Review of published literature and unpublished research on factors influencing beef quality

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EXECUTIVE SUMMARY

A wide range of factors influence consumer acceptability of red meat. This review is focused on eating quality, with some reference to visual characteristics. The MLC (Meat and Livestock Commission) Blueprint for Improved Consistent Quality Beef was launched in 1990 (MLC, 1990). This current review is based on the original literature review undertaken for the Beef Blueprint and draws on reviews undertaken since that time, updated with evidence from the last 10 years.

Research related to the entire production and marketing chain has been considered, in respect of improving the eating quality of prime beef.

Meat quality traits can be influenced by production methods on farm and a wide range of factors beyond the farm gate. The review summarises the available information on these various factors for cattle.

The practical messages that have been derived from this review are:

1. Where supply can be guaranteed and there is a marketing advantage, use of a single breed can be advantageous. This can also improve consistency and, for pure-bred Aberdeen Angus and Hereford may give an eating quality advantage. This is only likely to be perceived by the consumer if strict adherence to optimum post-slaughter handling is observed.

2. Selection for tenderness is possible but it is difficult to measure the phenotype. Gene markers could help but it is important that they are validated in the population of interest.

3. Quality prime beef can come from steers, heifers and young bulls. Young bulls, however, produce tougher meat than steers at the same age so an upper age limit of 15 months is recommended, together with additional post-mortem maturation of bull meat.

4. Bulls from the suckler herd produce more tender beef. This may also apply to steers and heifers but this has not been shown.

5. An upper age limit of 30 months for steers and heifers and 15 months for bulls protects against the toughening effect of animal maturity.

6. Overall, it seems that the best advice is to finish animals as young as possible within a given production system. In general this approach will also minimise cost of production and environmental impact.

7. Aim to maximise growth rate within the production system and avoid variation in growth rate within a group of cattle.

8. Avoid imposing nutritional challenge on the pregnant cow during mid-gestation.
9. Ensure adequate antioxidant provision for cattle to optimise colour and flavour stability in beef.

10. In non-forage rations supplement with vitamin E at 1000IU per head for 100 days pre-slaughter.

11. Limit feed withdrawal pre-slaughter to avoid DFD.

12. In specific supply chains it may be possible to minimise dietary variation to generate a more consistent beef flavour.

13. Careful consideration should be given to potential flavour issues before introducing novel feed ingredients.

14. Handle cattle considerately to avoid DFD and toughness issues.

15. Avoid mixing unfamiliar groups of animals.

16. Move young bulls to the slaughter point direct from the transport vehicle where possible.

17. Apply electrical stunning with care - monitoring pH/temperature relationship post-slaughter to avoid hot-shortening.

18. Aim for a minimum fat class of 3 and conformation class O+ as precautions against poor eating quality.


20. In the absence of electrical stimulation avoid excessive chilling.

21. Use electrical stimulation to enhance beef quality where hip suspension is not being used.

22. Mature beef in the bag or on the bone to enhance tenderness.

23. Use 'dry aging' only where there is a specific value added market for the product.


25. Monitor pH/temperature post slaughter and adjust stimulation/chilling rates to ensure pH 6 is reached at a muscle temperature below 35ºC and above 12ºC.

26. Monitor ultimate pH and review the handling and process if it is outside the normal range (5.5-5.8)
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1) INTRODUCTION

A wide range of factors influence consumer acceptability of red meat. In 2007 a review was undertaken for Defra on factors influencing consumer perception and purchasing of red meat (MLC, 2007). This concluded that many of the things of concern to consumers are perception issues which are addressed either by changes to the production system or communication. The important quality attributes that result from changes to meat’s physical or biochemical properties are appearance (colour and fat content), nutritional properties (primarily fat content and type) and eating quality (texture and flavour). This review is focused on eating quality, with some reference to visual characteristics.

The MLC (Meat and Livestock Commission) Blueprint for Improved Consistent Quality Beef was launched in 1990 (MLC, 1990). This document comprised recommendations for best practice related to eating quality. In defining these, a literature review was undertaken in order that the Blueprint was based on the available scientific literature, combined with results from MLC’s own research programme (much of which was undertaken by the University of Bristol (Fisher et al., 1994)). MLC scientists updated the review in 2001 as part of a project being undertaken for Quality Meat Scotland, including a literature search over the intervening years (Matthews and Warkup, 2001). Subsequently, as more information became available through research, a review focusing on beef flavour was commissioned at the University of Bristol (Wood and Richardson, 2004).

The current review draws on these earlier documents as a basis, updated with evidence from the last 10 years. As with the earlier reviews, this draws on the available scientific literature, levy-funded research (both published and unpublished) and contacts within the global meat science community. Database searches have been conducted for the last 10 years’ scientific publications and added to the information gathered in the earlier reviews. The literature review has been largely restricted to English language documents but knowledge of research in other countries (particularly within the EU) has also influenced the conclusions drawn. Most of the scientific literature on meat science (including eating quality) is based on work conducted on grilling and roasting cuts, particularly the loin. This review is therefore inevitably biased towards these cuts.

To make the final document as readable as possible, excessive quoting of references and detailed discussion of individual scientific papers has been mainly avoided. Sufficient references have been given to support the conclusions drawn.
Research related to the entire production and marketing chain has been considered, in respect of improving the eating quality of prime beef (information related to cull cow eating quality has not been exhaustively studied although is referenced in relation to age and quality).

A number of technologies are applicable to cuts on a batch basis (e.g., high pressure treatment, the hydrodyne process). These have not been included because their small batch nature means that they are not readily applied commercially. In addition, the review has not covered substances that can be added to meat post-slaughter, such as calcium chloride, because these are regarded as food additives and the resulting meat is no longer considered fresh meat.

There is a variable volume of scientific literature covering the various factors and the evidence can be conflicting. In forming a view on the factors of importance, the evidence has been distilled and a balanced judgement made.

Contradictory data sometimes originate from overseas. This can arise as a result of both major differences in practice, and differences in the expectations of quality, particularly where consumer panelling is used.

Meat quality traits can be influenced by production methods on farm and a wide range of factors beyond the farm gate. The review summarises the available information on these various factors for cattle. Many of these production and processing factors influence meat quality through changes to the process of conversion of muscle to meat. It can be useful to have a basic understanding of this process and this is presented (largely unedited from previous versions) in section 4.
2) FACTORS AFFECTING BEEF EATING QUALITY

Consumer research on beef eating quality has shown that the most important attribute in determining acceptability is tenderness (Warkup et al., 1993). Flavour is also important and, where tenderness is less variable, it is likely that flavour increases in relative importance.

An important piece of work in defining the practical factors that can influence beef eating quality under British conditions was large multi-factor project funded by the MLC at the University of Bristol as part of the development of the Blueprint for Improved Consistent Quality Beef (unpublished report to MLC, 1991, elements of which were summarised by Fisher et al (Fisher et al., 1994)). This will be referred to in several of the subsequent sections as the Beef Blueprint trial.

Genetic effects

Breed effects

Overall breed effects on eating quality in beef are small. The only large effect of genotype in cattle on eating quality is the toughness observed by many researchers in beef from cattle of Bos indicus (Zebu or Brahmin) breeding (Gazzola et al., 1999; Harper, 1999; Wheeler et al., 2010).

Within Bos taurus (European) breeds, it appears that if there is a breed effect it may arise from associated factors like fatness or rate of maturity, although there is some evidence for an effect mediated by differences in muscle fibre composition. An MLC trial completed in 1986 compared the eating quality of steers of different breeds slaughtered on the same day in a cross-section of abattoirs. The breeds represented were Hereford x Friesian, Continental x suckler and Friesian/Holstein. Eating quality was assessed by a consumer panel of 504 families and no significant breed differences were found. In another British study, comparing Aberdeen Angus and Charolais heifers, texture, juiciness and flavour were not significantly affected by breed (Hankey et al., 1987).

The USDA Meat Animal Research Center at Clay Center, Nebraska, has been conducting large scale evaluations of cattle breeds since the late 1970s (Koch et al., 1976; Koch et al., 1979; Koch et al., 1982; Wheeler et al., 1996; Wheeler et al., 2001; Wheeler et al., 2005; Wheeler et al., 2010). A wide range of breeds have been used as sires with common dams (either Hereford, Angus or the ‘MARC III’ composite). Each ‘cycle’ of the programme includes a different combination of breeds. The results have consistently shown that Bos indicus breeds, with the exception of the Tuli (a Sanga type), result in tougher meat. Among the Bos taurus breeds, the results have not been consistent between cycles of the programme, but taken overall there are small tenderness advantages for Aberdeen Angus and Hereford (Tatum, 2006). While these effects are small these breeds are often favoured in the US,
primarily because of their higher marbling levels and therefore USDA quality grades which, it must be noted, are not strong indicators of tenderness.

Chase Jr et al (2001) also found that *Bos indicus* cattle result in tougher meat than Sanga or *Bos taurus* cattle. Another American trial, comparing Hereford, Charolais, Chianina, Limousin, Maine-Anjou and Simmental bulls on Angus x Holstein-Friesian dams showed no significant breed difference (Wilson *et al.*, 1983).

In response to concern in the British industry that the increasing penetration of lean, late maturing continental breeds may contribute to a deterioration in eating quality, MLC coordinated a trial to look at the effect of sire genotype and fatness on eating quality of progeny from dairy dams (Homer *et al.*, 1997). In steaks there was no difference across the six sire breeds (Hereford, Aberdeen Angus, Charolais, Limousin, Belgian Blue and Piedmontese) for eating quality. In roast topside, the Belgian Blue produced higher tenderness scores than the other five sire types. Overall it was concluded that breed effects were unimportant. Interestingly, Polish researchers also found advantages for Belgian Blue x dairy bulls compared with Charolais and Aberdeen Angus crosses, although pure black and white bulls had equivalent tenderness to Belgian Blue! The authors cite other Polish workers finding that black and white cattle had superior eating quality to crosses! (Groth *et al.*, 1999).

Work in pure bred steers, aimed at studying the effect of growth rate on eating quality, showed a small tenderness advantage for the Aberdeen Angus when compared with the Holstein. Charolais was intermediate (Sinclair *et al.*, 2001). The Aberdeen Angus also gave higher flavour, juiciness and overall acceptability scores than both the other breeds.

It can therefore be concluded that, whilst breed effects are small, there is probably an eating quality advantage for purebred Aberdeen Angus, and possibly Hereford. In British cattle populations, there is very little evidence for a breed effect on eating quality where cross-breeds are used.

The benefit of Belgian Blue genes on eating quality can partly be attributed to the single gene that imparts the double muscling characteristic. This results in an increase in muscle mass through increasing muscle fibre numbers. This is thought to be brought about by a dilution of collagen in the muscle (see the section on conformation). Campo *et al* (1999), however, found that animals exhibiting the double muscling phenotype did not benefit from ageing to the same extent and therefore after extended ageing (14-21 days) the tenderness advantage was lost.
Practical messages

Where supply can be guaranteed and there is a marketing advantage, use of a single breed can be advantageous. This can also improve consistency and, for pure-bred Aberdeen Angus and Hereford may give an eating quality advantage. This is only likely to be perceived by the consumer if strict adherence to optimum post-slaughter handling is observed.

Within-breed effects

Within breed, different lines of cattle exhibit differences in calpastatin activity. In particular selection for high growth rate or net feed efficiency can increase calpastatin activity and therefore reduce proteolysis post slaughter (Oddy et al., 2001).

Selection for more tender lines should be possible but measuring phenotypes is difficult unless progeny testing through commercial slaughter is an option. Selection for markers, QTL or specific genes for eating quality traits is theoretically possible and several commercial tests are available. The difficulty is ensuring that these are validated in the population of interest. It is also clear that unless strict attention is paid to post slaughter handling of carcases, the genetic differences are not apparent. For example (Allais et al., 2011) found relationships with SNPs in the calpastatin and micro-calpain genes with tenderness/toughness but the polymorphisms that the markers are associated with, and the effects, differed by breed. This illustrates the caution that needs to be exercised in transferring gene markers from one population to another.

In one of the National Cattlemen's Beef Association commissioned research summary documents, (Tatum, 2006) concluded that tenderness is moderately heritable in Bos taurus cattle (0.24-0.53). The author referred to the potential of gene markers while, again, emphasising the need for validation in the population of interest. He also commented that flight-time has a strong genetic correlation with shear force (longer flight time, lower shear force) but a poor phenotypic correlation (see the section on handling).

Practical messages

Selection for tenderness is possible but it is difficult to measure the phenotype. Gene markers could help but it is important that they are validated in the population of interest.

Sex

There is little evidence of an eating quality difference between steers and heifers. Evidence from the Beef Blueprint trial showed no differences in
eating quality. The main issue for consideration with regard to sex of cattle is the treatment of bulls.

There is considerable evidence in the literature concerning the eating quality of young bulls compared with steers. Studies have been reported from several countries on a variety of breeds and production systems. The balance of published evidence indicates that the eating quality of bull beef is poorer than that of steers of the same age, particularly in terms of tenderness. There is evidence showing adverse eating quality for bulls from several different countries: eg Britain, Denmark, Eire, USA and Canada (Baron et al., 1978; Griffin et al., 1985; Hawrysh et al., 1980; Joseph and Connolly, 1974; Klastrup, 1984; Rodbotten et al., 2010; Seideman et al., 1989).

However, the results of the Beef Blueprint trial referred to above have indicated ways in which young bulls can be included in a quality specification. As stated above, bull beef was generally tougher than that of steers and heifers. Closer examination of the results led to the conclusion that young bulls can produce quality beef provided they meet some additional requirements. This requires that bulls be less than 15 months of age at slaughter and that the meat is aged for a minimum of 14 days between slaughter and retail sale.

Research attempting to refine the age recommendation for bulls has been carried out the Scottish Agricultural College (Sinclair et al., 1998). This showed no effect of age of bulls (from 43 to 79 weeks) on eating quality. In this trial, however, all the bulls were from the suckler herd and were more tender than steers selected randomly in the abattoir on the same slaughter days!

Work carried out by the University of Bristol for the MLC to further understand the issue resulted in very similar conclusions (Fisher et al., 2001). Bulls were generally tougher than steers at all age points and there was (up to 16 months of age) no significant effect of age on tenderness. Suckled bulls, again, proved to be more tender than weaned animals. The research also showed that meat from bulls improved in tenderness by ageing for 14 days. The conclusion, therefore, remains that it is therefore feasible to include young bulls in a quality specification provided ageing is extended to ensure tenderness is maximised. The benefit of ageing bull beef for about two weeks is also supported by Klastrap (1984) and Johnson et al (1988).

The benefits of suckled bulls has been recognised in the EBLEX Quality Standard Mark for beef, allowing for older bulls from the suckler herd than whether animals have been weaned from dairy cows. It is not known whether this effect may benefit heifers and steers as well as young bulls.
Practical messages

Quality prime beef can come from steers, heifers and young bulls. Young bulls, however, produce tougher meat than steers at the same age so an upper age limit of 15 months is recommended, together with additional post-mortem maturation of bull meat.

Bulls from the suckler herd produce more tender beef. This may also apply to steers and heifers but this has not been shown.

Age

Effect of age

The literature is consistent in supporting the existence of an effect of age on tenderness (see the review by Harper (Harper, 1999)). The effect of age on the eating quality of bulls has been discussed above.

From March 1996 to November 2005, the upper age for cattle slaughtered in the UK for human consumption was 30 months. This coincided with the upper age limit recommended in the MLC Beef Blueprint and would have given protection against potential eating quality problems from older and, perhaps, slower growing animals. Since 2005 there have been a number of cattle over thirty months of age slaughtered for prime beef, and therefore the eating quality of older cattle is once more an important consideration.

Simone et al (1959) in the USA compared the eating quality of 18 and 30 month old Hereford steers. They found the younger steers to provide significantly more tender meat in major hindquarter muscles. In Australia, Bouton et al (1978a) working with aitch-bone hung steers showed a non-significant tendency for toughness to increase from 9 to 42 months of age. Australian research led to the inclusion of age assessment within the Meat Standards Australia scheme for predicting eating quality. This is used particularly with carcase weight to give a weight-for-age as a measure of growth rate (Thompson, 2002). The effect of growth rate is considered below.

Reagan et al (1976) working in the USA on cattle of 9-30 months and groups older than that also showed a trend for younger cattle to be more tender than older cattle and to have more soluble collagen but the differences were not significant.

As with most meat quality work, age effects have generally been examined in the loin. The effects on other muscles, fillet and rump from cows for example, has not been specifically studied in most cases. Prost et al (1975a; 1975b) did examine the tenderness of different muscles from animals of different ages. Most muscles were tougher in animals of 2-5 years compared with those of 1.5-2 years. The Psoas major (fillet) did not differ in tenderness and the Quadriceps femoris (thick flank) was not significantly different.
Role of collagen maturity

It is clear, then, that generally increasing age is associated with decreasing tenderness. This may be associated with changes in collagen – an increase in the proportion of heat stable cross-links (Robins et al., 1973) which is associated with a decrease in collagen solubility (Gerrard et al., 1987). Under such slow growing conditions, collagen present is likely to have a higher proportion of heat stable cross-links. Heat stable cross-links are resistant to cooking and this makes the meat tougher (Bailey and Light, 1989).

The conclusions of a review carried out in 1989 (Purchas, 1989) are probably still applicable: age effects on tenderness are unlikely to be of practical significance in commercial meat producing systems where cattle are well grown and reasonably young at slaughter (up to 30 months). With regard to bulls, it is generally considered prudent to impose a lower age limit because earlier maturity and hence toughness is likely. This is reinforced by the observation that collagen in bulls matures more rapidly than in steers (Gerrard et al., 1987).

Dentition and eating quality

Several pieces of American work (Lawrence et al. (2001) and others cited by these authors) have examined the relationship between dentition (as an indicator of animal age) and eating quality. The range usually observed is 0 to 8 permanent incisors (up to 42-48 months of age). The results are split more or less equally between those that show an effect of age on eating quality and those that do not. This may reflect the variable relationship between dentition and chronological age.

Practical messages

An upper age limit of 30 months for steers and heifers and 15 months for bulls protects against the toughening effect of animal maturity.

Feed/production system

Growth rate

There is a substantial body of evidence, almost exclusively from feedlot systems, of beneficial effects of finishing cattle on high energy rations. For example, Huffhines et al. (1992) found a trend for increased sensory panel tenderness scores over the range 70 to 126 days on feed. Aberle et al. (1981) concluded from their study that growth rate is an important variable affecting tenderness and its relationship may be a consequence of variable enzyme activity at the time of slaughter. Further, Rompala and Jones (Rompala and Jones, 1984) suggested that the collagen in meat from animals finished on a high level of nutrition would be more soluble and, thereby, have an influence on meat quality. Recent evidence, however, suggests that this effect is not
seen across all muscles, mainly benefitting the sirloin (Archile-Contreras et al., 2010).

There is also Australian evidence of a positive effect of growth rate on tenderness (Perry et al., 2002; Perry and Thompson, 2005). This showed that growth rate was a minor but positive contributor to tenderness (with higher growth rate giving increased tenderness) within a group of cattle but did not account for differences between groups. This suggests that manipulation of growth paths is not a useful means of enhancing tenderness. On the other hand reducing variation in growth rate within a group might be an important means of reducing tenderness variation. This corresponds with the work of Sinclair et al (2001) which showed no effect of growth rate, when deliberately manipulated, on tenderness. A contemporary publication from Ireland (Moloney et al., 2001) showed a very interesting response. Cattle fed grass silage plus concentrates throughout finishing were the most tender. In comparison, where concentrates were introduced to a silage diet, the earlier the introduction the tougher the meat.

In his review, Harper (1999) cited a number of papers that provided evidence of improved tenderness through increased ‘days on feed’ prior to slaughter. On the other hand growth rate during the pre-finishing (‘stocker’) phase has not been found to affect eating quality (Duckett et al., 2007). Different growth patterns (compensatory growth or a period of high energy feeding) give rise to metabolic changes, as well as collagen re-modelling. It is suggested (Harper 1999) that this may reduce the connective tissue element of toughness. This is, however, poorly understood and it is difficult to define clear guidelines.

French work looking at the eating quality of animals finished on different commercial production systems found that those systems with the highest plane of nutrition resulting in younger animals at slaughter resulted in the most tender meat (Oury et al., 2007).

Maltin and colleagues, in their review (Maltin et al., 2003), cited several papers from the UK and Ireland that suggest no beneficial effect of pre-slaughter growth rate or compensatory growth on tenderness, and the authors suggest that the patterns of growth described by others are more extreme than those that would normally be observed in temperate climates.

Nevertheless, it seems appropriate to try to standardise growth patterns as much as possible in order to reduce tenderness variation.

There is also evidence that growth rate in utero can have an effect on eating quality. Du et al (2010) compared native with improved pasture during pregnancy and found that improved pasture during mid gestation improved finished weights in the offspring, which also had lower shear force and connective tissue and higher intramuscular fat.
**Practical messages**

Overall, it seems that the best advice is to finish animals as young as possible within a given production system. In general this approach will also minimise cost of production and environmental impact.

Aim to maximise growth rate within the production system and avoid variation in growth rate within a group of cattle.

Avoid imposing nutritional challenge on the pregnant cow during mid-gestation.

**Specific dietary components**

A number of studies, mainly in the US, have shown marked improvement in tenderness from the use of high levels of vitamin D3 in the diet (eg Swanek et al (1999)). This is probably brought about by accelerating the activity of the proteolytic enzymes in the meat. Some researchers have, however, found very little effect (eg Scanga et al (2001)). The legal position of using high levels of vitamin D3 in the diet of cattle in the UK is doubtful. Similarly, administration of a calcium gel prior to slaughter can accelerate ageing so that shear force at 7 days post mortem matches that at 14 days in untreated animals (Duckett et al., 2001). Tenderness at 7 days was also increased.

Colour and fat stability of beef can be enhanced by the use of another vitamin supplement - vitamin E. A large number of papers support the use of vitamin E in this respect for beef. In a review of the literature, Liu et al (1995) concluded that 500IU/head for 126 days prior to slaughter would assure benefits in increased shelf life. A research project at the University of Bristol, with a range of partners including MLC, indicated that 1000IU/head for 100 days would deliver a benefit in terms of shelf life. In mince this could increase by 4 days. In their review, Liu et al (1995) suggest a return of 10:1 for investment in vitamin E supplementation in terms of reduced wastage at retail.

Several recent studies have shown benefits of forage diets on colour and fat stability, presumably through antioxidants, including vitamin E, in the feedstuffs. The benefit of conserved grass (silage and dried grass) on the oxidative stability of beef steaks during retail packaging was shown by O'Sullivan et al (O'Sullivan et al., 2003; 2004). This work also showed that type of forage conservation influenced meat colour. Other work has also shown advantages of pasture or silage over concentrates in terms of colour stability (Gatellier et al., 2005; Warren et al., 2008). Wood et al (2007) presented a summary of evidence for the role of oxidation in undesirable flavours in beef, with forage diets producing more desirable flavour, probably through the presence of antioxidants.
Practical messages

Ensure adequate antioxidant provision for cattle to optimise colour and favour stability in beef.

In non-forage rations supplement with vitamin E at 1000IU per head for 100 days pre-slaughter.

Nutrition immediately prior to slaughter

To avoid the DFD condition, it is important to avoid excessive feed withdrawal prior to slaughter and ensure animals are on an adequate plane of nutrition. In abattoirs with a high incidences of DFD, it may be of value to include electrolytes in the water provided in lairage to replenish energy levels prior to slaughter. The results of trials in North America have, however, not been conclusive. Similarly a review from Australia concluded that the results are inconsistent (Ferguson et al., 2001).

Practical messages

Limit feed withdrawal pre-slaughter to avoid DFD.

Diet and flavour

There is increasing evidence that the flavour characteristics of beef are influenced by dietary composition. North American evidence shows a clear difference between grain and grass finished beef with Americans preferring the flavour of grain finished animals (eg Sapp et al (1999)) and even preferring ‘corn’ (maize) fed cattle over barley fed. On the other hand, British and Irish consumers seem to prefer the stronger flavour of grass finished animals, which Americans find to be high in off-flavours. MLC participated in a DEFRA LINK funded project aimed at understanding the role of diet in the flavour of British beef. Following this the review mentioned in the introduction was commissioned at the University of Bristol (Wood and Richardson, 2004). This indicated that diet is a key component of beef flavour.

Understanding of the precursors in meat that contribute to meat flavour has grown considerably in recent years, not least through the research undertaken in a levy-funded PhD project (Koutsidis, 2004). While the limiting precursors for beef flavour can be identified, it remains unclear how these can be modified through animal husbandry, given the homeostatic mechanisms in place to control their levels in living tissues.

A different aspect of meat quality which can be enhanced by dietary means is the nutritional quality. In cattle, as in other ruminant species, dietary fatty acids are modified in the rumen before absorption making it difficult to modify the fatty acid composition in the carcase. Nevertheless, the n-3 fatty acid
levels in concentrate fed beef have been increased by the use of linseed and/or fish oil in the diet (Scollan, 2001). Fish oil has, however, been found to result in abnormal flavours in the meat whereas linseed has resulted in higher overall liking scores. Grass fed beef, in any case, has higher n-3 levels than grain fed and this may contribute to its specific flavour.

**Practical messages**

In specific supply chains it may be possible to minimise dietary variation to generate a more consistent beef flavour.

Careful consideration should be given to potential flavour issues before introducing novel feed ingredients.

**Pre-slaughter transport and handling**

It is clearly best practice to minimise pre-slaughter stress. Thus cattle should be loaded on the farm, transported, unloaded at the abattoir and delivered to the point of stun with the minimum of stress and risk of physical damage to the animals. In the last few years there have been papers showing that there is an effect of animal temperament on eating quality (King et al., 2006) and animals showing nervous behaviour have higher shear force than calm or simply restless animals (Gruber et al., 2010) and more 'flighty' animals (measured by a flight speed and a 'crush score') give rise to tougher meat. This effect is more evident in Bos indicus breeds but can also be observed in Bos taurus types. Mixing can also be associated with tougher meat (Bass et al., 2010).

In terms of transport conditions, Tarrant et al (1988) in Eire studied the effect of stocking density on several physiological, behavioural and carcase characteristics of stress. They found that high stocking density (about 600kg/m²) adversely affected these characteristics and that bruising increased with stocking density. Poor handling of cattle before slaughter is also considered to be the major cause of dark cutting beef which presents a problem to many in the meat trade (Tarrant, 1991). The latter author reported the results of a survey of informed scientific opinion in 19 countries and the most frequently mentioned cause of dark, firm and dry (DFD) beef was management of cattle before slaughter and, in particular, the practice of penning cattle together in mixed lots at the abattoir and unsuitable transport conditions.

Van Logtestijn and Romme (1981), reviewing the evidence relating to welfare and lairage conditions, formed the view that there should be a good delivery systems which makes it possible to slaughter animals directly on arrival. Where cattle have to be lairaged before slaughter, the advice was to rest for at least 48 hours. This advice related primarily to bulls which are more prone to stress than steers and heifers. In a less extreme form, similar advice may be sound for steers and heifers. So far as bulls are concerned, it is widely considered best practice to slaughter immediately on arrival at the abattoir.
This requirement stems from research work and was the conclusion of an EEC Seminar on the problem of dark cutting in beef (Hood, 1981). EBLEX commissioned some practical work on factors influencing DFD incidence undertaken by the University of Bristol in 2008 (Warris and Brown, 2008). They found an incidence in Dark Cutting of around 10% in young bulls, mainly associated with mixing unfamiliar groups of animals.

Wythes et al (1988) in Australia found that steers rested for one day before slaughter were more tender than those rested for only a few hours. The authors did not test the effect of tailboard slaughtering. They advised that cattle should not be disturbed or mixed with others during the resting period.

There are several disadvantages associated with DFD beef. Abnormal colour and spoilage characteristics are the main problems. The more rapid spoilage of DFD beef is of particular concern when beef is aged to enhance tenderness. DFD beef is inherently tender but lacking in flavour (Dransfield, 1981).

It is possible that a 'nutritional therapy' in lairage or use of preslaughter electrolytes can help reduce the effects of long transport (eg Schaefer et al., 2006)). The benefits are generally only seen, however, in situations that pose more extreme conditions that prevail in the UK such as high temperature or extended feed withdrawal (Richards, 2011 #892).

A further factor relevant to pre-slaughter stress is the observation by Lawrie (1977) that fatigued animals are more easily infected by extraneous organisms and more susceptible to bacterial invasion from their own digestive tract. Such effects could affect the keeping quality of meat which is important to allow beef to be aged for the improvement of tenderness. It can also give rise to the condition known as ‘bone taint’ particularly when carcasses are cooled very slowly.

Overall, there is very little literature on the effect of stunning or sticking methods on meat quality. Head to back electrical stunning has been shown to reduce the risk of cold shortening (by a mild electrical stimulation effect) and give improved meat texture and reduced incidence of blood splash (rare in beef anyway). On the other hand, high voltage electrical stunning can result in hot shortening through a stimulating effect, and applied incorrectly can even increase blood splash. Care should be taken to look at electrical stunning in the context of all electrical inputs on the slaughterline.

The animal welfare requirement that cattle should be stuck without delay may also have meat quality advantages. Lawrie (1977) reported that delaying bleeding led to increased quantities of residual blood which promotes spoilage, ‘gamey’ flavours and discoloration. On the other hand, Warriss (1977) could find no unequivocal experimental evidence to support the widely held view that efficiency of bleeding out affects the eating or keeping qualities of meat. However, avoiding delays to bleeding have been reported to reduce the incidence of blood splash.
Williams et al (1983) examined the effect of delayed bleeding on eating quality characteristics. While a sensory panel preferred the eating quality of loin roasts from heifers stuck without delay after stunning compared with those stuck after a delay of 6 minutes, no significant differences were found among steers bled at 0, 3 and 30 minutes after stunning.

**Practical messages**

Handle cattle considerately to avoid DFD and toughness issues.

Avoid mixing unfamiliar groups of animals.

Move young bulls to the slaughter point direct from the transport vehicle where possible.

Apply electrical stunning with care - monitoring pH/temperature relationship post-slaughter to avoid hot-shortening.

**Carcass fatness and conformation**

There is evidence that the leanest of animals tend to produce poorer eating quality although this effect is not large. A widely used cut off is that of MLC fat class 3 with leaner animals excluded from quality specifications.

In terms of fatness, published evidence (mainly North American and Danish) indicates that at low levels of intramuscular (or marbling) fat, the tenderness and juiciness of beef is less satisfactory (Buchter, 1986; Dikeman, 1987). There is also some evidence that beef flavour requires a minimum level of intramuscular fat. Denoyelle (Denoyelle, 1995) found that 4% was needed as a minimum in the *longissimus lumborum* but found no effect in two other muscles. Low levels of intramuscular fat are generally associated with low external fat cover. The Blueprint Trial confirmed the favourable effect of fatness on texture although, again, the effect was not large. MLC carried out a large review of the effect of fatness on the eating quality of meat and concluded that there is an effect of marbling fat, but this is generally small. This small effect of marbling may be useful, as in the USDA grading, in excluding the leanest of animals which do exhibit an eating quality problem. On current evidence, a minimum fat level of 3 seems prudent to provide protection against very low intramuscular fat levels.

In terms of conformation O+ is widely accepted as a minimum. The evidence to support this rests partly on the physical fact that the muscles from animals of good conformation are relatively thicker than those of poor conformation carcases. This makes them less likely to suffer from toughening due to cold shortening (Locker and Hagyard, 1963). A further factor is that good conformation carcases are likely to have a lower proportion of their muscle weight as collagen which is one of the contributors to toughness (Bouton et al., 1978b). In addition, excluding very poor conformation carcases provides
some protection against cattle which have had a chequered growth and nutritional history and may be quite old before they reach slaughter weight.

This effect of conformation may well be the reason that the roast joints from Belgian Blue cattle described above had better eating quality than the other breeds. In the specific case of double muscled animals, it has been clearly demonstrated that collagen is a lower percentage in the majority of muscles (Touraille, 1991).

**Practical messages**

Aim for a minimum fat class of 3 and conformation class O+ as precautions against poor eating quality.

**Carcase Suspension**

Aitch bone (or hip) suspension is an important element of quality enhancing programmes in several countries (notably GB, Eire, Australia and Argentina). Several published papers report beneficial effects of suspension of hot carcases from the aitch bone during chilling (Ahnström et al., 2006; Ahnström et al., 2009; Joseph and Connolly, 1977; Lundesjo et al., 2001).

Aitch bone suspension has its effect through holding the major muscles of the hindquarter and loin under tension. This prevents shortening of the muscles and may also accelerate the ageing process. In Britain the use of the aitch bone has largely been replaced by the ischium (an alternative position in the pelvic region) for safety reasons. In terms of the tension on the muscles this achieves the same effect.

Hostetler et al (1975) examined the effect of aitch bone and achilles suspension at two temperatures: 2ºC and 16ºC. The best beef texture was obtained with aitch bone suspension and the higher chilling temperature. The major muscles in the rump, topside and sirloin were improved. Others have found no effect when cold shortening risk was avoided (Sørheim et al., 2001).

Further evidence in support of the use of aitch bone hanging comes from MLC’s own in-house trials and from the results of the Beef Blueprint trial. In addition to advantages in both tenderness and juiciness, aitch bone suspension also showed less drip loss from the meat.

There is, however, evidence that the benefit of hip suspension varies with the end point cooking temperature. Eikelenboom et al (1998) found that at lower cooking temperature (less than 65ºC) semimembranosus (topside) from aitch bone suspended sides were actually tougher. These workers did use low voltage stimulation which may have influenced the results.

Various alternative suspension methods have also been attempted. The most successful of these has been the Tendercut™ method and variations of it.
The Tendercut™ procedure involves the separation of the vertebrae between the 12th and 13th thoracic vertebrae and severing of the pelvic bone at the body of the ischium. The balance of evidence in the literature suggests that these methods are not as consistent in improving tenderness as hip suspension.

One alternative suspension method applied, by way of example, was reported by Aalhus et al. (1999). In this study the vertebrae were separate between the 12th and 13th thoracic vertebrae such that only the longissimus muscle remained to support the weight of the carcass. In addition, the pelvic bone was separated by saw at the narrowest part of the body of the ilium. This process resulted in reduced shear force in the anterior and posterior longissimus and the semimembranosus muscles. There was a small toughening effect in the psoas major and rectus femoris. Overall it was concluded that OLAS was a promising technique.

On balance, hip suspension is an effective method of improving beef tenderness and is less labour intensive than other modified suspension methods.

**Practical message**

Hip suspend for optimal eating quality of back and hindquarter cuts.

**Chilling rate and electrical stimulation (ES)**

As stated in the introduction, incorrect chilling can give rise to toughness through shortening. This has been demonstrated many times over the years. Recently, for example, Prado and de Felicio (2010) compared 'conventional' air chilling (air speed 2 m/s and temperature of 0°C with slow air chilling (2m/s but temperature of 10°C for the first 12 hours) and found marked difference in toughness of beef loin with the convention chilling resulting in higher shear forces. Differences remained after even 60 days of aging.

A useful rule of thumb for beef where no electrical stimulation is applied is that no part of any muscle should fall below 10°C within 10 hours of sticking (Bendall, 1972). If the temperature of muscles is reduced below about 10-14°C while they are still in the early pre-rigor condition (pH about 6.0-6.4) there is a likelihood of shortening and, thereby, toughness (Locker and Hagyard, 1963). The degree to which different muscle are susceptible to cold shortening depends on their rate of rigor development, the degree to which they are insulated by fat or other muscles and the tension they are placed under by the posture of the skeleton. The loin of a carcass is particularly prone to shortening because it cools relatively quickly.

There has long been a hypothesis that very fast chilling (a core temperature of 0°C in 5 hours after slaughter) can lead to more tender meat. Much research
in this area has yielded inconsistent results and when it fails the resulting cold shortening gives a huge toughening effect (Van Moeske et al., 2001).

Despite the published evidence concerning the effect of chilling rate on muscle tenderness, the Blueprint trial indicated that while rapidly chilled sides tended to yield tougher meat than slowly chilled side, the effects were small and, in most cases, not significant. The rapid chilling regime was expected to cause some toughening while the other was expected to avoid it. Given the current state of knowledge, however, it seems prudent to adopt procedures likely to minimise the risk of toughening.

The only circumstances in which it is not a problem for the temperature of muscles to fall below 10ºC in 10 hours is where high voltage ES (HVES) is applied. This is because the stimulation depletes the energy reserves in the muscle prior to chilling so that there is insufficient energy for the muscle to contract.

There is a large volume of literature on the value of ES for avoiding the toughening effects of cold shortening. In addition there is evidence that ES improves tenderness over and above the effect of avoiding cold shortening (eg (Strydom et al., 2005)). A review of over 50 research papers from around the World was conducted by MLC in 1992 (Matthews, 1992) and concluded that, whilst HVES was effective in improving the tenderness of the loin any effect on other muscles was generally small, and occasionally negative results have been reported. Other eating quality parameters are affected little by HVES but drip loss can be increased, unless rapid chilling is sufficient to reduce it. It has been shown that blast chilling (-20 ºC at 5 m/s air speed for 2h) after HVES (470V in this case) reduces weight loss considerably without perceptible effects on toughness (Aalhus et al., 1994).

There are various hypotheses regarding how electrical stimulation improves tenderness. It seems likely that there is a combined effect of pH/temperature profile and calcium release on both the state of contraction at rigor and proteolysis post-mortem, although some would argue only the pH/temperature relationship is important (Simmons et al., 2008). A very good recent review (Hwang et al., 2003) suggests that stimulation accelerates rigor mortis - preventing cold shortening, and accelerates proteolysis. The authors do not consider that heat shortening is a major problem (Devine, personal communication) because once rigor has occurred they consider that the proteins are protected from denaturation (including the calpains). In another excellent review of post mortem changes in muscle, Huff-Lonergan et al (2010) suggests that pH fall has an effect on tenderness beyond that resulting from shortening. It is proposed that this is through an effect on proteolytic enzymes. Intermediate pH at 3 hours has higher tenderness than high or low pH. More rapid pH fall accelerates the activation of micro-calpain and therefore proteolysis (ageing tenderisation). If the decline is too rapid (such as in deep beef leg when HVES is applied) proteolysis is much lower.

ES can be applied in high (normally 500-1000 V), low (less than 100V) or medium (100V) voltage forms. While all seem to be generally effective in
causing a rapid reduction in pH in meat, such as is thought to avoid cold shortening, there is evidence that high voltage ES is more effective. This may be related to the timing of application. Hwang and Thompson (2001a) found that stimulation at 3 minutes post mortem, whether high or low voltage, gave tougher meat than stimulation at 40 minutes (although all stimulation treatments improved tenderness over non-stimulated controls). A number of stimulation treatments have been compared in New Zealand. All were effective at reducing shear force, but chill rates were faster than generally seen in English plants and cold shortening may have been an issue in unstimulated carcasses (although this was not considered likely by the authors). High voltage stimulation (1130V peak, 14.28 bidirectional 10ms sinusoidal pulses/s) for 60s at 60 minutes post slaughter has been found to be the most effective at reducing shear force (Guransky et al., 2010).

Some abattoirs, for example in New Zealand, use a low voltage stimulation to immobilise animals after stunning and before/during sticking. Geesink et al (2001) found that if a total of 80 seconds stimulation was used (40 seconds before and 40 seconds during bleeding at 75V and 15Hz), then the resulting meat was actually tougher at 7 days than a less intense treatment (total of 20 seconds). This was because of greater shortening (despite higher proteolytic activity). This shortening was probably hot shortening, an effect brought about by rigor occurring (accelerated by stimulation) whilst the muscle is above 20°C with sufficient energy remaining for contraction. This effect might also be relevant to low voltage ES and, if this is to be applied, the optimum parameters need to be carefully established for each circumstance.

Work carried out by MLC technical staff (Matthews and Owen, 2000) has shown that high voltage ES as applied in a commercial slaughter plant was not as effective as the use of hip suspension, probably because of hot shortening when ES was applied. This trial showed no benefit of combining Hip suspension with HVES. Others have found an additive effect with low voltage ES and hip suspension (Derbyshire et al., 2007).

There are recent observations in the UK industry (Matthews, 2008) and in several research studies that high temperature in the deep muscles of the hind quarter can give a pale wet muscle rather like PSE in pig meat (De Boever et al., 2009; de Smet et al., 2010; Simmons et al., 2008). Others (Rosenvold et al., 2008), however, suggest that hot shortening does not occur after electrical stimulation in hot boned muscles. Nevertheless, it has been found that the deep semimembranosus muscle can have higher protein denaturation associated with a slower temperature decline during chilling, than the surface semimembranosus, resulting in lower levels of proteolysis and tougher meat (Huff-Lonergan et al., 2010; Kim et al., 2010a).

An alternative approach to avoiding shortening, when carcases are hot-boned, is to use a very tight wrapping around the muscle. Several workers have found this effective (Troy and Kerry, 2010), but as hot boning is rarely practices in the UK and requires a major change in process, it is not likely to be of major commercial relevance.
Practical message

In the absence of electrical stimulation avoid excessive chilling

Use electrical stimulation to enhance beef quality where hip suspension is not being used.

Monitor pH/temperature relationship (see section on pH)

Ageing

Ageing or conditioning of meat post-mortem has long been associated with an increase in tenderness and flavour (George et al., 1980; Joseph and Connolly, 1977; MacDougall, 1972; Sapp et al., 1999; Wheeler et al., 1999). Improvements have been seen commonly in loin up to 14 or 21 days, benefits have been seen up to as long as 60 days (Prado and de Felicio, 2010). Ageing is also an important means of reducing tenderness variation - generally reducing or removing differences associated with animal type, eg breed (Ibrahim et al., 2008; Monsón et al., 2005). On the other hand, care should be taken to avoid ageing for excessive lengths of time to avoid a decline in beef flavour and the development of abnormal flavours (Spanier et al., 1997) and several authors see no benefit beyond 14 days (eg (Monsón et al., 2005)). The most tender samples of beef loin steaks do not tenderise as much with ageing (Gruber et al., 2006), and can actually increase in toughness while the most tough tenderise. This improves consistency but suggests that an opportunity can be missed for selling tender meat without the need for maturation, through the lack of a means to measure meat quality (Novakofski and Brewer, 2006).

Results from the MLC Beef Blueprint trial, where beef was aged for 6, 10 and 14 days, also showed a trend for texture to improve with time. However, juiciness was adversely affected which may have arisen from the way in which the steaks were aged prior to taste panelling. Evidence from further MLC research showed that the tenderness and juiciness of 21 day aged beef can be achieved or exceeded in steers by adopting aitch bone hanging and only seven days ageing.

The benefits of ageing under commercial conditions in the United States has been surveyed at Supermarkets (George et al., 1999). This showed that ageing periods of less than 7 days were associated with reduced tenderness. Interestingly, ageing times varied from 2 to 91 days, a likely source of variation in tenderness.

It is clear that ageing effects differ by muscle. Longissimus clearly tenderises with maturation. In a study examining effects in several muscles, the effects in Longissimus were small beyond 15 days (Janz and Aalhus, 2004). For Semitendinosus maximum tenderness was reached at 7 days and Infraspinatus matured steadily up to 29 days. Semimembranosus did not
benefit from maturation. Others (Gruber et al., 2006) showed benefits from ageing for 16 of 17 beef muscles tested. In the study muscles were aged for up to 28 days. Juarez et al (2010) also found that effect of ageing on tenderness differed by muscle with the following muscles improving with ageing time (days at which minimum shear forces was achieved shown in parentheses): Longissimus (35), blade (mixture of muscles, 35), Semitendinosus (35) and Supraspinatus (35); Semimembranosus was unchanged and Biceps femoris (0 or 49) became tougher before becoming more tender again. Sensory tenderness scores, however, peaked earlier (at 14 or 21 days depending on muscle).

Wet ageing is widely used in commercial beef production in England. This involves storage of the meat at chill temperatures (less than 3ºC) in vacuum packs, usually for 7 to 21 days. There is an industry view that ageing on the bone has flavour advantages over ageing in the pack. Prior to the development of vacuum packaging, meat was dry-aged. Dry aging consists of placing unpackaged meat in a chill under controlled temperature, humidity and airflow. There is increasing interest in the use of dry ageing to produce a premium product because the beef flavour, in particular, is reputed to be superior to that of wet-aged beef. A comprehensive summary of the effects of dry ageing beef has been published by the National Cattlemen’s Beef Association (National Cattlemen’s Beef Association Center for Research and Knowledge Management, 2008).

MLC conducted a small scale comparison in 1996/7. The results showed an improvement in texture with ageing in both joints and steaks, whether aged on or off the bone, but no effect on flavour of ageing on or off the bone. Although there is not a strong consensus in the published literature, some papers support the benefit of dry ageing (eg Warren and Kastner (1992)).

The main disadvantage of dry ageing is the weight loss, as a result of two main factors: evaporative loss resulting in reduced water content of the meat (considered an important component of the improved quality) and discolouration/desiccation of externally exposed muscle resulting in the necessity of trimming.

Dry ageing is widely used in the US and there is interest in reducing the associated weight loss. Research has shown that dry ageing in a bag that is highly permeable to water vapour can be used to reduce weight loss. The aim is to facilitate the moisture loss associated with dry ageing but to reduce the overall weight loss. When aged for 21 days weight loss was reduced from 10.2 to 8.8% and Taste panel tests have demonstrated equivalent eating quality to dry ageing (Ahnstrom et al., 2006; DeGeer and Hunt, 2009). Additional advantages of the system include reduced trimming loss (from 17.9 to 15.6%) and improved bacteriological quality. Recent EBLEX funded work supported these findings.
Practical message

Mature beef in the bag or on the bone to enhance tenderness.

Use 'dry aging' only where there is a specific value added market for the product.

Retail packaging

Ageing (or maturation) of meat after slaughter is a widely used means of enhancing meat eating quality, particularly tenderness. It was generally been thought that ageing tenderisation occurs throughout the time under chill temperatures from slaughter to consumption. Tenderisation does not occur to any substantive degree during frozen storage or once the meat is cooked.

A significant proportion of high value meat cuts sold through the multiple retailers is packaged centrally in modified atmosphere packs (MAP, primarily 80% O\textsubscript{2}/20% CO\textsubscript{2}). This was estimated at 2.32 million packs in 1995 (Down, 1997). MLC guidelines have included the period in MAP as part of the maturation period (Blueprint recommendations state a minimum of 7 days interval from slaughter to retail sale).

Torngren (2003) at the International Congress of Meat Science and Technology (ICoMST) in 2003 reported that high oxygen (80% O\textsubscript{2}/20% CO\textsubscript{2}) packaging resulted in poorer eating quality (including reduced tenderness and lower flavour) of beef compared with vacuum packaging followed by overwrap. This has subsequently supported by a number of other studies others (Lagerstedt \textit{et al.}, 2010; Madsen and Claussen, 2006; Zakryswaliwander \textit{et al.}, 2010).

Following the publication of the work in 2003 EBLEX sponsored work to establish whether high oxygen packaging simply halted maturation or actually toughened the meat. The results conclusively demonstrated that the meat was toughened in high oxygen packs (MLC Technical Division, 2006).

It has now been shown that oxidation is having a number of effects on the meat:

- proteolysis is prevented - ceasing any further ageing tenderisation (Maddock Carlin \textit{et al.}, 2006)
- protein is toughened directly through protein oxidation (Kim \textit{et al.}, 2010b).
- oxidation damages the flavour of beef (mainly through development of rancid fat notes (Campo \textit{et al.}, 2006).

Of course, high oxygen packaging is used, primarily for maintaining a bright red colour. Vacuum packaging results in a darker, more purple, colour generally thought less desirable. It has been shown, however, that vacuum skin packaging achieves better colour stability than standard vacuum
packaging and equivalent colour to MAP after 5 days (Li et al., 2010). This provides an opportunity to move away from MAP while providing an acceptable visual appearance.

Practical message
Avoid high oxygen packaging wherever possible.

pH effects on quality

The relationship between pH and the DFD condition is described in the background information provided in section 4. It is worth considering here the possible usefulness of pH as an indicator of other quality attributes.

In a review, Lee (Lee, 1986) concluded that the combination of high temperature and rapid pH decline early post mortem tends to produce tougher meat unless ES has been used. This is likely to be in cases where hot shortening is occurring. The literature shows marked differences in pH changes post mortem between muscles in the carcase. A review of pH in beef was conducted by MLC in 1991 and this demonstrated conflicting and inconclusive evidence, with some workers (Marsh et al., 1980-1) finding intermediate rates of pH fall gave more tender meat and some (Martin et al., 1977) reporting that more rapid pH decline resulted in the most tender meat. There has been growing evidence supporting this latter finding, with evidence that a more rapid pH fall results in faster proteolysis. Research by Hwang and Thompson (2001b) has shown that the optimum rate of pH fall depends on the time after slaughter that tenderness is assessed with a rapid fall giving the most tender meat initially and intermediate rates of fall giving the most tender meat at 14 days. This is probably because a more rapid pH fall results in more rapid proteolysis (tenderisation with ageing) and therefore, after aging (around 7 days post-mortem) the meat that has undergone an intermediate pH fall catches up. This also explains why electrical stimulation is less beneficial when quality is assessed in matured meat.

Concentrate fed animals have higher rates of pH fall. It may be that any observed pH effect is an indicator of concentrate feeding and the observed tenderness advantages are brought about through an effect of growth rate. Overall the effect of pH decline post mortem is insufficiently understood to give clear guidance.

In summary, rate of pH fall is probably best targetted at the pH/temperature window adopted by the Meat Standards Australia (MSA) scheme, implemented by Meat and Livestock Australia to address variation in the eating quality of Australian beef (Thompson, 2002). This requires the temperature to be below 35ºC and above 12ºC when pH 6 is reached.

Higher ultimate pH values have also been associated with more tender meat (Beltran et al., 1997) but this observation should be treated with care, as DFD, which is more tender than normal beef, will be included in this classification.
Others have found the opposite association - Bass et al (2010) showed that higher pH (in the range 5.3 to 6.1) resulted in higher shear force values at 3 and 7 days post mortem but the difference had disappeared by 21 days.

A paper presented at the 2001 International Congress of Meat Science and Technology (Obanor et al., 2001) showed a curvilinear relationship between ultimate pH and tenderness with loin of 'intermediate' pH (6.0-6.2) having the highest shear force. In discussion it was stated that this was the normal pattern. The authors cited several papers which had presented similar results. The value of this finding is limited in that the proportion of ultimate pH values over 5.8 observed in practice is rarely more than a few percent and they would generally be DFD.

Overall it seems likely that optimum quality is achieved by ensuring ultimate pH is in the normal range (5.5-5.8)

**Practical message**

Monitor pH/temperature post slaughter and adjust stimulation/chilling rates to ensure pH 6 is reached at a muscle temperature below 35ºC and above 12ºC.

Monitor ultimate pH and review the handling and process if it is outside the normal range (5.5-5.8)

**Specifications and uptake**

Probably starting with the MLC Blueprint (MLC, 1990; Warkup, 1993), where specifications are applied, in various countries, bringing together elements from the whole production chain, they have proved successful in both improving quality and making it more consistent (Bickerstaffe et al., 2001; National Cattlemen’s Beef Association, 2006; Thompson, 2002). Indeed it is clear that standardising pre- and post slaughter treatment of animals and carcases reduces eating quality variation (Dolezal, 2010; Maher et al., 2004).

In the UK the SEERAD project 'Meat eating quality - a whole chain approach' endorsed the Blueprint recommendations. This project demonstrated the widespread adoption of best practice as described in the Blueprints by the Scottish industry and demonstrated their effectiveness in improving quality and its consistency (Simm et al., 2004). This is known to be similar across the UK.
3) BACKGROUND INFORMATION - The conversion of muscle to meat

From living muscle to rigor mortis

At the time of slaughter the muscles of the animal are predominantly metabolising aerobically (generating energy through biochemical pathways that consume oxygen). At the time of exsanguination (bleeding out) the blood supply to the muscles ceases. This means that the oxygen supply is cut off and the products of metabolism in the muscle cannot be removed via the bloodstream. These therefore accumulate in the muscle. The normal response of tissues to oxygen deprivation is to attempt to maintain cellular energy (ATP) levels. Tissues with a high oxygen requirement, such as the brain, will die very quickly, but some other tissues, particularly muscle, can have a high anaerobic capacity. This means that they are capable of producing ATP from glucose without the need for oxygen (glycolysis). One of the products of this anaerobic metabolism is lactic acid. This accumulates in the tissue and gradually reduces the pH of the muscle from about 7.2 in a normal resting live muscle to an ultimate pH (pH_u) of about 5.4 to 5.7 in normal meat. Muscle can generate energy from glucose until all the glucose is used up or until the accumulation of acid in the muscle destroys the metabolic processes.

This ability to generate energy even after slaughter means that muscle can continue to contract, for example in response to an external electrical stimulation (ES), for a considerable time after the animal's central nervous system is dead. Different muscles, or even different muscle fibre cells within a muscle, do not continue functioning for the same period after slaughter of the animal. It is an oversimplification to say that muscles consist of two fibre types, red and white, but it is a simplification that will suffice for the purposes of explanation. Some muscles or regions of muscles consist primarily of red fibres, whereas others are predominantly white. The species differences in this regard are strikingly obvious. Red fibres are more associated with sustained activity such as postural work or locomotion in animals active for long periods such as grazing animals. These fibres have higher levels of the oxygen binding pigment myoglobin. Most of their metabolic activity is oxidative and the rate at which they can derive energy in the absence of an oxygen supply is limited.

Conversely, white fibres are more associated with muscles that have short burst of high activity, and when most active cannot rely on oxygen based metabolism to provide sufficient energy. They therefore have a higher glycolytic capacity. This high glycolytic capacity means that white muscle fibres will exhaust their energy supplies after slaughter much more quickly than red muscle fibres.

The main bulk of the muscle fibres is made up of myofibrils which undertake the contractile function of muscle. The most abundant proteins in myofibrils are myosin and actin. When all of the available energy is exhausted in the
post mortem muscle the myosin and actin molecules bind firmly together and the muscle loses its extensibility and flexibility. This point is termed rigor mortis.

The rate at which a muscle of a given fibre composition will go into rigor mortis can be influenced by a substantial number of factors. These include: the energy stores available within the muscle when the animal leaves the farm; the degree to which these stores are depleted during transport and lairage; the stimulation of the metabolic processes via pre-slaughter stress; stimulation of muscular activity during the slaughtering process and the rate at which the muscle is cooled.

**Shortening**

Muscle will contract (shorten) naturally as it goes into rigor mortis if it is not restrained from doing so. Most muscles are under tension when the skeleton of the carcase is in its normal posture. If muscle is restrained it will develop tension as it goes into rigor but will not be able to shorten in its overall length. The extent to which muscles are able to shorten depends on the remaining energy (ATP) available at the time of shortening, the load on the muscle and the temperature of the muscle when these events occur. A shortened muscle will have shorter sarcomere lengths, ie shorter repeating units within the contractile myofibrils and a greater overlap between the contractile filaments.

Shorter sarcomere lengths are generally associated with tougher meat. In shortened muscle shear force values can increase by over 300%, but the response is not linear with the degree of shortening. Tenderness has been noted to be at its lowest with 25-40% shortening and severely shortened muscle (which had shortened 60%) was as tender as unshortened muscle (Marsh and Leet, 1966).

The temperature effect on the ability to shorten during rigor is particularly interesting, with the extent of beef muscle shortening varying with temperature at which rigor occurred according to the sequence 1 > 37 > 5 > 20 °C (Busch et al., 1967). From this and similar observations, the notion emerged that there were two types of shortening and that for minimum shortening muscle should be at about 15°C as it enters rigor mortis. This can never be achieved in practice for all muscle fibres because of the different rates of cooling in different locations of the carcase and the different rates of rigor development in different fibres. It is however a useful guideline.

The shortening that occurs with rigor above 20°C occurs as the energy supply is being exhausted and it is, therefore, generally quite weak. This form of rigor shortening is sometimes termed ‘hot’ shortening. It does have the potential to affect meat quality but its importance is still debated. ‘Cold’ shortening is quite different. It occurs if the muscle is exposed to low temperature (say <11°C (Locker and Hagyard, 1963)) prior to the development of rigor. Under these conditions the muscle spontaneously
contracts and, since it does so at higher levels of ATP and pH than rigor shortening, the degree of contraction can be considerable.

It must be stressed that many of the studies of shortening have been done in muscle which has been removed from the carcase and therefore is more able to shorten than muscle which is restrained in the carcase by its attachment to the skeleton. However, the degree of restraint will depend on the carcase suspension system and even a restrained muscle can still cold shorten at least to some extent, reducing sarcomere lengths in one area and stretching or breaking sarcomeres in another (Marsh and Leet, 1966).

There seems little doubt from the literature and practical industrial experience that 'cold' shortening can occur and in some circumstances, especially in beef and lamb, can be a significant source of toughening. However, the picture is not so clear for 'hot' shortening. In one study (Locker and Daines, 1975) muscle removed from the carcase soon after slaughter and allowed to go into rigor at 37 °C had shortened 31.5% and yet had lower shear force than muscles held at 15-34 °C which had shortened less. The explanation of this is unclear but the possible higher activity of enzymes associated with post-mortem tenderisation of muscle is one possibility. It has been proposed by a number of researchers that beef tenderness is more closely related to the temperature of the muscle two hours post-mortem than later temperatures (Marsh et al., 1980-1; Roschen et al., 1950). Marsh et al (1987) proposed that intermediate rates of rigor development, which reduce the risk of rigor at too high a temperature but ensure rigor is achieved before 'cold' shortening temperatures are reached, are most desirable for tenderness. For beef they proposed this could be determined by a pH of ~ 6.1 at three hours post mortem.

**Proteolysis**

The action of enzymes that damage or destroy proteins (proteolytic enzymes) in post-mortem muscle is remarkably limited (Greaser, 1986), but what activity there is seems to be a highly significant source of variation in the tenderness of meat. Many of the major proteins of muscle are relatively undegraded, but significant proteolysis to others is associated with increasing fragmentation of myofibrils as post mortem storage time progresses. Although the fact that meat tenderises with post mortem storage time has been known for very many years, the debate as to which processes within the muscle are responsible has been a long one. There is now largely a consensus that the enzymes responsible for the tenderisation process are a family of calcium activated enzymes, called the calpains, and their inhibitor calpastatin (Koohmaraie, 1994; Taylor et al., 1995). There remain significant unanswered questions as to how the calpains are regulated, the way that they interact with the development of rigor mortis and, importantly, whether other processes (perhaps non-enzymic) are also involved in the tenderisation of meat during ageing.
Generally proteolytic degradation and hence tenderisation is considered to occur more quickly in white fibres, and muscles made up predominantly of these, than in red fibres/muscle (see for example (Dutson et al., 1974)). This is reflected in differences in the rate of tenderisation (and hence optimum ageing time) between muscles within a carcase and between the species. The significance of the calcium dependency of these calpain enzymes should not be over looked. The enzymes are more active at nearer neutral pH and at higher temperatures, therefore their greatest level of activity may be around the time of rigor when sufficiently high levels of calcium may become available. Recently, measurements of the activity of calpain enzymes in the early post-mortem period have been associated with the tenderness of pork after 8 days of ageing (Sensky et al., 1998). It seems possible that interactions between the processes of rigor mortis and proteolysis may be important to tenderness variation days later. This remains as active area of research but the practical consequences, based on current knowledge, are different recommended ageing periods for different meat cuts.

**Abnormal conditions 1. - DFD**

If the energy reserves of the muscle are depleted prior to slaughter the degree of glycolysis which can occur is diminished and the ultimate pH (pH_u) will not be as low as in normal muscle with higher energy reserves. If the pH_u is greater than 6.0 the muscle will have a dark and dry appearance with a firm texture. This condition is termed Dark Firm Dry meat (DFD) or sometimes ‘dark-cutting’ meat. It is most commonly seen in beef, but can also be seen in pigmeat and, rarely, lamb. A higher level of oxygen consumption by the tissue and hence a reduced depth of oxygen penetration into the meat results in less visible red oxymyoglobin pigment (bright red) and hence the dark appearance. The dryness is thought to be a consequence of the higher pH leading to a higher water holding capacity of the myofibrillar proteins. DFD meat is normally found to be more tender, perhaps due to enhanced proteolysis, but the higher pH also leads to a better environment for the growth of spoilage bacteria and consequently a poorer shelf-life (Gill and Newton, 1981).

**Abnormal conditions 2. - PSE**

PSE stands for Pale Soft and Exudative. This condition is of considerable economic significance in pigmeat, being first described as muscle degeneration in 1954 (Ludvigsen, 1954). It is described here because of its relevance to the problem of protein denaturation in the deep leg of beef carcases. A similar condition can be seen in some beef muscles held at high temperatures for prolonged periods (Locker and Daines, 1975). The basic causal mechanism is the combination of low pH and relatively high muscle temperatures that can occur if post-mortem glycolysis progresses at an accelerated rate. The two main pre-slaughter causes of the rapid pH decline are either a genetic defect in muscle calcium metabolism (the halothane gene) or a stimulation of glycolysis via pre-slaughter stress or inappropriate application of electrical stimulation. In PSE muscles the rate of pH decline is
at least twice as fast as in normal muscles and rigor may occur as early as 15 minutes after slaughter.

This combination of low pH and high temperature is thought to result in denaturation of proteins and a consequent change in the lateral spacing of the contractile filaments of the muscle cell. This in turn changes the distribution of fluid within the muscle, with an increased proportion of the fluid becoming distributed in the extracellular space, from where it can more easily escape from the meat (Offer and Knight, 1988). This is of obvious economic importance with PSE carcases having much higher fluid losses. Individual chop drip losses can be 5.8% compared with 3.0 % (Sather et al., 1998).
4) REFERENCES


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