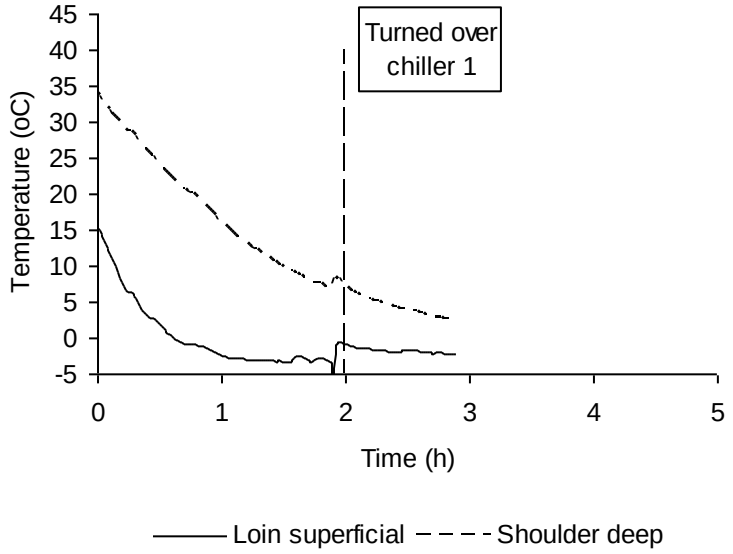
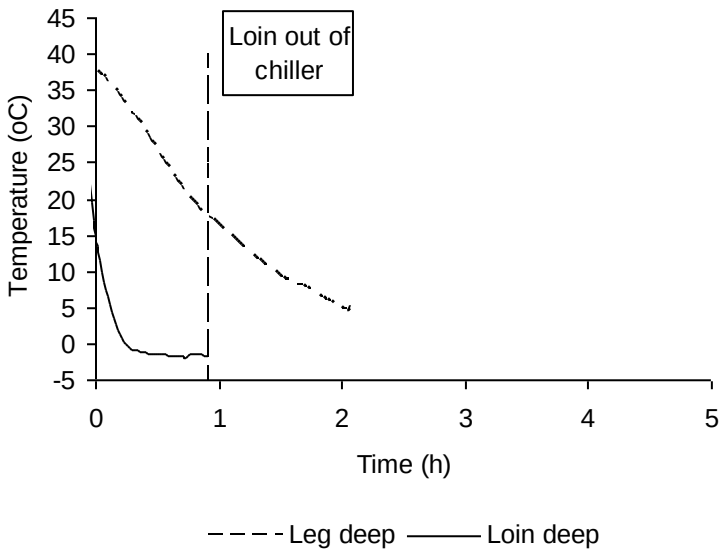


Figure 22 Carcass 6 deep loin and leg



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