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Review

Some biochemical aspects pertaining to beef eating quality and consumer health: A review

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ABSTRACT

The objective of the current review is to highlight biochemical processes and products, from slaughter to the time of beef consumption, that relate to response to stress at slaughter, meat quality and consumer health. Biochemical processes and products involved in the use of catecholamine and dopamine levels at slaughter, in predicting meat quality, are reviewed. Furthermore, meat quality characteristics, such as colour, pH, drip loss, sarcomere length (SL), water-holding capacity (WHC), cooking losses, myofibrillar fragmentation length (MFL), Warner Bratzler shear force (WBSF), fatty acid profiles and sensory characteristics, are reviewed. The review also covers how certain fatty acids relate to human health. At the end, relationships among different meat quality traits are considered. The review rounds off by identifying possible areas requiring further research.

Contents

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1. Introduction

Beef is one of the widely consumed protein sources in the world. Furthermore, modern consumers are increasingly concerned about production of safe meat with no undesirable effects on their health (Andersen, Oksbjerg, Young, & Therkildsen, 2005). With more red meat consumers becoming health conscious, there is scope in studying the biochemical processes and products that affect meat quality. Several biochemical processes and products that affect beef eating quality are at play during the transportation of cattle to the abattoir, the immediate pre-slaughter period, the slaughtering process and meat handling after slaughter. Several factors affect such processes and the levels of their products.

Most studies on biochemical processes and products affecting cattle adaptation (Muchenje, Dzama, Chimonyo, Raats, & Strydom, 2008a; Ndlovu et al., 2007), growth and meat production (Muchenje, Dzama, Chimonyo, Raats, & Strydom, 2008b; Muchenje et al., 2007; Strydom, Naude, Smith, Scholtz, & van Wyk, 2000; Strydom et al., 2001) have covered these aspects separately. These studies left out biochemical processes and products that relate to animal welfare, especially during transportation, handling at loading, off-loading and at the abattoir, and its effects on meat quality. There are, however, recent reports (Muchenje, Dzama, Chimonyo, Strydom, & Raats, submitted for publication-a; O'Neill, Webb, Frylinck & Strydom, 2006) on the relationship between stress responsiveness in animals at slaughter, as determined by catecholamine levels, and beef quality.

Beef fat is a significant source of saturated fatty acids in the human diet because red meat has a relatively high ratio of saturated to unsaturated fatty acids in its lipids, which is a risk factor for the development of vascular and coronary diseases (Barton, Marounek, Kudrna, Bures, & Zahradkova, 2007). The adverse effect of saturated fatty acids on human plasma cholesterol levels makes it imperative to consider biochemical processes and products that affect levels and composition of beef intramuscular fat (IMF). It is also important to note that the health risk factor of animal-derived lipids has often been overemphasized, although it is evident that these lipids provide physiologically functional and potentially health-beneficial fatty acids (Razminowicz, Kreuzer, & Scheeder, 2006). Furthermore, fatty acid composition affects sensory attributes of meat, such as flavour and juiciness (Elmore, Mottram, Enser, & Wood, 1999; Enser, 2001).

In addition to the relationship between fatty acid composition and sensory evaluation, there are other changes in biochemical processes and products in meat that affect relationships among different meat quality traits. For example, feeding management and nutritional status (Andersen et al., 2005; Sañudo et al., 2004; Wheeler, Cundiff, Koch, & Crouse, 1996) affect glycogen depletion, and meat quality parameters, such as ultimate pH (pHu), colour, cooking losses and tenderness. Knowledge of relationships among meat quality characteristics can be used to predict meat characteristics that are expressed much later *post-mortem*, such as tenderness, shelf life, water-holding capacity (WHC) and cooking losses which can be indicated on the basis of the knowledge of pH soon after slaughter. Razminowicz et al. (2006) used cooking loss determination to estimate water-holding capacity (WHC) of meat. The relationships among meat quality traits may, however, differ, depending on breeds (King et al., 2006; Muchenje et al., 2008b), feeding management and nutritional status (Andersen et al., 2005; Wheeler et al., 1996).

While the biochemical changes that occur due to transportation, handling and pre-slaughter stress and after animal slaughter affect the eating quality of beef, the effects of such changes have been reported separately. This review, therefore, focuses on some biochemical processes and products that relate to stress responsiveness and meat quality from the immediate pre-slaughter period until beef is ready for consumption.

2. Biochemistry and meat quality

2.1. General

Meat quality refers to the compositional quality and the palatability of meat. The major parameters considered in the assessment of meat quality are appearance, juiciness, tenderness, and flavour (Lawrie & Ledward, 2006). Meat should have a desirable colour that is uniform throughout the entire cut. The colour is related to the level of the protein pigment, myoglobin, present in the muscle. Meat should also have marbling (intramuscular fat) throughout the cut. Marbling increases juiciness, tenderness, and flavour of the meat. Water-holding capacity is a factor that also determines the juiciness of meat. It is defined as the ability of meat to retain its water during application of external forces, such as cutting, heating, grinding or pressing (Lawrie & Ledward, 2006). If excess water is observed at the bottom of the retail package, it may lead to a dry cooked product.

In each stage, from growth to slaughter, there are factors such as stress, ageing, pH, breed, and others that may affect the quality of meat. The transformation of slaughter animals into meat is a chain of events, including handling and loading on the farm, transport to the market, pens or slaughterhouse, off-loading and holding and finally slaughter. During these procedures, poor operational techniques and facilities will lead to unnecessary suffering, injury and poor quality meat production. Breed type and slaughter weight influence carcass and meat quality parameters in several ways, including the properties and structure of muscle and meat physiology (Sañudo et al., 2004).

Although it is established that breed and feeding management influence the quality of meat (Andersen et al., 2005; Sañudo et al., 2004; Wheeler et al., 1996), there are conflicting reports on the effect of feeding management on meat quality (Priolo, Micol, & Agabriel, 2001). Meat is composed of physical and chemical components. The physical and chemical meat quality parameters described in this review are summarised in Table 1. Most of these meat quality parameters can be affected by the way the animals respond to stress associated with loading, transporting, off-loading and pre-slaughter environment novelty.

2.2. Stress hormones and meat quality

The two main stress-responsive neuroendocrine systems, that play a critical role in the regulation of energy fluxes, are the hypothalamic–pituitary–adrenocortical (HPA) and the sympathetic nervous system (SNS) (Foury et al., 2005). The HPA axis influences feeding behaviour, pancreatic hormone secretion, energy expenditure and the protein/lipid balance, while the catecholamines (epinephrine and norepinephrine) released by the SNS increase the use of energy stores (glycogen and lipids; Scheurink & Steffens, 1990) and exert anabolic effects on protein metabolism (Navegantes, Migliorini, & Kettelhut, 2002). It is also possible that the adrenal cortex and medulla are somehow co-activated, but that the HPA axis and the SNS are largely independent (Foury et al., 2005).

Animals waiting for slaughter can be stressed by either psychological factors, such as restraint, handling, or the novelty of the pre-slaughter environment, or physical factors, such as hunger, thirst, fatigue, injury or thermal extremes. Animals' stress responsiveness can be assessed using the concentrations of catecholamines and dopamine in urine (Hay & Mormede, 1998; Muchenje et al., submitted for publication-a; Parker, Hamlin, Coleman, & Fitzpatrick, 2004; Young, Rosa, & Landsberg, 1984). Catecholamines are often

Table 1
Ranges of values of some beef quality characteristics as reported in literature

Meat quality characteristic	Range of values	Sources
Lightness (L^*)	33.2–41	Muir et al. (2000), Strydom, Frylinck, and Smith (2005), Zhang et al. (2005), Razminowicz et al. (2006), Muchenje et al. (2008b)
Redness (a^*)	11.1–23.6	Muir et al. (2000), Byrne et al. (2000), Strydom et al. (2005), Zhang et al. (2005), Razminowicz et al. (2006), Muchenje et al. (2008b)
Yellowness (b^*)	6.1–11.3	Muir et al. (2000), Strydom et al. (2005), Zhang et al. (2005), Razminowicz et al. (2006), Muchenje et al. (2008b)
Colour saturation	16.1–20.9	Strydom et al. (2005), Zhang et al. (2005), Muchenje et al. (2008b)
Sarcomere length (μm)	1.75–2.31	Strydom et al. (2000), Maher et al. (2005), Stolowski et al. (2006), Muchenje et al. (2008b)
WBSF2 (N)	38.1–143.6	Byrne et al. (2000), Campo et al. (2000), Muir et al. (2000), Maher et al. (2005), Muchenje et al. (2008b)
WBSF21 (N)	16.9–59.9	Campo et al. (2000), Muir et al. (2000), Sañudo et al. (2004), Muchenje et al. (2008b)
MFL2 (μm)	26.2–34.2	Strydom et al. (2005), Muchenje et al. (2008b)
MFL14 (μm)	19.2–24.7	Strydom et al. (2005), Muchenje et al. (2008b)
pH	5.50–6.70	Lahucky, Palanska, Mojto, Zaujec, and Huba (1998), Maher et al. (2005), Razminowicz et al. (2006), Muchenje et al. (2008b)
Drip loss (%)	0.14–3.89	Byrne et al. (2000), Strydom et al. (2005), Revilla and Vivar-Quintana (2006), Muchenje et al. (2008b)
Water-holding capacity (%)	37.0–72.7	Strydom et al. (2005), Zhang et al. (2005), Revilla and Vivar-Quintana (2006) and Muchenje et al. (submitted for publication-a),
Cook loss (%)	13.1–34.54	Byrne et al. (2000), Vestergaard et al. (2000), Strydom et al. (2005), Razminowicz et al. (2006), Muchenje et al. (submitted for publication-a)
Moisture (%)	73.87–77.9	Maher et al. (2005), Muchenje et al. (2008b)
Protein content (%)	20.0–22.87	Maher et al. (2005), Muchenje et al. (2008b)
Fat content (%)	0.76–3.0	Vestergaard et al. (2000), Maher et al. (2005), Aldai et al. (2006), Alfaia et al. (2007), Muchenje et al. (2008b)

implied as the cause of the depletion of glycogen in the pre-slaughter period (O'Neill, Webb, Frylinck & Strydom, 2006).

If any animal is stressed in an environment, such as the immediate pre-slaughter period, there is a rapid release of catecholamines, which rapidly mobilise and deplete glycogen (Lacourt & Tarrant, 1985). Epinephrine activates muscle adenylate cyclase and thereby stimulates glycogen breakdown (Voet & Voet, 1995). The concentrations of these hormones are the result of neuronal washout from tissues with sympathetic nerves and are therefore important indicators of sympathetic nervous system activity (Young et al., 1984). The depleted levels of glycogen result in high ultimate pH (pHu) levels that are not good for the conversion of muscle into meat. According to Tarrant (1989), when pre-slaughter muscle glycogen reserves fall below the critical threshold of 45–55 mmol/kg, the normal pHu in meat (5.5–5.6) will not be attained. The measurement of the stress hormones in urine is non-invasive and their levels in urine are not affected by the massive release of catecholamines and dopamine associated with slaughter because there is a delay between elevation of their concentration in plasma and subsequent elevation in the urine (Hay, Meunier-Salau, Brulaud, Monnier, & Morme'de, 2000; Lay, Friend, Bowers, Grissom, & Jenkins, 1992).

Most of the reports on stress responsiveness and meat quality tend to either separately focus on animal welfare (Ahmadzadeh, Barnes, Gwazdauskas, & Akers, 2006; Lay et al., 1992; Sowers, Beck, Stern, & Asp, 1983), endocrinology (Hay & Mormede, 1998; Koch, 2004; Parker et al., 2004) and meat quality (Mounier, Dubroeucq, Andanson, & Veissier, 2006; Silva, Patarata, & Martins, 1999; Zhang, Farouk, Young, Wieliczko, & Podmore, 2005), on single quality traits, such as pH (Mach, Bach, Velarde, & Devant, 2008), or speculate on the relationships between the three (Gardner, McIntyre, Tudor, & Pethick, 2001; Mota-Rojas et al., 2006; O'Neill, Webb, Frylinck & Strydom, 2006) without quantifying the relationships among them. Muchenje et al. (submitted for publication-a) established the strength of the relationship of stress responsiveness and meat quality within cattle breeds under natural pasture grazing conditions (Table 2).

2.3. Biochemistry and physical meat attributes

2.3.1. pH and meat quality

Although Muchenje et al. (2008b) reported no relationships among meat tenderness, pHu and meat colour, several authors have reported relationships among these meat quality traits (Byrne, Troy, & Buckley, 2000; Strydom et al., 2000; Vestergaard et al., 2000). Stress, prior to slaughter, is said to be one of the most important influences on pHu and ultimate meat tenderness. It may result from transportation, rough handling, inclement temperatures, or anything that causes the animal to draw on its glycogen reserves before slaughter.

Grass-fed animals have darker meat than have grain-fed ones (Muir, Beaker, & Brown, 1998). This is caused by the higher pHu values found in beef from grass-fed compared to grain-fed cattle. Muir et al. (1998) hypothesised that grass-fed steers are more susceptible to pre-slaughter stress and associated pre-slaughter glycogen depletion than are grain-fed steers, as the latter would be

Table 2
Correlations between stress responsiveness hormones from urine and meat lightness (L^*), pH, tenderness and cooking loss of meat from all, Nguni, Bonsmara and Angus steers

Meat Quality characteristic	Epinephrine				Norepinephrine				Dopamine			
	All	Nguni	Bonsmara	Angus	All	Nguni	Bonsmara	Angus	All	Nguni	Bonsmara	Angus
Lightness (L^*)	−0.13	−0.65**	−0.07	−0.77	0.00	−0.52*	0.04	−0.82	0.09	−0.14	−0.39*	0.54
pH	−0.10	0.02	0.00	0.32	0.09	0.13	−0.01	0.41	−0.04	−0.22*	0.54*	−0.20
WBSF2[a]	0.11	0.21	−0.15	0.84	0.14	0.13	0.00	0.79	−0.10	0.53*	−0.52*	−0.80
WBSF21[b]	0.20	0.42	−0.23	0.36	0.12	0.13	−0.16	0.38	0.12	0.29	−0.13	−0.73
Cook loss 2[c]	−0.13	−0.29	0.09	0.55	−0.10	−0.30	−0.10	0.47	−0.12	0.00	−0.62*	−0.57
Cook loss 21[d]	0.04	−0.09	0.22	−0.22	0.00	−0.29	0.19	−0.26	−0.18	−0.02	−0.61*	0.61

NB. Correlation coefficients between meat lightness (L^*) and pH for all steers was −0.43 ($P < 0.001$), for Nguni steers was −0.21 ($P = 0.22$), for Bonsmara steers was −0.58 ($P < 0.001$), and for Angus steers was −0.6 (P = 0.02). Significantly correlated at $^{*}P < 0.05$, $^{**}P < 0.01$, $^{***}P < 0.001$.
Source: Muchenje et al. (submitted for publication-a).
[a] WBSF2, Warner Bratzler value for meat aged for 2 days.
[b] WBSF21, Warner Bratzler value for meat aged for 21 days.
[c] Cook loss 2 (%), Cooking loss after ageing for 2 days.
[d] Cook loss 21 (%), Cooking loss after ageing for 21 days.

better accustomed to penning and handling. However, French et al. (2000) and Razminowicz et al. (2006) reported no such difference in ultimate pH between grass-fed and grain-fed steers.

2.3.2. Colour and meat quality

Meat colour is the most important factor affecting consumer acceptance, purchasing decisions and satisfaction of meat products. Colour measurements are done using the Commission International De I' Eclairage (CIE) colour system (Commission International De I' Eclairage, 1976). The three fundamental colour coordinates are L^*, a^* and b^*. The L^* measures the lightness and is a measure of the light reflected (100 = white; 0 = black); a^* measures positive red, negative green and b^* measures positive yellow, negative blue (Commission International De I' Eclairage, 1976).

Meat colour may be influenced by many factors, such as enzymes, diet and age of the animal and even the activity undertaken by the animal. For example, myoglobin, a protein, responsible for the majority of the red colour in meat, does not circulate in the blood but is fixed in the tissue cells and is purplish in colour. When it is mixed with oxygen, it becomes oxymyoglobin, and produces a bright red colour which is measured objectively by a^* coordinates (Priolo et al., 2001). The remaining colour comes from the haemoglobin which occurs mainly in the circulating blood, but a small amount can be found in the tissues after slaughter (Priolo et al., 2001). When the muscle glycogen has been used up rapidly during the handling, transport and pre-slaughter period, after slaughter there is little lactic acid production which results in DFD meat, and this condition is measured by L^* coordinates (Commission International De I' Eclairage, 1976). This DFD meat is of inferior quality as the less pronounced taste and the dark colour are less acceptable to the consumer and it has a shorter shelf life, due to the abnormally high pH value, which is conducive to bacterial growth (Priolo et al., 2001). Zhang et al. (2005) found that high pH meat had lower L^* (lightness), a^* (redness), b^* (yellowness), hue angle (degrees) and chroma (saturation) values than normal pH meat, indicating that high pH meat is darker and less brown than is normal pH meat.

Animals fed on pasture have a yellow fat colour because of the high levels of beta-carotene contained by grass. This yellow fat colour is measured objectively by b^* coordinates. Consumers often perceive meat with yellow fat as having come from an old or diseased animal. In addition, forage-based rations, as well as different forage and seasonal changes, allow for carcasses with a darker lean appearance or fat that is yellow in appearance (Baublits et al., 2004). The darker lean (low L^* values) may be attributed to increased myoglobin, decreased muscle glycogen, or both, and the yellow fat (Priolo et al., 2001). Grass-fed cattle could be more stressed than grain-fed cattle due to differences in human exposure (Andersen et al., 2005) or that grazing animals exhibit more myoglobin than do confined animals, due to differences in physical activity (Shorthose & Harris, 1991), and hence differences in meat colour. There are also differences in *ante-mortem* glycogen and its effect on pH of meat, or differences in marbling and its effects on lean colour (Baublits et al., 2004). Vestergaard, Oksbjerg, and Henckel (2000) reported less glycogen, a higher pH, and darker lean meat from younger bulls that were fed a forage-limited diet than from those fed a concentrate *ad libitum*. These authors speculated that the decreased dietary energy on the forage-limited diet favoured an increase in oxidative muscle metabolism. An increase in oxidative muscle metabolism could possibly allow for the decreased necessity to store comparable amounts of muscle glycogen as muscle with a higher glycolytic capacity. The resultant pH differences caused differences in yellowness (b^*). Vestergaard et al. (2000) reported a negative correlation between pH and b^* values.

Although there are contrasting reports on breed effects on meat colour, differences in meat colour have been associated with variations in intramuscular fat and moisture contents, age-dependent changes in muscle myoglobin content (Lawrie & Ledward, 2006) and the pHu of the muscle (Hector, Brew-Graves, Hassen, & Ledward, 1992), with higher pHu being associated with dark cuts. Some authors (Chambaz, Scheeder, Kreuzer, & Dufey, 2003; Muir, Wallace, Dobbie, & Bown, 2000; Revilla & Vivar-Quintana, 2006) reported no breed effects on colour. According to O'Neill, Webb, Frylinck and Strydom (2006) and Muchenje et al. (2008b), Nguni steers produced darker meat than did the improved breeds. Although the causes of the differences in meat colour were not fully understood, O'Neill, Webb, Frylinck and Strydom (2006) observed that Nguni cattle released more catecholamines than did exotic breeds raised on a feedlot, during the pre-slaughter period, causing the depletion of glycogen. Muchenje et al. (submitted for publication-a), however, reported that Nguni steers had the lowest catecholamine levels at slaughter as compared to Bonsmara and Angus steers when they were raised on natural grazing. Furthermore, Muchenje et al. (submitted for publication-a) reported significant relationships between catecholamine levels and lightness in beef from Nguni steers, but such relationships were not reported between catecholamine levels and lightness in beef from Bonsmara and Angus, implying that the relationships between catecholamines and lightness in beef may be breed-dependent and complex to interpret.

2.3.3. Water-holding capacity and drip loss

Water-holding capacity (WHC) is defined as the ability of meat to retain its water during application of external forces, such as cutting, heating, grinding or pressing (Zhang et al., 2005). In detailed studies of myofibrils, Offer and Trinick (1983) presented evidence that most of the water in muscle is held by capillary forces between the thick and thin filaments. Water-holding capacity of meat is greatly affected by pH (Offer & Knight, 1988). It is important to meat processing in that, as proteins are able to hold more water, they become more soluble. In meat, WHC is at a minimum at the iso-electric point (pI) of proteins (Zhang et al., 2005). At this point, equal positive and negative charges on the amino acid side chains result in a maximum number of salt bridges between peptide chains and a net charge of zero. The pI of meat is in the pH range of 5.0–5.5 which is also the pH of meat after it has gone through *rigor mortis* (Zhang et al., 2005). The exposure of proteins to a low pH at high temperatures causes less water to be retained between actin and myosin filaments, thus increasing exudates (drip loss). Actin and myosin are important in the formation of a protein lattice, necessary for binding water and fat in further processed meat products (Zhang et al., 2005).

In contrast, increasing or decreasing the pH away from the pI will result in increased water-holding capacity by creating a charge imbalance (Zhang et al., 2005). A charge imbalance is a predominance of either positive or negative charges which will lead to a repulsion of charged protein groups of the same charge. This repulsion results in increased capacity for water retention and leads to a juicy meat. Zhang et al. (2005) reported higher water-holding capacity in high pH meat than in normal pH meat.

Drip loss is the loss of fluid from beef cuts from the shrinkage of muscle proteins (actin and myosin) in the form of drip (Yu et al., 2005). Aldai et al. (2006) and Uytterhaegen et al. (1994) reported breed effects on drip loss with double-muscled animals, showing increased drip loss in beef. Oliván et al. (2004) also found that raw meat of double-muscled animals had higher drip loss and hence lower water-holding capacity than had meat from heterozygous bulls. This effect could be the result of several factors, including, higher glycolytic metabolism in muscle of double-muscled animals (Gagniére, Picard, Jurie, & Geay, 1997; Oliván et al., 2004), differences in collagen structure (Uytterhaegen et al., 1994), or the lower IMF content of double-muscled meat (Oliván

et al., 2004). Aldai et al. (2006) found that, when IMF content was high, there was a concomitant lower result for juice loss from raw meat, measured as the expressible juice under pressure. A rapid pH fall or a lower pH would tend to cause protein denaturation and greater drip loss (Offer & Knight, 1988). However, Muchenje et al. (2008b) and Muchenje et al. (submitted for publication-a) found no differences in drip loss and water-holding capacity.

2.3.4. Meat tenderness

Tenderness can be attributed to a person's perception of meat, such as: softness to tongue, resistance to tooth pressure and adhesion. Sources of tenderness variation in beef for instance may be attributed to animal's age, sex, liveweight, breed and *ante-mortem* stress. Tenderness varies, mainly due to changes to the myofibrillar protein structure of muscle in the period between animal slaughter and meat consumption (Muir et al., 2000). For example, if the carcass is refrigerated too hastily immediately after slaughter, muscle fibres contract severely, and the result is 'cold-shortening' which will require a force to shear the fibres after cooking (Razminowicz et al., 2006). Thus, the tougher the meat, more force is required to shear it, and that is known as the Warner–Bratzler shear force (WBSF) test.

Muir et al. (2000) and Monson, Sañudo and Sierra (2005) argued that meat tenderness is a function of the collagen content, heat stability and the myofibrillar structure of muscle. These, however, appear to be affected mainly by the rate of growth of the animal rather than breed *per se*. The myofibrillar component of tenderness can also be influenced by the calpain proteolytic enzyme system during ageing of the carcass *post-mortem* (Chéret, Delbarre-Ladrat, de Lamballerie-Anton, & Verrez-Bagnis, 2007). Wheeler and Koohmaraie (1991) suggested that the myofibrillar component could be a more important factor than the connective tissue characteristics in influencing meat tenderness. Pasture beef turned out to have a WBSF higher than conventional beef (Razminowicz et al., 2006). However, French et al. (2000) found no difference in WBSF between beef samples produced on grass-based and concentrate-based diets.

While the biochemical changes that occur in beef muscle *post-mortem* are largely understood, the relationship between these changes and variation in meat tenderness remains unclear and requires quantification (Koohmaraie, 1996). Koohmaraie, Kent, Shackelford, Veiseth, and Wheeler (2002) suggested that sarcomere length, connective tissue and proteolysis of myofibrillar proteins could explain most of the variation observed in aged meat, with proteolysis being the main biochemical factor contributing to the variation in tenderness. Maher, Mullen, Buckley, Kerry, and Moloney (2005) found that variation in proteolysis was greater than the other biochemical, chemical and tenderness quality attributes in Belgian Blue steers managed homogeneously pre- and post-slaughter. Furthermore, Koohmaraie et al. (2002) hypothesised that protein degradation occurs at different rates in different animals, which may contribute to the variation in tenderness of beef.

Different breeds of cattle have a wide spectrum of fibre types in muscles (Campo et al., 2000; Gil et al., 2001) but these are not always reflected by differences in instrumental analyses using Warner Bratzler or sensory panels. However, several authors have reported no differences in WBSF values due to breed when animals are slaughtered at the same age (Muchenje et al., 2008b; Muir et al., 2000; Revilla & Vivar-Quintana, 2006). Strydom et al. (2001) also reported no differences in WBSF values among Nguni and Bonsmara steers that were raised in a feedlot. Stolowski et al. (2006) reported significant breed- and breed-by-ageing interaction effects on meat tenderness, with those animals with higher levels of Angus blood being tenderer than those that had lower Angus blood levels. Sañudo et al., 2004 found that differences between breed types for most WBSF values were more pronounced at the lower carcass weight than at higher carcass weights. It has also been reported that different breeds had a wide spectrum of fibre types in muscles, but these were not always reflected by differences in instrumental analyses using WBSF or sensory panels (Sañudo et al., 2004). Seideman, Crouse, and Cross (1986) reported significant breed effects on total and insoluble collagen, which could be more important than weight or even production system in determining meat tenderness. Sañudo et al., 2004 reported significant differences in WBSF values among breeds at short ageing times, but the differences disappeared at 21 days, implying that longer ageing times tend to homogenise the product, especially in the heavier animals. A higher slaughter weight and longer ageing time could make the product more homogeneous, independently of the breed type (Sañudo et al., 2004).

Indigenous breeds, such as the Nguni and Zebu, are perceived to have poorer carcass characteristics (Muchenje et al., 2008a) and to have tougher meat, which is more variable in tenderness compared to beef from exotic breeds, such as the Angus and Hereford. This is because indigenous breeds have greater amounts of calpastatin that reduces *post-mortem* degradation of muscle by calpains, resulting in tough meat (Koohmaaie, 1996; Gil et al., 2001). Another factor may be that these breeds walk long distances in search of grazing and water; therefore, by that long walking activity, their muscles get tough hence there will be more force needed to break their muscle (Scholtz, 2005). Most indigenous breeds grow naturally without any growth supplements (Muchenje et al., 2008b) such that, by the time they reach a required slaughter weight, they are already mature and give a less tender meat. The opposite can be true about the exotic breeds, because of growth supplements they get from the farm; they reach a required slaughter weight rapidly at a younger age and so yield a more tender meat.

Meat tenderness improves with ageing of the muscle. Ageing can be used to decrease shear force values during *post-mortem* storage as a result of the proteolysis of myofibrillar proteins, which is mediated in part by calpains (Koohmarie, 1996). This tenderization through ageing involves several aspects that affect myofibrillar fragmentation, including animal characteristics, pH and *pre-rigor* conditioning (Sañudo et al., 2004). The same authors reported a higher rate of tenderization in heavier animals (92% within the first week) than in lighter animals (67% within the first week). Stolowski et al. (2006) found that ageing can improve WBSF values up to 14 days; and, post-mortem ageing beyond 14 days may not be effective in improving WBSF of steaks from cattle with a large *Bos indicus* influence. Muir et al. (2000) and Muchenje et al. (2008b) reported no differences in WBSF shear force measurements in meat tenderness between breeds when compared at the same age, with ageing complete by six days after slaughter.

2.4. Muscle histological and biochemical attributes

2.4.1. Sarcomere length

Sarcomere length is used to determine the effectiveness of electrical stimulation as a way of preventing cold-shortening. Electrical stimulation reduces the pH of the muscle rapidly and hastens the onset of *rigor mortis*. Electrical stimulation was primarily developed to accelerate *post-mortem* glycolysis so that muscles are prevented from excessive shortening when they enter *rigor*. Stolowski et al. (2006) found that electrically stimulated muscles had longer sarcomeres than had their non-electrically stimulated counterparts. Cold-shortening occurs most often in carcasses when muscle temperature drops below 10 °C within 8–12 h *post-mortem*, while the muscle pH remains above 6.1. The lowering of the pH of muscle is a result of the conversion of muscle glucose to lactic acid. Cold shortens sarcomere length and meat becomes tough, although this may not happen in some cases (Stolowski et al., 2006). Whipple

et al. (1990), Stolowski et al. (2006) and Muchenje et al. (2008b) reported that sarcomere length was not affected by breed type.

2.4.2. Myofibrillar fragmentation length, ageing, tenderness

Ageing is the holding of certain kinds of meat, principally beef, after slaughter, under refrigeration at temperatures ranging from 0 ℃ to 4 ℃, to enhance tenderness and develop flavour. During ageing, an enzyme collagenase, produced by bacteria within the meat, breaks down the myofibrillar protein structure and connective tissue protein (Zhang et al., 2005). Since myofibrils make up nearly 80% of the volume of the muscle cell, their disruption greatly influences meat tenderness (Zhang et al., 2005). Other changes that are correlated with increased tenderness include breakages within the myofibrils themselves, particularly within the I-band. These breakages lead to increased fragility and fragmentation of the myofibrils. The increase in myofibrillar fragmentation is indicative of the amount of tenderization that has taken place in meat (Sañudo et al., 2004). Muchenje et al. (2008b) reported ageing effects on beef, but did not find breed effects on beef aged for two or 21 days.

2.5. Cholesterol and fatty acids

2.5.1. General

Beef contains cholesterol and fat which is a significant source of saturated fatty acids in the human diet. This is a risk factor for the development of heart problems (Barton et al., 2007; Mills et al., 1992). It is, therefore, important to evaluate cholesterol levels and fatty acid profiles in beef meat.

2.5.2. Cholesterol and consumer health

Cholesterol can be both good and bad for food consumers. Abnormally high levels of cholesterol and abnormal proportions of low-density lipoproteins (LDL) and high-density lipoproteins (HDL) are associated with cardiovascular diseases. Rule, Macneil, and Short (1997) emphasized that breed, nutrition, and sex do not affect the cholesterol concentration of bovine skeletal muscle. These authors suggested that differences in muscle cholesterol concentration would probably be associated with marked changes in the structure of the muscle cells. Thus, altering cholesterol concentration in muscle may require a marked redistribution of membrane fatty acids (Rule et al., 1997). A common serving of beef from pasture-based production systems has low levels of cholesterol (Muchenje et al., submitted for publication-b; Padre et al., 2007). Muchenje et al. (submitted for publication-b) reported that the consumption of 200 g of beef represented cholesterol intakes of 83, 73 and 81 mg from beef from natural pasture-based Nguni, Bonsmara and Angus, respectively, which corresponds to less than 30% of the recommended maximum daily cholesterol intake (300 mg/day, Greene & Feldman, 1991; Jiménez-Colmenero, Carballo, & Cofrades, 2001). Costa, Restle, and Brondani (2002) and Alfaia (2007) observed that cholesterol content in beef depended on IMF content. Meat with high levels of IMF has high levels of cholesterol. Furthermore, plasma cholesterol levels are influenced by the fatty acid composition of the diet (Flynn, Naumann, Nolph, Krause, & Ellersieck, 1985), with high levels of some long-chain SFA's such as lauric (C12:0), myristic (C14:0) and palmitic acid (C16:0) increasing serum cholesterol levels (Grundy & Denke, 1990; Rowe, Macedo, Visentainer, Souza, & Matsushita, 1999).

The C18:1cis fatty acids reduce human LDL-cholesterol and increase HDL-cholesterol concentrations in blood (Katan, Zock, & Mensink, 1994), which result in lower risk of coronary problems. Studies have demonstrated a strong relationship between LDL-cholesterol levels and human cardiovascular diseases and that HDL-cholesterol has an inverse relationship with the risk of cardiovascular diseases (Kwiterovich, 1997). Furthermore, the 20:4 $n-6$ has been noted to have cholesterol-lowering attributes *in vitro* (Viljoen, 1999). According to Rowe et al. (1999), myristic (C14:0) and C16:0 acid raise both LDL and HDL serum cholesterol, although C18:0 has little effect. Therefore, the high levels of LDL fatty acids in beef are not desirable.

2.5.3. Fatty acid profiles

Breed of cattle and the way cattle are managed may affect fatty acid composition, since fatty acid composition is closely related to the fatness level (Barton et al., 2007; Zembayashi, Nishimura, Lunt, & Smith, 1995). Fatty acid composition of edible tissues of cattle is influenced by diet and genotype (Barton et al., 2007). Padre et al. (2007) reported breed differences in lipid content in tissue of cattle, which were indirectly related to conjugated linoleic acid (CLA) contents. Some breeds that have a tendency to deposit higher amounts of fat on muscle produce a higher quantity of CLA. The CLA's have been reported to have various antioxidant and anti-tumor properties (Belury, 2002a). Studies on CLA in humans show a tendency for reduced body fat, particularly abdominal fat, changes in serum total lipids and decreased whole body glucose uptake (Thom, Wadstein, & Gudmundsen, 2001).

Baublits et al. (2006) and Muchenje et al. (2007) reported no differences between biological types for fatty acid profiles. Breed differences reflect underlying differences in gene expression or activities of enzymes involved in fatty acid synthesis, desaturation or chain elongation, and thus deserve further attention (Barton et al., 2007; Choi, Enser, Wood, & Scollan, 2000). Differences in fatty acid composition between breeds can often be explained by differences in the proportion of intramuscular fat as the ratio of polyunsaturated fatty acid to saturated fatty acid (PUFA/SFA). This ratio decreases with the increasing fat level of beef (Barton et al., 2007) that depends on breed and nutrition. It is therefore imperative to assess the fatty acid profiles of meat from cattle raised on pasture.

Forage-fed beef contains higher proportions of CLA (Padre et al., 2007), which exhibits anticarcinogenic properties, and can increase animal body protein (Baublits et al., 2006). Furthermore, forage-fed beef can exhibit an improved $n-6$ to $n-3$ fatty acid ratio that has a positive cardiovascular impact (Baublits et al., 2006; Muchenje et al., 2007; Razminowicz et al., 2006). Realini, Duckett, Brito, Dalla-Rizza and Mattos (2004) pointed out that pasture-fed animals have higher concentrations of PUFA, stearic (18:0), linoleic (LA), linolenic (LNA), arachidonic (20:4 $n-6$, AA), eicosapentaenoic (20:5 $n-3$, EPA), and docosapentaenoic (22:5 $n-3$, DPA) acids than have animals fed on protein concentrates. Fatty acids affect human health in several ways. Table 3 summarises fatty acid levels reported by several authors.

2.5.4. Fatty acids and health

Meat healthiness is largely related to its fat content and its fatty acid composition (Fisher et al., 2000). Lipids of green forage contain high proportions of α-linolenic acid (ALA). This basic $n-3$ (omega -3) fatty acid can be endogenously desaturated and elongated to long-chain $n-3$ fatty acids ($n-3$ LC-PUFA) (Razminowicz et al., 2006), i.e. eicosapentaenoic acid (EPA), docosapentaenoic acid (DPA), and docosahexaenoic acid (DHA). Omega -3 fatty acids, particularly the $n-3$ LC-PUFA, have been shown to exert various beneficial health effects (Simopoulos, Leaf, & Salem, 1999).

Increasing $n-3$ contents in beef can be relevant to improving human supply with $n-3$ LC-PUFA (Razminowicz et al., 2006).Raes, Balcean, Dirink, De Winne, Claeys, & Demeyer (2003) reported that $n-6/n-3$ ratios were higher (5–7) for animals fattened under highly intensive production conditions, compared with values of 2.5–3 for animals from extensive production systems. The recommended maximum $n-6/n-3$ is 5:1 (Razminowicz et al., 2006).

Table 3
Fatty acid profile (as percentage of the total fatty acids identified) of the *Longissimus thoracis et lumborum* muscle as reported in literature

Fatty acid	Range of values	Sources
C14:0	1.54–4.64	Aldai et al. (2006), Alfaia et al. (2007), Muchenje et al. (2007)
C14:1*c*9	0.16–0.45	Aldai et al. (2006), Muchenje et al. (2007)
C15:0	0.30–0.67	Aldai et al. (2006), Alfaia et al. (2007), Muchenje et al. (2007)
C16:0	21.8–30.9	Aldai et al. (2006), Alfaia et al. (2007), Enser, Hallett, Hewett, Fursey, and Wood (1996), Muchenje et al. (2007), Wood et al. (2003),
C16:1*c*9	1.51–3.76	Aldai et al. (2006), Alfaia et al. (2007), Muchenje et al. (2007)
C17:0	0.85–1.12	Aldai et al. (2006), Muchenje et al. (2007)
C17:1*c*10	0.37–0.65	Aldai et al. (2006), Muchenje et al. (2007)
C18:0	13.4–18.5	Aldai et al. (2006), Alfaia et al. (2007), Enser et al. (1996), Muchenje et al. (2007), Wood et al. (2003)
C18:1*t*9	1.40–5.66	Aldai et al. (2006), Muchenje et al. (2007)
C18:1*c*9	6.34–35.2	Aldai et al. (2006), Alfaia et al. (2007), Muchenje et al. (2007)
C18:2*c*9,12 ($n-6$)	9.86–23.7	Aldai et al. (2006), Muchenje et al. (2007)
C18:2*c*9*t*11 ($n-6$)	0.28–0.37	Alfaia et al. (2007), Muchenje et al. (2007)
C20:0	0.17–9.68	Aldai et al. (2006), Muchenje et al. (2007)
C18:3*c*9,12,15 ($n-3$)	0.14–2.34	Aldai et al. (2006), Muchenje et al. (2007)
C22:0	0.40–1.85	Aldai et al. (2006), Muchenje et al. (2007)
C20:3*c*11,14,17 ($n-3$)	0.40–1.16	Aldai et al. (2006), Muchenje et al. (2007)
C22:2*c*13,16 ($n-6$)	0.22–0.49	Aldai et al. (2006), Muchenje et al. (2007)
PUFA[1]	13.6–32.2	Aldai et al. (2006), Muchenje et al. (2007)
MUFA[2]	26.4–36.5	Aldai et al. (2006), Muchenje et al. (2007)
SFA[3]	40.8–49.8	Aldai et al. (2006), Muchenje et al. (2007)
$n-6$[4]	5.23–29.5	Aldai et al. (2006), Alfaia et al. (2007), Muchenje et al. (2007)
$n-3$[5]	1.18–8.46	Aldai et al. (2006), Alfaia et al. (2007), Muchenje et al. (2007)
PUFA:SFA[6]	0.11–0.81	Aldai et al. (2006), Alfaia et al. (2007), Enser et al. (1996), Muchenje et al. (2007)
$n-6$: $n-3$[7]	1.32–1.8	Aldai et al. (2006), Alfaia et al. (2007), Enser et al. (1996), Enser et al. (1998), Muchenje et al. (2007)

Increasing the $n-3$ fatty acid content of animal feed can therefore be a promising and sustainable way to improve the dietetic value of beef without forcing consumers to change their eating habits.

Conjugated linoleic acids (CLA) are another group of fatty acids, which naturally occur in ruminant-derived food and to which various beneficial health effects are ascribed (Belury, 2002b). However, scientific evidence for beneficial health effects in humans is variable and still unconvincing (Kramer et al., 1997). There is clear evidence of an enhanced proportion of $n-3$ fatty acids and CLA in beef from grass-fed bulls compared with beef from bulls fed maize silage and concentrate (Dannenberger et al., 2004; Nürnberg et al., 2002). Among the various CLA isomers, *cis*-9, *trans*-11 18:2 (18:2*c*9*t*11) is the predominant isomer naturally occurring in ruminant products and is particularly believed to be beneficial for human health (Kramer et al., 1997; Razminowicz et al., 2006; Vatansever et al., 2000). The 18:2*c*9*t*11 is mainly a product of endogenous desaturation of *trans*-vaccenic acid (18:1*t*11), which is the predominant 18:1-*trans* isomer in grass-fed cattle (Dannenberger et al., 2004). Accordingly, Chin, Liu, Storkson, Ha, and Pariza (1992) claimed that the best dietary sources of CLA are foods produced by grass-fed ruminants.

In addition to possible health effects (Aharoni et al., 1995; Barton et al., 2007; Padre et al., 2007), fatty acid profiles may affect the sensory characteristics of meat (Wood et al., 2003). The negative influence of the intramuscular fat (IMF) content of meat on health aspects, therefore, competes with its positive influence on meat juiciness and flavour (Issanchou, 1996). Assessment of fatty acid profiles of cattle breeds in particular production systems is therefore needed.

2.6. Sensory evaluation of meat

In order to determine the acceptance of a food product, consumers consider several characteristics, such as its sensory characteristics, nutritional value, convenience and impact on health (Wood et al., 2003). The sensory, health-related and nutritional properties are the most important motivators for liking and purchasing of meat (Verbeke & Viaene, 1999). Components of the palatability of meat include tenderness, juiciness and flavour. Aroma, the impression that you form on the first bite of meat and the amount of connective tissue in meat are also important sensory characteristics (Hoffman, Kroucamp, & Manley, 2007). The most important quality aspects of beef are tenderness, juiciness, the way that it tastes and that it is fresh, lean, healthy and nutritious (Grunert, 1997). Muir et al. (2000) reported that, despite the yellower fat of the Friesian steers, there was no difference in eating quality of the meat produced by Hereford and Friesian steers, suggesting that fat colour has no measurable relationship with meat eating quality.

Dransfield et al. (1984) postulated that tenderness and juiciness were the properties that most influence meat acceptability. Monsón, Sañudo, and Sierra (2005) reported that partial correlations between sensory variables indicated that tenderness ($r = 0.60$), juiciness ($r = 0.59$) and beef flavour intensity ($r = 0.49$) were the attributes that most influenced the acceptability of meat. The same authors found that the highest correlation coefficient was observed for beef flavour (0.22) and the lowest for bitter flavour (-0.10). Furthermore, WHC has been reported to be one of the most important factors that affect juiciness of meat on mastication (Lawrie & Ledward, 2006).

Table 4
Ranges of sensory scores of some meat quality characteristics aged for 2 and 21 days as reported in literature

Meat sensory characteristic	Range of values	Source
Taste at 2 days	4.7–5.5	Strydom et al. (2005), Revilla and Vivar-Quintana (2006)
Taste at 14 days	5.8	Strydom et al. (2005)
Aroma at 2 days	5.21–5.70	Monsón et al. (2005), Muchenje et al. (2008c)
Aroma at 21 days	5.02–5.70	Monsón et al. (2005), Muchenje et al. (2008c)
Juiciness at 2 days	3.3–6.6	Byrne et al. (2000), Muchenje et al. (2008c)
Juiciness at 21 days	4.38–5.60	Monsón et al. (2005), Muchenje et al. (2008c)
Flavour at 2 days	3.1–5.89	Byrne et al. (2000), Monsón et al. (2005), Muchenje et al. (2008c)
Flavour at 21 days	5.39–5.93	Monsón et al. (2005), Muchenje et al. (2008c)
Tenderness at 2 days	2.1–6.4	Byrne et al. (2000), Maher et al. (2005), Monsón et al. (2005), Muchenje et al. (2008c)
Tenderness at 21 days	5.50–6.47	Monsón et al. (2005), Muchenje et al. (2008c)
Residual at 2 days	4.19–4.98	Monsón et al. (2005)
Residual at 21 days	4.21–4.76	Monsón et al. (2005)
Overall acceptability at 2 days	1.8–5.65	Byrne et al. (2000), Monsón et al. (2005)
Overall acceptability at 21 days	4.26–4.94	Monsón et al. (2005)

Sensory values for tenderness tend to be higher as the ageing time increases (Campo, Panea, Albertí, & Santolaria, 1999; Monsón et al., 2005; Muchenje et al., 2008c; Spanier, Flores, McMillin, & Bidner, 1997). In a study by Monsón et al. (2005), ageing time did not affect juiciness in the Spanish Holstein and the Blonde d'Aquitaine while it affected juiciness in the Limousin and the Brown Swiss, the values found at 3 and 7 days being the highest in both breeds. Juiciness values decreased from 14 days of ageing (Monsón et al., 2005). This could be partly explained by the weakening of muscle structure, which may produce higher losses of liquid during cooking.

Relationships have been reported between physical meat quality characteristics and sensory characteristics, such as muscle fibre and overall tenderness (Hoffman et al., 2007; Muchenje et al., 2008c); and between quantity and composition of intramuscular fat and flavour (Calkins & Hodgen, 2007; Melton, 1990; Wood & Enser, 1997). However, flavour is a very complex attribute of meat palatability (Calkins & Hodgen, 2007) and its relationship with fat content and composition vary with the breed of cattle (Muchenje et al., 2008c). Juiciness also depends on the quantity and composition of fat in the meat (Melton, 1990; Wood & Enser, 1997), although its relationships with fat content and composition vary with the breed of cattle (Muchenje et al., 2008c). In addition, there have been reports of relationships between pH and several sensory characteristics (Calkins & Hodgen, 2007; Muchenje et al., 2008c). The relationships between IMF, several physical meat quality characteristics and sensory characteristics are likely to depend on the condition of the animal. Table 4 summarises sensory scores reported by several authors.

2.7. Correlations among meat quality traits

Modern meat production techniques aim to increase muscle weight and meat quality, but these characteristics are not always positively correlated (Sañudo et al., 2004). There are various reports on relationships among meat quality traits. For example, meat tenderness is related to ultimate pH (pHu) value and meat colour (Byrne et al., 2000; Strydom et al., 2000; Vestergaard et al., 2000), although there are some cases where such relationships may not be significant (Muchenje et al., 2008b). There are also some relationships between meat quality traits, fatty acid profiles and sensory characteristics of meat (Jeremiah, Alhus, Robertson, & Gibson, 1996; Muchenje et al., 2008c; Wood et al., 2003).

Strydom et al. (2000), Revilla and Vivar-Quintana (2006) and Muchenje et al. (2008b) reported negative correlations between sarcomere lengths and WBSF values. This can be ascribed to the fact that muscles with short sarcomere length are generally tough. Usually there are positive correlations between WBSF values and MFL values in most cattle breeds (Muchenje et al., 2008b). This can be attributed to the fact that meat tenderness is a function of the collagen content and the myofibrillar structure of muscle (Muir et al., 2000; Revilla & Vivar-Quintana, 2006). Furthermore, the variation in WBSF values depend more on the myofibrillar content than the total collagen content or its solubility, especially considering that shear force on cooked meat may also be a measure of myofibrillar toughness (Sañudo et al., 2004). Strydom et al. (2000) reported significant within-breed correlations between myofibrillar fragmentation index (MFI) and tenderness. Beef crosses with

Table 5
Correlations between glycogen level and some technological meat quality values

	glycogen (ante-mortem)	glycogen (1 h post mortem)	glycogen (3 h post mortem)	glycogen (48 h post mortem);	pH at 48 hours	cooking loss	Warner- Bratzler shear force.
Glycogen (ante-mortem)		0.60**	0.70**	−0.04	−0.67**	0.65**	0.44*
pH glycogen (1 h post mortem)			0.81**	−0.01	−0.73***	0.70**	0.36
Glycogen (3 h post mortem)				0.02	−0.78**	0.75**	0.39*
Protein glycogen (48 h post mortem);					− 0.04	0.08−	0.06
pH at 48 hours						−0.79**	−0.58*
Cooking loss							−0.48*

Source: Lahucky et al. (1998).
* Significantly correlated at $P < 0.05$.
** Significantly correlated at $P < 0.01$.
*** Significantly correlated at $P < 0.001$.

Table 6
Correlations among quality traits of meat from Nguni, Boinsmara and Angus steers

	pH	Moisture	Protein	Fat	Drip loss	Sarcomere	MFL2[a]	MFL21[b]	WB2[c]	WB21[d]
Lightness (L*)	−0.31	0.38*	−0.41**	−0.30	−0.17	0.26	−0.02	−0.18	−0.21	−0.18
pH		0.43**	−0.32*	0.05	−0.21	−0.11	−0.06	0.30	−0.12	−0.15
Moisture			−0.86***	−0.36*	−0.25	0.23	0.10	−0.21	−0.16	−0.22
Protein				0.05	0.23	−0.23	0.10	0.17	0.19	0.21
Fat					−0.01	−0.20	0.20	−0.41*	−0.03	−0.08
Drip loss						−0.42**	0.24	0.28	0.62***	0.78***
Sarcomere							−0.30	−0.21	−0.47**	−0.58***
MFL2[a]								0.26	0.42**	0.43**
MFL21[b]									0.34*	0.31
WB2[c]										0.79***

Source: Muchenje et al. (2008b).
* Significantly correlated at $P < 0.05$.
** Significantly correlated at $P < 0.01$.
*** Significantly correlated at $P < 0.001$.
[a] MFL2, Myofibrillar fragment length for meat aged for two days.
[b] MFL21, Myofibrillar fragment length for meat aged for 21 days.
[c] WB2, Warner Bratzler value for meat aged for two days.
[d] WB21, Warner Bratzler value for meat aged for 21 days.

more Angus blood aged faster than those crosses with less Angus blood (Stolowski et al., 2006).

There is a relationship between drip loss, IMF and pH. Aldai et al. (2006) found that, when IMF content was high there was a concomitant lower result for juice loss from raw meat, measured as the expressible juice under pressure. A rapid pH fall or a lower pH would tend to cause protein denaturation and greater drip loss. However, there are some cases where such relationships may not be significant (Muchenje et al., 2008b). Some meat quality correlations are reported in Tables 5 and 6.

3. Conclusion

From the preceding review it can be seen that there are several biochemical processes and products that interact and affect meat quality and the consumer perception of meat eating quality. The major processes include glycogen breakdown, *rigor mortis*, glycolysis, proteolysis, oxidation and lipolysis. Ultimate pH and fatty acid quality are, arguably, the major factors that influence meat eating quality. These are affected by pre-slaughter handling of the cattle and post-slaughter handling of the meat. The important meat quality characteristics are tenderness, flavour and colour The factors that can be manipulated to improve meat eating quality include improving the body condition of animals before slaughter, reducing pres-slaughter stress, ageing of meat, and developing appropriate feeding management strategies. Most studies on improving meat eating quality have been conducted in high input large-scale production systems. The different methods of improving meat eating quality and consumer health also need to be evaluated in low input production systems. In addition, it is necessary to determine meat consumption patterns to enhance human health.

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