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Critical control points for meat quality in the Australian sheep meat supply chain

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Abstract. The sheep meat eating quality research program has identified a number of outcomes and critical control points in the supply chain from live sheep genetics to cooked meat. The critical control points, which are largely independent of each other, can be translated into quality management systems to increase average eating quality of all cuts and lower variability. The choice of sire was a critical control point in that selecting for high growth rate and muscling can adversely affect eating quality. The challenge is to make sure that high yield traits are not promoted at the expense of eating quality. Animal age was a critical control point but it was clear that the definition of hogget could be revised to include slightly older animals with teeth in eruption but not in wear. Moreover, *M. longissumus dorsi* from older animals had only slightly lower eating quality than that from lamb such that this cut could be positioned as a premium product at all maturities, complementing the universally tender muscle *psoas major*. There was no doubt, however, that over all muscles, lamb remained the premium product. The critical control point for nutrition is that it be adequate, typically to ensure growth of at least 50 g/animal.day. Meat quality is improved through higher glycogen concentrations in muscles at slaughter, higher intramuscular fat content, and possibly reduced collagen crosslinking. Critical control points between muster and slaughter are more difficult to define but are generally aimed at stress reduction to minimise occurrence of the high ultimate pH condition. They include avoiding temperature extremes, loud noises and use of dogs, implementation of good lairage design and the use of skilled animal handlers. Stress is best monitored by ultimate pH measurements in abattoirs, rather than at remote points down the supply chain. After slaughter, the use of electrical stimulation to accelerate post mortem glycolysis is a critical control point. Its use is indicated where 2 conditions are simultaneously met: carcasses are Achilles-hung throughout processing, and the meat is destined for early consumption, as would normally be the case for the domestic market. By accelerating glycolysis, the temperature at rigor can be optimised for rapid tenderisation of low-connective tissue muscles through ageing. The alternative to electrical stimulation of these muscles for the local market is Tenderstretch hanging where rapid ageing is less temperature dependent. Where electrical stimulation is applied the monitoring of its effects with a temperature probe and a pH metre is a critical control point. Even where stimulation is not applied, measurement of average muscle temperature and pH is useful for defining any process. This is because the first 24 h after slaughter sets the scene for later meat storage/distribution, which has its own critical control point: the temperature at which meat is held between abattoir and consumption. Where meat is destined for early sale, the temperature of processing and storage can and should be higher than where the meat is destined for long-term storage as in export markets. For early sale, rapid ageing to optimum eating quality is promoted by higher temperature (2–4°C), whereas for export sale, very cool meat will slowly age in the weeks before consumption while at the same time minimising spoilage and maximising display life. Thus, matching the time–temperature profile of processing and storage to a particular market is a critical control point. The retail end of the supply chain has its own control points, principally display temperature and choice of display packaging, which have major effects on chilled display life. The cooler the better. Compared with conventional overwrap packs, modified atmosphere packs extend display life by typically 80%. However, these more sophisticated packs cost more and will not suit all domestic retailers. The matching of muscles by age with recommended cooking method is a critical control point at retail for ensuring consumer satisfaction. The challenge is effective communication with consumers and is part of the wider challenge of effectively communicating quality-related information at all links of the supply chain.

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Introduction

The supply chain of sheep meat can be seen as an industrial process. The more successful industrial processes are characterised by control at critical points so that the qualities of outcomes are consistently acceptable to the intended market. In formal statistical terms, successful outcomes, typically products, have high accuracy and high precision in product attributes.

Successful outcomes in the sheep meat supply chain similarly demand control at critical points. To date, the sheep meat supply chain in Australia has been well aware of the critical control points that determine hygiene. If these were not managed, the supply chain could not legally operate so there has been a powerful incentive to manage hygiene. In the meantime, managing eating quality has been largely overlooked. By contrast, the vertically integrated chicken industry exercises tight control throughout the supply chain, thus ensuring consistent eating quality. This fact, coupled with the low price of table-ready chicken and perceived health risks of eating red meat, has resulted in a decreasing market share for sheep meat and beef in Australia. Consumption of lamb has declined from a peak of 21 kg/capita in the late 1960s to 12 kg in 2000 (AusStats 2000). Consumption of beef has recorded 3–4% annual falls in the late 1990s continuing a trend from the 1970s. Poultry consumption has continued to rise and in 2000 was about 32 kg per capita, and remains the market leader (AusStats 2000).

In this special publication, the inputs to sheep meat supply chains have been investigated to expose the critical control points that determine sheep meat eating quality. Following an introductory paper by Russell *et al*. (2005), 13 research papers describe experiments and analyses spanning from pasture to plate. The aim of this paper is to review the main outcomes and critical control points, and briefly to examine their implementation.

Sheep breed

Hopkins *et al*. (2005*a*) investigated the eating quality of lamb from Poll Dorset sires. Three sires were selected for high growth rate, 3 for high muscling scores and 3 were controls. Muscles from 2 of the 9 sires (high growth rate, high muscling) had high shear force scores, meaning tougher meat. When tested by consumer panel the same sires were again distinguished and it was clear that lack of tenderness and juiciness were the most affected attributes. The Carwell gene was implicated in these effects and is an example where selection for 1 trait can have detrimental effects on others. The callipyge gene in sheep that results in markedly better meat yields but tougher meat is a good example (Jackson and Green 1993). Although the effects observed with the Carwell gene are not as great as for callipyge, they are, nonetheless, measurable.

Therefore, choice of sire is a critical control point in sheep meat eating quality. The challenge is to make sure that meat yield traits are not over-promoted at the expense of eating quality. Balancing production and eating quality goals to achieve optimised profitability will be facilitated by the development of vertically integrated supply chains where producers are rewarded for using specific sire lines that yield superior eating quality.

Hopkins *et al*. (2005*b*) researched the eating quality from common Australian sheep breeds and crosses in various age categories. A feature of first cross (Border Leicester × Merino) and Merino weaned lambs was often higher meat pH. Prior research (Young *et al*. 1993; Hopkins and Fogarty 1998; Gardner *et al*. 1999) has also shown that sheep with Merino genetics are more prone to the high pH condition; a clear indication of greater stress susceptibility.

Because 70% of ovine genetics in Australia is Merino, the creation or maintenance of existing low stress handling systems is an imperative. At the same time, the often disjointed supply chain between muster and slaughter makes any management system difficult to apply. This is discussed in a later section. In the meantime a critical control point can be defined: to monitor stress management and other factors leading to the high pH condition. Rather than further down the supply chain, pH should be measured in abattoirs. Abattoirs interested in quality control will already have pH meters, and as a general control principle, the closer detection of a problem to its source, the sooner control can be re-established. With existing technology, the cost of pH testing each ovine carcass would be prohibitive and the only realistic approach may be to develop a sampling protocol to point to upstream conditions giving rise to the problem.

Hopkins *et al*. (2005*b*) observed an interesting first-cross breed effect where Poll Dorset × Merino lambs had a higher myoglobin content than Border Leicester × Merino lambs. This result suggests colour differences between breeds that could be exploited in retail marketing. The belief that Merino has inherently darker meat irrespective of stress sensitivity was not supported by Wiese *et al*. (2005), who showed that the myoglobin concentration was similar in pure Merino and crosses. In earlier work Gardner *et al*. (1999) clearly showed lower myoglobin concentrations in Merino compared with other breeds.

Hopkins *et al*. (2005*b*) noted a large variation in eating quality within breeds and between muscles such that recommendations about using specific muscles from specific breeds and crosses cannot be made. This is an important result for the Merino breed, which has an anecdotal reputation of poorer eating quality. Provided Merino lambs are fed to achieve their optimum growth rate and handled in a low stress way at slaughter, the eating quality matches that of cross breeds. The Merino genome is not a fundamental block to high eating quality, as is clear from Hopkins and Fogarty (1998) and Safari *et al*. (2001).

Sheep age

Animal age is particularly important in the sheep meat industry because legal definitions apply to the age-based names lamb, hogget and mutton. Young and Lim (2001) showed that on name alone New Zealand consumers perceived that lamb had the highest quality sheep meat, while hogget and mutton were 23 and 36% lower in quality, respectively. A similar outcome could be expected in Australia.

As animals age, intramuscular collagen becomes increasingly crosslinked and insoluble (Kopp and Bonnet 1987), making all meat intrinsically tougher. There are at least 7 studies employing an objective test, or a trained sensory panel, which confirm this generality with sheep meat. However, the degree of quality deterioration with age as measured by consumers has been poorly researched. The issue is particularly important for Australia where wool production results in a significant pool of older sheep at slaughter. Five papers included sheep age as an eating quality factor.

Hopkins *et al*. (2005*b*) showed that sucker lambs had a lighter meat colour than weaned lamb and hogget. On colour grounds alone sucker lambs can be marketed as a niche product. Moreover, eating quality scores for *M. longissimus* clearly showed that sucker lambs had the best eating quality score (65) ahead of weaned lambs (62) and hogget (58) [panellists scored on a scale of 0 (very low) to 100 (for high) of 4 sensory attributes: tenderness, juiciness, flavour, and overall]. However, these differences between sheep categories were not as clear for the *M. biceps femoris* which, throughout the research program, demonstrated poorer eating quality irrespective of the age of the animal.

Using *M. longissimus* and *M. biceps femoris* as model muscles in Merino aged between 8.5 and 69 months, Pethick *et al*. (2005*a*) showed that of the 4 sensory attributes, tenderness decreased the most with increasing age and was most marked in *M. biceps femoris*. This is consistent with the concept of collagen hardening with age. The most significant decline in tenderness occurred between 20 and 33 months. 'Overall liking' also declined but not as much. Intramuscular fat content, which showed an overall increase with age, may be the moderating influence here because it is important in the sensory attributes, juiciness and flavour [a striking result was obtained at 69 months where the expected dislike of tenderness was strongly moderated by flavour that was probably positively affected by the high intramuscular fat content (9%) at that age]. In a parallel experiment with lamb and hogget (milk, 2 and 4 tooth), the eating quality of *M. longissimus* did not decline significantly. In contrast the eating quality of *M. biceps femoris* and *M. semimembranosus* declined markedly.

The maturity points at which eating quality begins to deteriorate for different muscles are clearly of major interest. In Australia, the boundary between lamb and hogget is defined by any evidence of the first permanent teeth in eruption. Wiese *et al*. (2005) compared the eating quality of 3 dentition categories of sheep aged between 14 and 19 months: no eruption of first permanent teeth (youngest on average), erupted but not in wear, and fully erupted and in wear. A trained sensory panel found no difference in the eating quality of *M. longissimus* between the categories for any sensory attribute. In hindsight, a parallel sensory trial with *M. biceps femoris* would have been useful considering its potential for quality deterioration with age (Pethick *et al*. 2005*a*). However, because first permanent teeth eruption normally occurs before the critical period between 20 and 33 months for eating quality of both those muscles (Pethick *et al*. 2005*a*), it follows that the definition of lamb can be changed without loss of eating quality (see below).

In an experiment mainly directed at processing factors, Thompson *et al*. (2005*a*) showed that age (6 *v*. 48 months) was the most important factor affecting eating quality. While the 2 ages were possibly confounded by subtle breed difference, the results are consistent with the other studies presented here. Likewise, Thompson *et al*. (2005*b*) showed a clear age effect, which was not surprising considering the age difference (9 *v*. 96 months).

Overall, it is clear that animal age is a critical control point but there are interactions with muscle and cooking method. For the muscles assessed in the experiments reviewed here, the eating quality of *M. longissimus* deteriorated the least with age. The universally tender muscle *M. psoas major* can be expected to behave similarly.

The results show that the current definition of lamb can be redefined towards the inclusion of slightly older animals with first permanent teeth erupted but not in wear. Not all producers will benefit from a redefinition and this presents a political challenge. But as discussed by Wiese *et al*. (2005), the change should be generally beneficial for producers and consumers. By allowing lambs to be slightly older at slaughter, the industry would be able to ensure the supply of lambs over a longer period. Merino lambs comprise a substantial part of the Australian industry and, being leaner and later maturing, are suited to a classification system that allows older animals to be classified as lambs. The lucrative markets of Europe and the USA require a large lamb, but the existing definition of lamb limits the number of large carcasses. Whatever the new definition, the names 'hogget' and 'mutton' present a major marketing hurdle (Young and Lim 2001). When (and if) new names are adopted, the short-term reaction of retailers and consumers is unpredictable. Given time, however, new names will become accepted and an increasingly smaller fraction of the population will recognise the older names. The important point is to use the new names at all times.

Nutrition

Three papers included the effect of nutrition on eating quality and other meat attributes. As another factor in the

Poll Dorset sire experiment, Hopkins *et al.* (2005*a*) raised the lambs on 2 pasture nutrition planes, high and low. Meat pH was higher where the lambs had been poorly fed. Lower glycogen concentration was presumably the cause of this effect given the well-known relationship between muscle glycogen and ultimate pH (see e.g. Przybylski *et al.* 1994). Shear force values were higher in both *M. longissimus and semimembranosus* indicating a pH-dependent toughening effect as previously described by Purchas and Aungsupakorn (1993) and Watanabe *et al.* (1996). However, after 5 days ageing a consumer panel detected no difference in *M. longissimus* due to nutrition plane.

In an experiment that imposed dietary extremes, Pethick *et al.* (2005*b*) finished Suffolk × Merino 6-month-old lambs on 4 diets: pasture, high-energy pellets, moderate energy pellets and poor quality straw. Allocation to treatments was intended to result in equal carcass weights, which was achieved for all but the straw treatment carcasses, the mean of which was 5% lighter. Both pasture and pellets resulted in high growth rates (up to 190 g/animal.day), whereas lambs on straw lost weight at 200 g/animal.day. Ultimate pH in 3 muscles was highest in the straw treatment, but tenderness after ageing was unaffected by diet. In contrast, the intramuscular fat content was lowest in the straw diet and this was clearly reflected in lower consumer scores for juiciness and flavour. The importance of maintaining intramuscular fat was noted earlier in the animal-age trial by Pethick *et al.* (2005*a*). An outcome of the collective experiments was that a 1 percentage point drop in intramuscular fat content in the range 4–9% of wet weight is responsible for about a 2 percentage point drop in consumer score.

Pethick *et al.* (2005*b*) also measured muscle glycogen concentration on-farm in *M. semimembranosus* and *semitendinosus*. The concentration was highest in the high-energy pellet treatment (a mean of 1.88% in *M. longissimus*) but was easily high enough in the pasture treatment (1.50%) to result in normal ultimate pH values. This effect of high-energy diets has been observed previously (Pethick and Rowe 1996; Daly *et al.* 1999; Pethick *et al.* 2000) and in other research in this program (Jacob *et al.* 2005*a*).

Importantly there were no significant differences in eating quality between pellet diet and pasture. This means that producers are free to choose between these finishing systems based on production cost and maintenance of weight gain, not on perceived flavour advantages; at least for the Australian consumer. However, pure legume (leafy phase), pure brassica, and complete grain finishing diets can each cause flavour problems (Park *et al.* 1972*a*, 1972*b*; V. H. Oddy unpublished data). But if these are avoided, choice of finishing diet is not a critical control point.

The critical control point for nutrition is that it be adequate, typically to ensure growth of at least 50 g/day. Meat quality is improved through adequate muscle glycogen as a buffer against high ultimate pH, higher intramuscular fat, and possibly reduced collagen crosslinking (Rompala and Jones 1984; Bailey and Light 1989). Moreover, good welfare is seen to be practised with well-fed animals and meat yields are higher from heavier animals. The only potential conflict arising from increased intramuscular fat favouring juiciness and flavour is the contemporary societal view that dietary fat is bad for health. However, the dietary consequences of 3 *v.* 4+ % intramuscular fat in a food that makes up only a fraction of total energy consumed is negligible. Above all the sheep meat industry has to provide an excellent eating experience and this is best provided by an intramuscular fat content between 4 and 5% in lambs finished to a fat score of 2 or 3, corresponding to a GR fat depth of 6–19 mm.

Muster, transport and lairage

It is intuitively believable that the transport of sheep from feedlot or farm by truck to the unfamiliar environment of abattoir lairage causes stress. All animals are equipped with homeostatic mechanisms to minimise the effects of stress on metabolism but these can be swamped when stress is excessive or chronic, or the animal is prone to stress effects through gender or breeding as in the case of bulls (Graafhuis and Devine 1994; Young *et al.* 2004) and modern pig breeds (Gregory 1998).

The most obvious sign of animal stress on the resulting sheep meat is glycogen depletion that leads to higher pH in usually valuable cuts; the high ultimate pH condition. The challenge was to identify critical control points governing this condition in typical Australian supply chains. Jacob *et al.* (2005*a*) surveyed 13 representative lamb consignments of various ages, dates, transport distances, and times to slaughter. Although it is difficult to assign cause in survey work, 4 results stood out. One consignment had the lowest lamb growth rate, the lowest muscle glycogen concentration and the highest occurrence of high pH meat. Of the 2 muscles studied, *M. semimembranosus* and *M. semitendinosus*, the latter suffered more glycogen loss during transport and is consistent with its more glycolytic metabolic profile. Length of time in lairage had no clear effect on muscle glycogen concentration. However, there was an indication that slaughter of sucker lambs immediately on arrival caused an increase in meat pH, so ‘tailgate slaughtering’ of this category cannot be recommended on the basis of this experiment.

Jacob *et al.* (2005*b*) surveyed the effects of lairage time on meat quality attributes and consumer scores for 3 age categories. After varying times between muster and arrival (16 to 43 h), sheep were held for 0, 24 and 48 h before slaughter. Slaughter at these 3 times had no effect on ultimate pH, confirming the previously observed resilience to fasting (Pethick *et al.* 1999; Jacob *et al.* 2005*a*), but not the effect of tailgate slaughtering on sucker lambs (Jacob *et al.* 2005*a*). None of 4 eating quality attributes were affected by length of lairage. Although the statistically significant effect of hue angle with lairage time probably has no commercial importance, 3 statistically insignificant trends certainly are commercially important: GR fat depth, dressing percentage and hot carcass weight trended down with time. For this reason long lairage times should be avoided.

In an experiment designed to avoid the uncertainties of survey experiments Warner *et al*. (2005) examined the effect of vigorous pre-slaughter exercise on the ultimate pH of Merino cross lambs. Exercise increased the pH of 3 muscles indicating that minimisation of exercise in the supply chain from farm to slaughter is a critical control point.

Other critical control points are more difficult to define for muster, transport and lairage than for other links in the supply chain because stress is difficult to measure. Responsibility for meat quality problems is difficult to assign and is thus a potential cause of conflict between the people involved. In establishing an effective quality control system some aspects will be easier than others, such as dog-free handling in lairage and design to facilitate low-stress handling (Grandin 2001). The effects of adverse weather are difficult to avoid but extremes should be wherever possible. Another general principle is adoption of short times between muster and slaughter to minimise weight loss etc. Short times are also more consistent with cost-saving just-in-time supply chain philosophies, and real and perceived welfare issues in the eyes of the public. Handling during muster and stock truck loading will remain most difficult to monitor and control.

Tailgate slaughtering is the epitome of just-in-time management, but it cannot be recommended for sucker lambs. Its avoidance for this age category is probably a critical control point, but equally, tailgate slaughtering is difficult to organise where stock comes from many producers supplying 1 abattoir.

Carcass hanging and cooling

In the supply chain from pasture to plate, the point of slaughter marks a clear division. For example, before slaughter the homeostatic mechanisms of the animal ameliorate the effects of adverse weather and handling stress. After slaughter, when muscle becomes meat, homeostasis does not apply.

While some pre-slaughter variables like animal growth rate are easy to measure, others like stress and individual responses to it are difficult or impossible to measure with present technology. After slaughter, however, variables are generally more amenable to measurement, with weight, time and temperature being the best examples. Nonetheless, some individual animal differences are retained as muscle becomes meat. A long-term goal of processing control is to tailor it to suit individual animals, thus reducing between-animal differences. Meat processing technology is not yet at that point so the short-term goal is to process carcasses to avoid adding variability and simultaneously to optimise the average eating quality of individual muscles.

Thompson *et al*. (2005*a*) examined the impact of age category (6-month-old lambs; 48-month hoggets), electrical stimulation (yes, no), hanging (Achilles, Tenderstretch), muscle (*M. biceps femoris*, *longissimus*, *serratus ventralis*), chilling rate (fast, slow) and ageing (2, 5 or 14 days) on consumer response to eating quality. These variables were chosen because prior research has shown that these are important in objective measures of quality.

Age had the largest impact on sensory scores. Across all muscles, lambs were about 9 points above hogget (64 *v.* 55) for overall liking. This result emphasises the importance of livestock variables on eating quality, an aspect that should not be overlooked in comparing the relative importance of critical control points. However, there were age category × muscle interactions as discussed later.

Muscles were the next most important factor. After statistical adjustment for temperature at rigor *M. longissimus* was expected to be well liked, and the data confirmed this. The surprise muscle in this experiment was *M. serratus ventralis* from lamb, which matched *M. longissimus* in eating quality. *M. biceps femoris* was the least liked, as shown elsewhere in the program, but overall differences in eating quality between muscles were not marked. The implication from temperature adjustment is that with good processing, differences between muscles will be minimal. Therefore, in general terms, processing for quality is a critical control point.

Age category × muscle interactions exposed the economic potential of *M. longissimus* from older animals. Muscles other than *M. longissimus* were more affected by age, presumably arising from their higher collagen content that becomes increasingly insoluble with age. Juiciness appears to be the main attraction in *M. serratus ventralis*, likely to be traceable to a higher fat content that is common in forequarter muscles.

Chilling rate and stimulation only accounted for a relatively small proportion of the variance in sensory scores, despite the extremes applied. These factors had variable effects on glycolytic rate so these processing treatments were expressed in terms of muscle temperature at rigor, pH 6.0. Thompson *et al*. (2005*a*) observed an interaction of rigor temperature and hanging method. When carcasses were Tenderstretch-hung, rigor temperature had little effect on eating quality, contrasting with Achilles-hung carcasses. In a clear inverted parabolic relationship for Achilles-hung carcasses, the lower the rigor temperature below 17°C, the lower the sensory score. This was due to cold shortening, which is a classic cause of toughness (Davey *et al*. 1967). The higher the rigor temperature above 17°C, the lower the sensory score due to heat shortening, also known as rigor shortening (Hertzman *et al*. 1993). This effect of rigor temperature applied to not just tenderness but to all sensory attributes, demonstrating the effect that 1 important attribute can have on the perception of others.

In Achilles-hung carcasses, a temperature at rigor (pH 6) below 25°C is a critical control point. The lower limit depends on the intended market.

Tenderstretch also resulted in a general improvement in meat quality compared with Achilles-hung carcasses, presumably through avoidance of shortening. This resulted in apparent faster ageing to optimum eating quality, a result consistent with prior research (Hostetler *et al*. 1972; Bouton *et al*. 1973; O'Halloran *et al*. 1998). Moreover, there was less variation in eating quality between mutton muscles when Tenderstretch was employed.

These clear effects of hanging method mark it as a critical control point. Electrical stimulation is not needed with Tenderstretch. The rapid ageing and greater consistency in eating quality from older animals suggests a market opportunity: a processor without electrical stimulation may exploit Tenderstretch on hogget and mutton carcasses where muscles are intended for early domestic retail sale under a brand that guarantees eating quality. Tenderstretch particularly suits niche markets and lends itself to branding.

The eating quality outcomes of ageing to 2, 5 or 14 days indicate that electrical stimulation is a critical control point for Achilles-hung carcasses. The eating quality of unstimulated carcasses slowly increases with time which means that sea freight exporters of chilled lamb need not electrically stimulate. The weeks in transit are sufficient to ensure ageing to an optimum eating quality. In contrast, electrical stimulation as a tool to help achieve the optimum temperature at rigor for fast ageing is important for Achilles processors targeting the local market.

Although not examined in Thompson *et al*. (2005*a*), temperature of the supply chain from the point of slaughter to the point of cooking is a critical control point for eating quality. This is discussed in more detail under meat ageing below. For the moment, however, it can be stated that the choice of the temperature profile in processing and storage regimes, broadly 'warm' or 'cold', is a critical control point in respect of matching sheep meat eating quality to different markets.

Electrical stimulation

Thompson *et al*. (2005*a*) showed that for Achilles-hung carcasses, temperature at rigor (pH 6) is a critical control point. Electrical stimulation and chilling rate are the 2 tools required to achieve this. Thompson *et al*. (2005*a*) also showed that electrical stimulation had inconsistent effects between abattoirs and slaughter groups within abattoirs. They concluded that in any industry implementation program, care will be required to ensure that treatments are actually achieving the desired outcomes. Predictive models that include stimulation and other electrical inputs like stunning and immobilisation currents are useful introductions to process management, but ultimately there is no substitute for measurement of temperature at rigor.

Monitoring the outputs of stunners, immobilisers and electrical stimulators, and their combined effects on temperature at rigor are critical control points.

To meet the quality demands of local markets, some processors will have to adopt electrical stimulation. In persuading industry to install stimulation equipment the facts surrounding the technology must be made clear. To this end, Shaw *et al*. (2005) compared the efficacy of new and older stimulation equipment in 2 trials. The older equipment is designated 'high voltage' and the more modern equipment 'low voltage', the latter offering lower capital cost and better worker safety.

High and low voltage electrical stimulation were both effective in accelerating glycolysis to the point that rigor was achieved on average between 28 and 13°C compared with 7 and 4°C for the controls. In 1 trial, the eating qualities of *M. longissimus lumborum* and *gluteus medius* were superior after 2 days of ageing where electrical stimulation was applied. There are 2 possible reasons for this: some degree of cold shortening was avoided and/or ageing (which starts at rigor) has a head start due to the higher temperature at rigor.

Channon *et al*. (2005) tested the effect of stimulation treatments on display colour at any time up to 35 days of ageing. Stimulation had no effect on colour. In these experiments rigor (pH 6) was attained around 27 to 28°C. Had cooling been slower than this with stimulated muscles entering rigor well above 30°C, drip would have been excessive and browning problems would occur after extended storage (Ledward 1985; Young and West 2001). These potential quality problems emphasise the importance of monitoring the outcomes of electrical stimulation and cooling to achieve a desired temperature at rigor.

Electrical stimulation is best viewed as a tool rather than a factor affecting quality. In itself it is not important for improving average quality and reducing variability. Rather it is the control of temperature at rigor onset (pH 6.0) that is important by setting the muscles up for a rapid ageing to optimum eating quality within a few days of slaughter, if indeed optimum eating quality is required within a short time.

Meat ageing and eating quality

Meat ageing is fundamentally important for optimum eating quality. This is clear from earlier work and 4 of the current research papers (Channon *et al*. 2005; Hopkins *et al*. 2005*a*; Thompson *et al*. 2005*a*; Shaw *et al*. 2005). Notably, Thompson *et al*. (2005*a*) clearly show that poor eating quality due to process-induced shortening is overcome by extended ageing. At its root, ageing is the sum of a number of biochemical reactions, principally proteolyses, which occur from the time of rigor to cooking. As with all biochemical reactions it is particularly affected by 2 easily monitored inputs: temperature and time.

The time-temperature profile from processing through to the point of cooking is well established as a critical control point for hygiene, with the fundamental requirement being to achieve a deep muscle of ≤7°C with 24 h. It is also very important for eating quality. By way of illustration, a 'cold' time–temperature profile would involve rapid chilling and maintenance of cold chill-store temperature (as low as –1.5°C) through to and best extending into the point of retail sale. Meat will age slowly and, critically, hygiene is maintained. A cold profile is particularly suited to export markets. A 'warm' process by contrast is needed for rapid sale of meat in a domestic market. Chilling should be slower and the storage temperature for the short time required can be relatively high, say 2°C. Slow chilling and warmer storage contribute to rapid ageing to achieve optimum eating quality in as few as 4 days for stimulated Achilles-hung or unstimulated Tenderstretch product.

Matching the time–temperature profile of processing and storage to a particular market is a critical control point. Failure to do so will increase the frequency of poor eating experiences through toughness (not enough ageing) but at the other extreme, over-ageing (Thompson *et al*. 2005*a*).

Meat ageing, packaging and display life

Meat ageing is also important for appearance on retail display. Although colour of hygienic meat is a poor guide to eating quality, consumers persist in judging meat quality by its perceived 'freshness' through colour (e.g. Carpenter *et al*. 2001; Young and Lim 2001) and few consumers will buy red meat unseen (Young *et al*. 2002). Fresh sheep meat is perceived to be red, preferably bright red, and certainly not brown due to surface formation of metmyoglobin. The tendency for meat to brown increases with storage time and storage temperature (e.g. George and Stratmann 1952; Seman *et al*. 1988; Jeremiah and Gibson 1997; Channon *et al*. 2005). Thus, the time–temperature profile of storage is a critical control point for colour, but one that also interacts with eating quality through meat ageing.

In addition to storage time (7, 21 or 35 days), Channon *et al*. (2005) also examined the effect of packaging method and display time on the display life of *M. longissimus dorsi* chops and boneless leg steaks (*M. quadriceps*). The packaging methods were the conventional overwrapped lamb muscles where meat is exposed to atmospheric oxygen but prevented from drying, and modified atmosphere packs (MAP, with 80% oxygen, 20% carbon dioxide) where blooming intensity is increased (due to oxygen) and microbial growth is minimised (carbon dioxide). Over all treatments, the display life of MAP packs was about 80% longer than with an air permeable overwrap. Choice of display packaging is therefore a critical control point.

Although not specifically addressed in this eating quality research program, temperature of display is a critical control point for display life. The cooler the better (Brown and Mebine 1969).

Channon *et al*. (2005) also showed the display life of *M. longissimus dorsi* was, after any time in storage, longer than that of *M. quadriceps*. The colour stability of different muscles is a critical control point for retailers handling sheep meat after longer-term storage. This control point is particularly important for export markets because the difference in display life became exacerbated the longer meat was in storage.

Muscles, cooking and eating quality

Thompson *et al*. (2005*b*) examined the eating quality effects of grilling and roasting on 7 muscles from 9-month-old lamb and 96-month-old mutton. Grilling and roasting are the 2 most popular methods of cooking sheep meat in Australia. The differences in muscle and age were intended to create variation in eating quality through variation in collagen concentration (due to muscle) and collagen solubility (due to age category).

Summed over all muscles, sensory scores from both the grilling and roasting protocols were highly correlated, some of which may be attributed to the 'halo' effect (Shorthose and Harris 1991) where 1 attribute shapes consumers' view of another unrelated attribute. Comparing between muscles for each of the attributes was very different for the 2 cooking methods. For the grilling protocol, the individual sensory attributes of different muscles were well correlated, particularly tenderness and overall liking. In contrast, roasting sensory scores showed few significant correlations between muscles, probably due to reduced sample thickness and/or connective tissue effects. Roasting is a slower cooking method than grilling and effects due collagen concentration and solubility are lessened in roasting (Resurreccion 1994).

Muscle and age effects on eating quality were much more significant for grilling than roasting. This indicates a critical control point. The matching of muscles by age with recommended cooking method is a critical control point at retail for ensuring consumer satisfaction. To this end, Thompson *et al*. (2005*b*) present a clear series of tables that can be translated into specific recommendations for matching muscles and age to cooking method.

Modelling eating quality

Pleasants (2005) took the eating quality data collected in this program and constructed a linear model of the sensory variables to derive an eating quality rate on a scale of 3: unsatisfactory, good everyday, superior. Consumer perception of sheep meat eating quality of animal groups (but not individual animals) can be correctly predicted with about 74% accuracy based on measurements of 4 attributes, tenderness, juiciness, flavour and overall liking.

The applicability of the model to the real world lies in knowing how all the factors from pasture to plate impinge on the 4 attributes. The sheep meat eating quality program has identified these factors. They have quantifiable costs, and eating quality has quantifiable financial benefits. As an example consider optimisation of a marketing strategy for hogget in domestic markets. The costs of production, processing and distribution to achieve a known eating quality grade can be compared with the likely income from that guaranteed eating quality.

To be of use the model needs to be coded into a computer program with inputs that participants in the supply chain can change. The user-friendliness of this program is a critical control point for its utility.

Conclusion

The collective research effort has identified around 14 critical control points for which clear management procedures can be designed and implemented. Other critical control points, particularly those in muster, transport and lairage, almost certainly exist but are more difficult to define. These present an ongoing opportunity for research and ultimately control.

Perhaps the most important critical control point of all is education of the human resource, for if workers can see no reason for a procedure and/or no value to self, then control will not be established. Continuing education at all points in the supply chain is the way to achieve acceptance of control systems to improve quality. However, communicating the reasons behind procedures will be particularly challenging at some points in supply chains due to low literacy levels and high staff turnover. Another challenge in communication will be between adjacent parts of the supply chain where the needs of one link should determine upstream behaviour. In vertically integrated supply chains this should be relatively easy but the meat industry supply chains are more often fragmented, making communication difficult.

In an ideal Australian sheep meat industry all participants in supply chains would improve their performance simultaneously to achieve a quantum leap in quality and consistency within months. This will not happen. But because the possible improvements are largely independent of each other, every improvement will help in reducing the rate of unsatisfactory eating experiences. This in turn should fuel consumer demand domestically and internationally and at the same time reinforce Australian sheep meat as a valuable consumer food with a bright future.

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