Effect of South African beef production systems on *post-mortem* muscle energy status and meat quality

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Abstract

Post-slaughter muscle energy metabolism and meat colour of South African production systems were compared; steers (n=182) of Nguni, Simmental and Brahman crossbreds were reared on pasture until A-, AB-, or B-age, and in feedlot until A- and AB-age. After exsanguination carcasses were electrically stimulated (400 V for 15s); *m. longissimus dorsi* muscle energy samples were taken at 1, 2, 4 and 20 h *post-mortem* and samples for meat quality studies were taken at 1, 7 and 14 days *post-mortem*. Production systems affected muscle glycogen, glucose, glucose-6-P, lactic acid, ATP, creatine-P and glycolytic potential ($P<0.05$), with the muscles of feedlot carcasses having faster glycolysis rate than pasture carcasses. Energy metabolites correlated ($0.4<r<0.9$) with meat colour (CIE, L*a*b*), and ($0.3<r>0.5$) water holding capacity, drip loss, and Warner Bratzler shear force. Muscle energy only affected muscle contraction of the A-age-pasture system (shortest sarcomere length of 1.66 µm vs 1.75 µm and highest WBS of 6 kg vs 5 kg; 7 days *post-mortem*).

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1. Introduction

In South Africa there are different beef production systems dictated mostly by the availability and type of natural resources, local consumer demand and commercial viability. Animals are reared on either pasture or in feedlots and mostly slaughtered at a young age of about 12 to 16 months before the eruption of permanent incisors (A-age class according to SA Beef Carcass Classification System (SABCCS, Government Gazette, R.342 of 1999)) or after development of up to two permanent incisors (AB-age class (SABCCS)). Sometimes pasture reared animals are slaughtered after the eruption of three to six permanent incisors developed and are carcasses classified in the B-age class. B-age animals are rarely produced from the feedlot system. Production systems have the potential to affect the physiology of muscle (energy status of muscle and baseline quality attributes at the point of slaughter) that contribute to meat attributes such as colour, juiciness and tenderness because of different breeds used, feeding regimes, slaughter ages of animals and handling and exercise conditions Owens & Gardner, 1999; Muir, Deaker, & Bown, 1998).

Breed effects on meat quality in terms of proteolytic enzyme activities affecting tenderness is well known. For instance the increase of proportion of *Bos indicus* content results in the increase in beef toughness (Johnson, Huffman, Williams & Hargrove, 1990; Wheeler, Savell, Cross, Lunt & Smith, 1990). Much more basic breed differences were attributed to differences in carcass weight and/or fatness (Koch, Dikeman & Crouse, 1982), which could determine the susceptibility to cold shortening. Negative tenderness effects were substantially reduced when electrical stimulation was applied (Seideman & Cross, 1982; Wheeler *et al.,* 1990). Voisinet, Grandin, O'Connor, Tatuma

and Deesing (1997) found that feedlot cattle with excitable temperaments, that can be a genotype characteristic of e.g. *Bos indicus*, had tougher meat and higher incidence of borderline dark cutters.

Pasture-fed cattle normally do not have the same degree of finish as grain-fed cattle due to the decreased energy available in the forage depending on quality of pasture available (Muir *et al*., 1998). Pasture-fed beef mostly have darker muscle (Priolo, Micol & Agabriel, 2001; Bruce, Stark & Beilken, 2004) and Mancine & Hunt (2005) reviewed research that gave evidence that diets affect muscle colour by promoting oxidative metabolism, rather than anaerobic muscle metabolism and glycogen storage. These factors ultimately have influences on pH, oxygen consumption, and metmyoglobin reducing activity. Physical activity could influence muscle fibre type and metabolism also affecting ultimate muscle colour (Vestergaard, Oksbjerg, & Henckel, 2000). The consumer judge meat on colour and approximately 15% of retailed meats are discriminated against due to colour (Smith, Belk, Sofos, Tatum, & Williams, 2000). Killinger, Calkins, Umberger, Feuz and Eskridge (2004) reported that most consumers preferred bright, cherry-red meat that was neither too pale nor too dark. Darker coloured meat is often associated with pre slaughter stress that leads to a condition called dark, firm and dry meat, where the pH of the meat did not drop below 5.8 (Tarrant, 1989).

Age of the animal could, irrespective of feeding regime influence both colour and tenderness of meat (Powell, 1991). Age of bovine animals has been used in South Africa since 1936 as a characteristic to grade their carcasses, presumably because carcasses of younger cattle were considered to be of “better” quality than those of older cattle (Government Notice No. 1548 of 1936). A research project funded by the South African Meat Board was carried out by scientists of the Meat Industry Centre (MIC) from ARC-Irene in the early 1990s (Crosley, Heinzé, & Naudé, 1994). The results of this project showed that meat tenderness decreased, as the slaughter age of the animals increased, in the order of zero, two, four, six and eight tooth. When slaughtered at an older age the producer at present receives a lower price per kg for the carcass.

Most studies on meat quality performed in South Africa, like studies elsewhere, the effects of one or two production factors or a single dimension within a production factor are investigated (Swanepoel, Casey, De Bruyn, & Naude, 1990, and Strydom, Frylinck, Van der Westhuizen, & Burrow, 2008, breed within grain feeding; Du Plessis & Hoffman, 2007, breed and age on pasture diet, Muchenje, Dzama, Chimonyo, Strydom, & Raats, 2008, breed on pasture diet).

A large proportion of South African grain fed and pasture cattle are Brahman and Simmental crossbreds, while the Nguni breed (representative of the Sanga breed) is used extensively on pasture and were therefore selected for this study and on different feeding regimes and slaughtered at different ages according to the status of their permanent incisors. Supportive data such as muscle energy status before and during rigor mortis and sarcomere length was recorded to explain variation in meat quality among treatment combinations.

Scientists and producers question the merit for discriminating between the production systems producing meat from older animals especially if modern technology applications such as post-slaughter electrical stimulation are taken into account. This motivated industry to fund a project to investigate the combined breed, diet and age as reflected in the South African beef industry to determine their effects on meat quality. In this article we discuss muscle energy status related effects on tenderness and meat colour and in a following article we will discuss the role of intra muscular connective tissue and proteolysis.

2. Methods and Materials

2.1 Animals and experimental design

One hundred and eighty two (n=182) were selected on phenotype from various commercial producers to represent a Brahman (Br-X, *Bos indicus*; n = 60), Simmental (Si-X, continental *Bos*

taurus; n = 58) and Nguni (Ng-X, *Sanga*; n = 64) cross-breed groups. All the animals were castrated shortly after weaning. At least 10 animals of each cross-breed were raised in a feedlot or on pasture, until reaching A-age, AB-age, or B-age (only pasture) and fat class 2 or 3, according to the SABCCS. The pasture animals were raised on the ARC-Roodeplaat Experimental Farm (2 067 ha) situated in the Gauteng Province, South Africa approximately 30 km north-east of Pretoria, between southern latitudes 25°20` and 25°40` and eastern longitudes 28°17` and 28°25` which receives an annual precipitation of between 380 and 700 mm. The average daily maximum and minimum temperature for this climatic region is 32 °C and 18 °C in January and 22 °C and 4 °C in July (AGROMET, 1994). The vegetation in this area is described as Savanna (Rutherford & Westfall, 1994), and as Sourish Mixed Bushveld (Veld Type 19) (Acocks, 1988). Except for the grazing the animals also received summer lick (200 kg/ton Ca^{2+}phosphate; 300 kg/ton salt; 50 kg/ton urea; 450 kg/ton maize meal) and winter lick (150 kg/ton mono calcium phosphate; 250 kg/ton salt; 150 kg/ton urea; 450 kg/ton maize meal) supplementation. The feedlot animals were raised in a feedlot situated on the experimental farm of the Agricultural Research Council - Animal Production Institute, Irene, South Africa. A standard type of high concentrate diet was supplied to the feedlot animals (12 MJ/kg DM, 13.5% protein) for a period of 90-110 days which included a 14 day adaption period. Normal animal husbandry practices were applied. All the animals were weighed every two weeks, and during summer the pasture animals received a weekly treatment against ticks. For comparative purposes the same non-aggressive growth promoter (Ralgro; 36 mg zeranol; Schering-Plough, South Africa) was implanted at the beginning of the finishing period. This research was approved by ARC-API Ethics Committee (Ref no. APIEC11/025).

2.2 Slaughter and sampling procedures

The animals underwent the following typical South African pre- and post-slaughter practices the animals were transported the same number of kilometres to the abattoir (approximately 50 km) and feed were withdrawn 3 hours before slaughter. Water was available at all times. Carcasses were electrically stimulated for 15 s (400 V peak, 5 ms pulses at 15 pulses/s) after exsanguination and entered the cold rooms (1-4 °C) 45 min after exsanguination. Warm and cold carcass weights were recorded. Carcasses were classified according to the official SABCCS for age (by dentition) and fatness (visual appraisal). Samples for muscle energy status were collected from the *m. longissimus dorsi* (LD), between the fourth and fifth lumbar vertebrae at 1, 2, 4 and 20 h *post-mortem*. Muscle pH and temperature were recorded in the same position at the same time intervals with a digital hand-held meat pH meter (Sentron, Model 1001, Sentron Technologies, Roden, The Netherlands) Carcasses with ultimate pH (pH_{20h}) > 5.8 were classified as being dark, firm and dry (DFD) (Tarrant, 1989; Thompson, 2002). Samples for muscle energy status were snap frozen in liquid nitrogen and stored at –70 °C. The LD of the left carcass sides were sampled between the third last rib and last lumbar vertebra on the day after slaughter for measurements of colour, drip loss, and water holding capacity (WHC), sarcomere length (SL), and tenderness determined by Warner Bratzler shear force (WBS) at 1, 7 and 14 days *post-mortem*,. Drip loss, WHC, SL and colour measurements were performed on fresh samples (1 day *post-mortem*). Samples WBS were vacuum packaged, aged for 1, 7 or 14 days *post-mortem* at 2 ±2 °C and then frozen (-20 °C).

2.3 Muscle energy status early post-mortem

Lactic acid concentration in the muscle was determined by using a modified method of Dalrymple and Hamm (1973) as described by Gutmann and Wahlefield (1974). A 3 g muscle

sample was homogenized with 15 ml 0.6 N perchloric acid. Glucose and glycogen concentrations in the muscle were determined according to a modified method of Dalrymple and Hamm (1973) as described by Keppler and Decker (1974). A 3 g muscle sample was homogenized with 15 ml 0.6 N perchloric acid. Glucose-6-P, ATP and creatine-P concentrations in the muscle were determined by a modified method of Dalrymple and Hamm (1973) as described by Bernt, Bergmeyer and Möllering (1974) and Lamprecht, Stein, Heinz and Weisser (1974). Glycolytic potential (GP) was expresses in µmol/g lactate and calculated as follows: Glycolytic potential = 2*(glucose-6-phosphate + glucose + glycogen) + lactic acid (Monin & Sellier, 1985).

2.4 Drip loss, water holding capacity and colour of fresh meat

Drip loss was measured as described by Strydom, Frylinck, Montgomery & Smith, 2009 using 50 g of fresh LD (1 day *post-mortem*) sliced into cubes of 10 x 10 x 20 mm that were suspended on a pin inside a sample bottle (200 ml). Duplicate samples were stored for 3 days at 4 ±2 °C. Drip loss percentage was calculated as:

% Drip loss = ((sample mass before storage
- sample mass after storage)/sample mass before storage) x 100.

WHC was determined by calculating the ratio of meat area and liquid area after pressing a 400 to 600 mg meat sample on a filter paper (Whatman 4) sandwiched between two perspex plates, and pressed at constant pressure for 5 min according to the method described by Grau and Hamm (1953). The areas were measured by means of a video image analysis (VIA) (Soft Imageing System, Olympus, Japan) described by Irie, Izumo and Mohri (1996) and WHC was expressed as the area of the meat divided by the area of the moisture.

Meat colour was measured with a Minolta meter (Model CR200, Osaka, Japan) on fresh samples 1 day *post-mortem*. Two freshly cut steaks of 15 mm thickness each of the LD were allowed to bloom for 60 min at chiller temperatures (4 ±2 °C) before recording. Three recordings were performed on each steak. The steak colours were recorded as three components; luminance or lightness, L^* (dark to light), and two chromatic components; a^* (green to red) and b^* (blue to yellow) values (CIE, 1978). The following calculations were done to determine the physiological attribute of chroma (intensity of the red colour) also known as saturation index (S) = $(a^{*2}+b^{*2})^{1/2}$) (MacDougall, 1977) and hue angle (discolouration) = $\tan^{-1}$ (b^*/a^*) (Young, Priolo, Simmons & West, 1999). Mean values were used for statistical analysis.

2.5 Sarcomere length measurements

Samples for sarcomere lengths of fresh LD samples (1 day *post-mortem*), were prepared according to the method of Hegarty and Naudé (1970). Fifty sarcomeres per sample were measured by means of VIA using an Olympus B340 system microscope at a 31000 magnification equipped with a CC12 video camera (Olympus, Tokyo, Japan). AnalySIS Life Science software package (Soft Imageing Systems Gmbh, Münster, Germany) was used to process and quantify measurements.

2.6 Warner Bratzler shear force

Samples for WBS were measured at 1, 7 and 14 days *post-mortem*. Frozen samples (-20 °C) were processed into 30 mm steaks by means of a band saw. The frozen steaks were thawed at 4 °C for 24 h and were then cooked using an oven-broiling (Mielé, model H217, Mielé & Cie, Gűtersloh, Germany) method with direct radiant heat (American Meat Science Association (AMSA), 1995).

The steaks were broiled at 260 °C (pre-set) to 70 °C internal temperature and cooled down to room temperature (±18 °C). Eight round cores (12.7 mm diameter) were removed from the steaks parallel to the long axis of the muscle fibres (AMSA, 1995). Each core was sheared once through the centre, perpendicular to the fibre direction, by a Warner Bratzler shear device mounted on a Universal Instron apparatus (Model 4301, Instron Ltd, Buckinghamshire, UK; crosshead speed = 200 mm/min). WBS was measured as the peak force (kg) average for eight cores per sample.

2.7 Statistical analyses

The effect of the 5 production systems, the 3 different breeds (see test groups and number of animals per test group in Table 1) and their interactions on carcass characteristics, WBS, sarcomere length, drip loss, WHC, and energy components were evaluated by means of MANOVA on GCM (SAS, 2004) at a significance level of $P<0.05$. Bonferroni multiple range tests were used for the comparison of means between production systems as well as between breeds. Partial correlation coefficients were calculated between variables by means of the two tailed student t-test to determine significance.

3. Results and discussion

3.1 Frequency of DFD phenomenon in the production systems and breed.

The frequency of DFD phenomenon detected among three cross-breeds and five production systems are summarised in Table 1. Despite attempts to minimize pre-slaughter stress by limiting the transport distance and the time between feed withdrawal and slaughter DFD still occurred ($pH_u > 5.8$) and it seems that the Ng-X steers were more susceptible to stress compared to Br-X and

Table 1. Number of animals per test group and frequency of dark, firm and dry (DFD)[1] phenomenon detected among the three cross-breeds and five production systems[2].

	Cross-breeds[3]			
Production systems[2]	Br-X	Si-X	Ng-X	Total number of
	n	n	n	carcasses
AF	12	12	12	36
	0(0%)[4]	0(0%)	1(8%)	1(3%)
ABF	12	10	14	36
	0(0%)	1(10%)	0(0%)	1(3%)
AP	11	12	10	33
	1(9%)	0(0%)	4(40%)	5(15%)
ABP	10	11	14	35
	0(0%)	1(9%)	1(7%)	2(6%)
BP	15	13	14	42
	2(13%)	2(15%)	1(7%)	5(12%)
Total	60	58	64	182
	3(5%)	4(7%)	7(11%)	14(8%)

[1] Carcasses with ultimate pH (pH_{20h}) > 5.8 were classified as being dark, firm and dry (DFD).

[2] Production systems: AF= A age classification, grain fed at a feedlot, ABF= AB age classification grain fed at a feedlot, AP = A age classification, pasture finished, ABP = AB age classification, pasture finished, BP = B age classification, pasture finished.

[3] Cross breeds: Br-X =Brahman cross bred animals, Ng-X = Nguni cross bred animals, Si-X = Simmental cross bred animals.

[4] Number of DFD carcasses and percentage.

Si-X steers. With regards to productions system, AP showed a higher percentage of DFD compared to the other systems). Seven of 14 DFD cases were Nguni's and 4 of these were from the AP group. DFD phenomenon seems to be part of the effect of production system and therefor the DFD related data was not eliminated from this study - pH_u values will thus be influenced by the DFD phenomenon.

3.2 Effect of production system and breed on carcass weight, pH and temperature, muscle contraction (sarcomere lengths) and Warner Bratzler shear force (WBS)

The effect of production system and breed ($P<0.05$) on cold carcass weight, ultimate pH, muscle contraction (sarcomere lengths) and Warner Bratzler shear force (WBS) are summarised in Table 2. Carcass weight influences pH/temperature ratios and was therefore recorded in this study. Pasture finished steers (AP and ABP) recorded lower carcass weights than their grain fed counter parts ($P<0.05$), indicating the effect of the lower nutritional density of pasture combined with a relative short feeding period. The steers from the BP system had the highest carcass weights as a result of their older age and longer growth period (36 months), despite low nutritional density. In general the Ng-X animals, a phenotypically small frame breed, produced lighter carcasses than that of the Br-X and Si-X although not always significant for all production systems (see AP and ABP systems). ABF and BP systems showed the biggest differences between Ng-X vs Br-X and Si-X carcasses. The Brahman breed is known to adapt to temperate, subtropical or tropical pasture areas rather than feedlot conditions (Randle, 2000) although this phenomenon was not experienced in the present trial. Simmental animals do well in the feedlot situation (Comerford, Benyshek, Bertrand & Johnson, 1988). The Nguni is a tropically adapted *Bos taurus* (Sanga) indigenous to Southern Africa, extensively used by commercial and resource poor farmers to produce grass fed beef in South Africa. Because of their smaller carcass size, these animals are not popular with commercial feedlotters, although their

Table 2. Effects of production system and breed on carcass weight, pHu, muscle contraction (sarcomere lengths) and Warner Bratzler shear force.

Characteristic	*P*-Value	Production systems[1] AF $\bar{X}$ ± SD	ABF $\bar{X}$ ± SD	AP $\bar{X}$ ± SD	ABP $\bar{X}$ ± SD	BP $\bar{X}$ ± SD
Cold carcass weight (kg):						
Average for production groups[1]	<0.001	218 ± 17^{bc}	210 ± 41^{b}	162 ± 24^{a}	176 ± 30^{a}	235 ± 51^{c}
Average for cross-breeds[2] x production groups[1]:						
Br-X	<0.001	218 ± 6^{c}	240 ± 40^{c}	175 ± 22^{ab}	201 ± 33^{bc}	260 ± 42^{c}
Si-X		234 ± 6^{c}	231 ± 26^{c}	165 ± 15^{ab}	177 ± 20^{ab}	285 ± 38^{c}
Ng-X		201 ± 18^{abc}	172 ± 13^{ab}	143 ± 27^{a}	157 ± 21^{a}	182 ± 23^{abc}
Ultimate pH:	<0.001	5.48±0.11^{a}	5.64±0.081^{b}	5.68±0.12^{b}	5.64±0.12^{b}	5.66±0.18^{b}
Sarcomere length:						
1 day *post-mortem*	<0.001	1.75 ± 0.08^{b}	1.75 ± 0.07^{b}	1.66 ± 0.09^{a}	1.73 ± 0.06^{b}	1.72 ± 0.08^{b}
Warner Bratzler shear force (kg/12.5mm θ)						
1 day *post-mortem*	0.001	6.7 ± 1.4^{ab}	6.0 ± 0.9^{a}	**7.4 ± 1.6^{b}**	6.6 ± 1.3^{ab}	6.6 ± 1.9^{ab}
7 days *post-mortem*	0.010	5.3 ± 1.1^{ab}	4.8 ± 1.0^{a}	**6.0 ± 2.0^{b}**	5.5 ± 1.4^{ab}	5.3 ± 1.6^{ab}
14 days *post-mortem*	<0.001	4.2 ± 0.9^{a}	3.8 ± 0.7^{a}	**5.2 ± 1.9^{b}**	4.6 ± 0.9^{ab}	4.0 ± 0.8^{a}
Warner Bratzler shear force (kg/12.5mm θ) cross-breed[2] x productions system[1]:						
1 day *post-mortem*	0.027					
Br-X		7.0 ± 1.3^{ab}	6.3 ± 0.9^{ab}	7.4 ± 1.2^{ab}	7.2 ± 0.9^{ab}	6.9 ± 1.4^{ab}
Si-X		6.0 ± 1.4^{ab}	6.0 ± 0.9^{ab}	6.9 ± 0.9^{ab}	6.6 ± 1.5^{ab}	7.2 ± 2.7^{ab}
Ng-X		7.1 ± 1.2^{ab}	5.7 ± 0.9^{ab}	**8.1 ± 2.4^{b}**	6.3 ± 1.4^{ab}	**5.6 ± 0.8^{a}**
7 days *post-mortem*	0.540					
Br-X		6.0 ± 1.0	5.4 ± 1.3	6.4 ± 1.6	5.8 ± 1.1	5.3 ± 1.7
Si-X		4.6 ± 1.0	4.6 ± 0.8	5.5 ± 1.0	5.4 ± 1.7	5.5 ± 2.0
Ng-X		5.4 ± 0.8	4.5 ± 0.6	6.3 ± 3.1	5.4 ± 1.4	5.0 ± 0.6
14 days *post-mortem*	0.063					

Br-X	4.6 ± 0.7^{ab}	4.1 ± 0.9^{ab}	5.2 ± 1.2^{bc}	5.0 ± 0.9^{abc}	4.0 ± 0.8^{ab}
Si-X	3.8 ± 0.5^{ab}	4.0 ± 0.7^{ab}	**6.3 ± 2.9^{c}**	4.6 ± 1.0^{ab}	4.1 ± 1.1^{ab}
Ng-X	4.1 ± 1.2^{ab}	**3.6 ± 0.4^{a}**	4.3 ± 0.8^{ab}	4.2 ± 0.8^{ab}	3.9 ± 0.4^{ab}

^{abcd} Means in a rows with different superscripts differ significantly ($p<0.05$) based on the Bonferroni multiple range tests**.**

$\overline{X}$±SD ~ mean ± standard deviation.

[1] Production systems: AF = A age classification, grain fed at a feedlot, ABF = AB age classification grain fed at a feedlot, AP = A age classification, pasture finished, ABP = AB age classification, pasture finished, BP = B age classification, pasture finished.

[2] Cross-breeds: Br-X ~ breed average for Brahman cross bred animals, Ng-X ~ breed average for Nguni cross bred animals, Si-X ~ breed average for Simmental cross bred animals.

adaptability in the feedlot is acceptable (Strydom *et al.*, 2008) and their meat quality compares favourably with *Bos taurus* breeds (Frylinck & Heinze, 2003; Strydom, Naude, Smith, Scholtz & van Wyk, 2000).

The rate and extent of *post-mortem* pH/temperature decline are main factors controlling meat quality development (Monin & Sellier, 1985). Early *post-mortem* muscle temperature, depending on its rate of decline, can initiate two tenderness restricting mechanisms, i.e. cold or heat shortening and change proteolytic rates also known as cold toughening (Locker & Hagyard, 1963; Marsh, 1985). These phenomena led to the pH/temperature window concept also implemented by the Meat Standards Australia (MSA) grading scheme to manage meat tenderness (Thompson, 2002). According to Pearson and Young (1989) cold shortening occurs when the muscle pH is greater than 6.0 with ATP still available for muscle contraction and the muscle temperature less than 10 °C. Heat toughening occurs when the combination of high temperature and low pH in muscle exhausts proteolytic activity as a result of accelerated protein denaturation (Thompson, 2002). The window set to avoid this phenomenon is the pH/temperature relationship of greater than pH = 6 for muscle temperature greater than 35 °C (Thompson, 2002). In our own study the risk of cold shortening was evident since carcasses of Nguni was relatively small and would chill quicker than the other 2 breeds. In addition, the lighter and leaner carcasses anticipated in the AP production system could run the risk of reaching temperatures below 10 °C before the pH dropped below 6. Hence we opted for a short electrical stimulation treatment. The duration of stimulation was also limited to avoid over stimulation of the larger carcasses, e.g. Br-X and Si-X in AF and ABF.

The rates in pH and temperature decline differed among production systems ($P<0.001$) (Figure 1). Overall the pH/temperature decline rates ($P<0.05$) of carcasses from the pasture systems were slower than those of the feedlot systems. The mean loin muscle temperature of AP carcasses (~28 °C) was lower than those of carcasses from ABP and BP systems (~32 °C), which in turn were lower than those of AF and ABF (~37 °C) at pH 6. We used the pH/temperature window concept

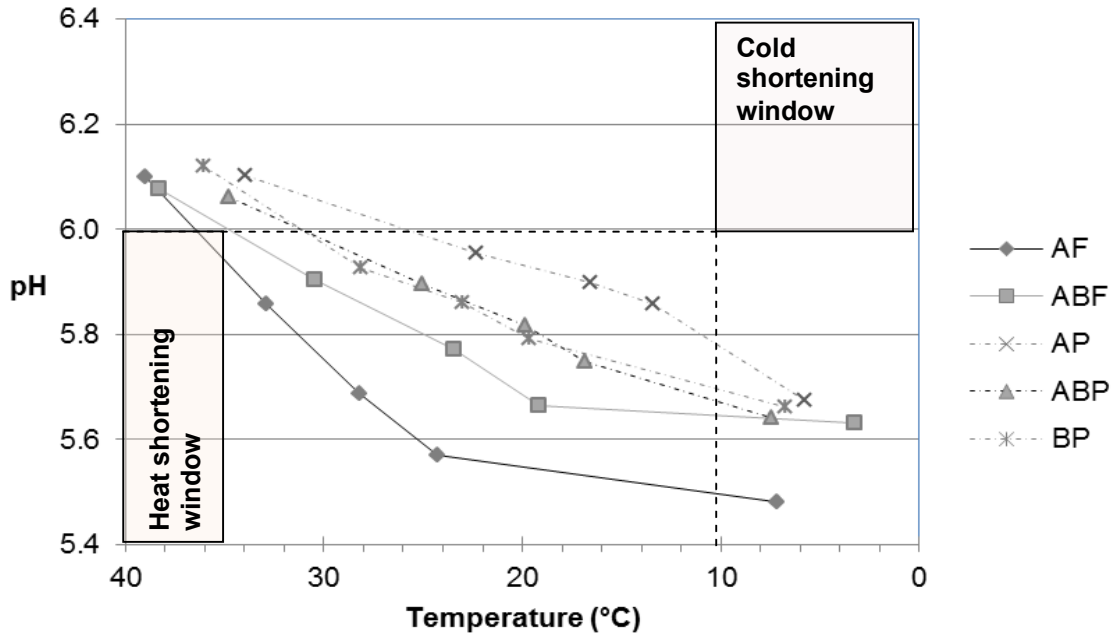


Figure 1. Temperature and pH decline profiles of the production systems; AF, ABF, AP, ABP and BP carcasses. AF ~ average for the animals reared at the feedlot until A age, ABF ~ average for the animals reared at the feedlot until AB age, AP ~ average for the animals reared on the pasture until A age, ABP ~ average for the animals reared on the pasture until AB age, BP ~ average for the animals reared on the pasture until B age. Cold shortening and heat shortening windows according to Pearson and Young (1989) and as discussed in review of Thompson (2002).

as implemented by the Meat Standards Australia (MSA) grading scheme to monitor or identify carcasses in danger of cold shortening (pH <6 at T <10 °C) or heat toughening (pH <6 T>35 °C) (Thompson, 2002). Although the average of AP carcasses did not fall within the cold shortening window it is possible that individual carcasses or even individual muscle fibres within the carcasses could have been subjected to cold shortening. Not all fibres enter rigor at exactly the same time (Jeacocke, 1984) and partial cold shortening could have taken place. In fact, AP loins recorded shorter SL (1.66 μm) than those from the AF, ABF, ABP and BP systems (~1.75 μm) (P<0.05; Table 3). SL also showed a positive relationship with muscle temperature at 1, 2, 3, and 4 h *post-mortem* (r=0.302, 0.417, 0.414, and 0.414 respectively; P=0.05) which explains the shorter SL of AP loins as a result of lighter carcasses (Table 2) and higher chilling rates (Figure 1). However, this effect was not apparent for ABP carcasses that were also relatively light and chilled faster than grain fed carcasses. Breed had no effect on SL within a particular production system. Considering the relationship between shortening and tenderness measurement, Marsh and Leet (1966, as cited by Takahashi, Lochner, & Marsh, 1984) reported that a shortening in SL of less than 20% produced almost negligible effects on beef tenderness. If the resting sarcomere length (SL) of bovine loin muscle is taken as 2.1mm (Marsh and Carse, 1974, as cited by Takahashi *et al*., 1984), then percentage shortening on average for AP was 21% compared to the 17-18% of the other groups. Since AP loins recorded the highest initial and subsequent WBS values (AP > AF, ABF, BP; P<0.05 at 14 days *post-mortem;* Table 3), it is reasonable to believe that partial cold shortening in AP loins could have contributed to the higher WBS values. WBS at 1, 7 and 14 d *post-mortem* also had a negative correlation (r=-0.3) with SL (P<0.05).

Table 3. Effects of production system and breed on *the water holding capacity, drip loss and meat colour.*

Characteristic	*P*-Value	Production systems[1]				
		AF	ABF	AP	ABP	BP
		$\overline{X}$ ± SD	$\overline{X}$ ± SD	$\overline{X}$ ± SD	$\overline{X}$ ± SD	$\overline{X}$ ± SD
Water holding capacity:	<0.001	0.38 ± 0.03^{a}	0.43 ± 0.00^{bc}	0.42 ± 0.06^{bc}	0.40 ± 0.04^{ab}	0.44 ± 0.06^{c}
Drip loss (%):	0.001	2.23 ± 0.78^{c}	1.61 ± 0.59^{ab}	1.56 ± 0.71^{a}	1.69 ± 0.77^{abc}	1.75 ± 0.62^{bc}
Meat colour						
*L**	<0.001	39.0 ± 1.7^{b}	38.2 ± 2.1^{b}	37.8 ± 2.5^{b}	37.8 ± 2.5^{b}	35.3 ± 2.5^{a}
a*	0.001	15.9 ± 1.4^{b}	14.4 ± 1.4^{a}	15.0 ± 1.4^{ab}	15.0 ± 1.4^{ab}	15.4 ± 1.9^{ab}
b*	<0.001	7.2 ± 0.8^{b}	6.3 ± 0.9^{a}	6.4 ± 0.7^{a}	6.4 ± 0.7^{a}	6.6 ± 1.1^{a}
Hue angle = $\tan^{-1}$ (b*/a*)	0.001	2.0 ± 0.2^{a}	2.2 ± 0.2^{b}	2.2 ± 0.2^{b}	2.2 ± 0.2^{b}	2.2 ± 0.2^{b}
Chroma = $(a^{*2}+b^{*2})^{1/2}$	0.001	17.5 ± 1.5^{b}	15.7 ± 1.6^{a}	16.3 ± 1.5^{a}	16.3 ± 1.5^{a}	16.7 ± 2.2^{ab}

[abcd] Means in a rows with different superscripts differ significantly ($p<0.05$) based on the Bonferroni multiple range tests**.**

$\overline{X}$±SD ~ mean ± standard deviation.

[1] Production systems: AF = A age classification, grain fed at a feedlot, ABF = AB age classification grain fed at a feedlot, AP = A age classification, pasture finished, ABP = AB age classification, pasture finished, BP = B age classification, pasture finished.

3.3 Effect of production systems and breed on the water holding capacity (WHC), drip loss and meat colour.

The effect of production system on the WHC, drip loss, and meat colour, are summarised in Table 3. Breed did not show an effect on WHC, drip-loss. The WHC measured in the AF system was the lowest (~0.38), followed by the AF, ABF, ABP and the BP system the highest (~0.44) (P<0.001). Correspondingly the drip loss measured in the AF system (2.2%±0.8) was similar to the ABF and BP systems, but higher than that of the AF and ABP systems (~1.7%). Higher WHC and lower drip loss is associated with faster pH decline (Offer & Knight, 1988) and this corresponds with our findings where the higher drip loss and lower WHC of AF carcasses were associated with a faster pH decline between 1 and 4 h *post-mortem* and a lower pH_u compared to the other groups (Figure 1). Swatland (2004) reported that meat with a low pH_u (AF) is generally paler than meat with higher pH due to more light scattering. Similarly, Schäfer, Knight, Wess and Purslow (2000) found meat with high drip loss to have a more open structure, with greatly increased extracellular space development during the first 24 h *post-mortem* causing light scattering. While AF did not differ from the ABP, ABF and AP, it recorded the highest light reflection (L^*=39.00), while BP loin steaks were darker (L^*=35.31; P<0.05) than all other groups. Lightness also showed a negative correlation (r=-0.421; P=0.05) with WHC and pH_u (r=-0.325). BP loins recorded the same pH_u as AP, ABP and ABF, the highest WHC and an intermediate drip loss, suggesting that lightness (L^*) was also a function of other factors. Bruce *et al.* (2004) found that muscle from pasture finished steers was darker than grain-finished steers and *post-mortem* carcass chilling was slower *than that of of grain* fed carcasses, which when combined with lower muscle pH should increase protein denaturation in grain finished animals relative to pasture finished animals. This was true for the BP vs the AF group in our study but did not apply to the other pasture raised groups. Bidner, Schupp, Mohamad, Rumore, Montgomery, Bagley, and McMillin (1986) associated darker meat from

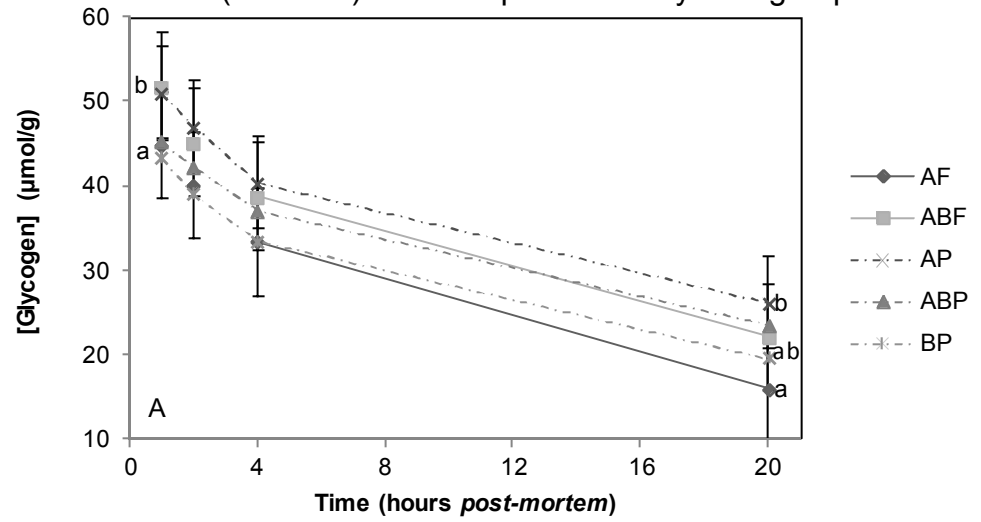
pasture raised steers with higher myoglobin compared to grain fed steers due to age differences. Steaks from grain fed steers recorded sensory colour scores closer to cherry red while grass fed steaks were scored dark red. In the present study AF steaks recorded higher redness (a^*=15.9) values than that of the ABF system (a^*=14.4; P<0.05) with AP, ABP and BP falling in between, but not significantly different. Meat samples from the AF system had higher yellowness (b^*=7.2) than that of ABF, AP, ABP and BP (b^*~6.4). Hue angle and chroma followed similar patterns; AF had the lowest hue angle (2.0) (less discolouration) and the highest chroma (17.5). Breed effect on colour characteristics was only apparent in the hue angle. Meat samples from the Ng-X had a higher hue angle (2.22) compared to that of the Br-X and Si-X (~2.13) (P<0.05; data not shown). According to Liu, Scheller, Arp, Schaefer, and Frigg (1996) an increase in hue angle and a reduction of S or a* indicates a higher degree of meat browning. Redness (a^*), yellowness (b^*) and chroma correlated negatively (-0.396>r>-0.230) with pH that correspond with reports of Abril, Campo, Önenç, Sañudo, Albertí, and Negueruela (2001) and Mancini and Hunt (2005).

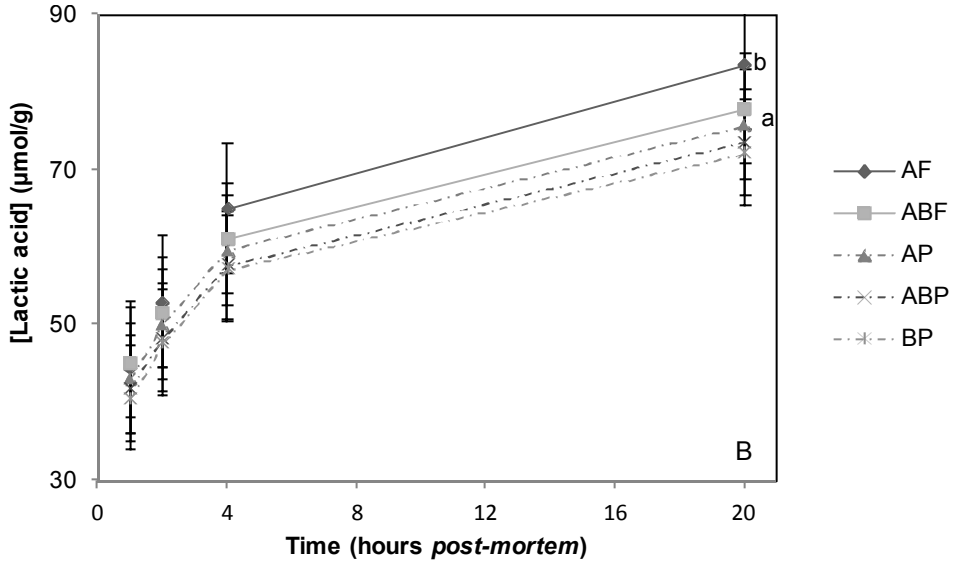
3.4 Effect of production system and breed on muscle metabolism.

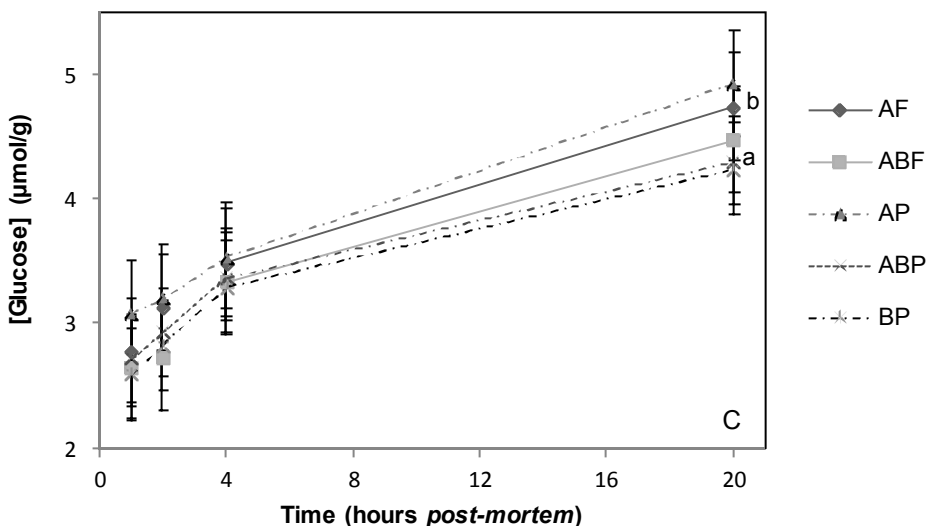
The energy status of muscle immediately post-slaughter affects meat tenderness and colour (Monin & Sellier, 1985; Scheffler, Park & Gerrard, 2011). The effect of production system on the elements of LD *post-mortem* glycolysis: viz.; glycogen, creatine-P and ATP depletion, and glucose, glucose-6-P, and lactic acid production, measured at 1, 2, 4 and 20 h *post-mortem* and calculated glycolytic potential are represented in Figures 2, A - G.

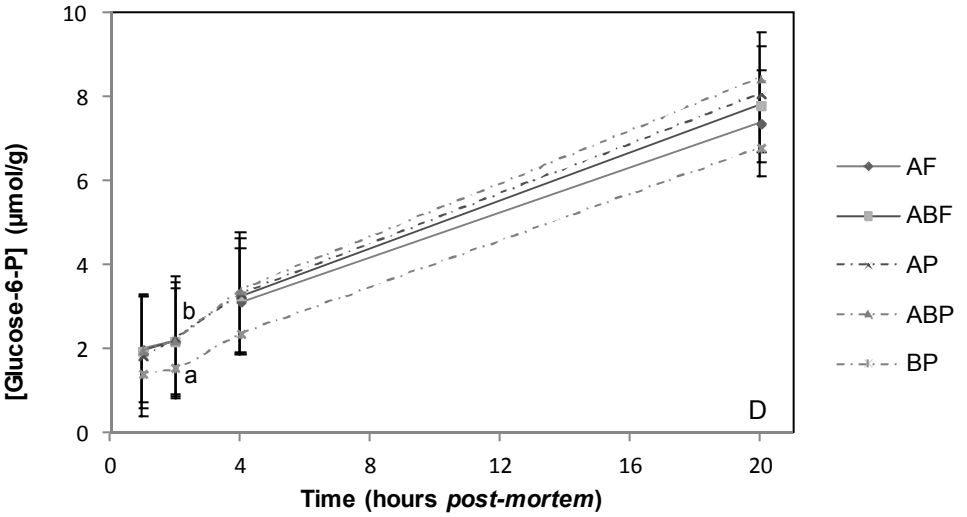
According to Immonen, Ruusunen and Puolanne (2000) dark firm and dry (DFD) meat occurs in beef with muscle glycogen levels below 50 µmol/g at slaughter. Thompson (2002) sets the critical threshold from 45-57 µmol/g below which the normal ultimate pH in meat (5.5.-5.6) will not be attained (Tarrant, 1989). First collection of samples occurred at almost an hour after electrical

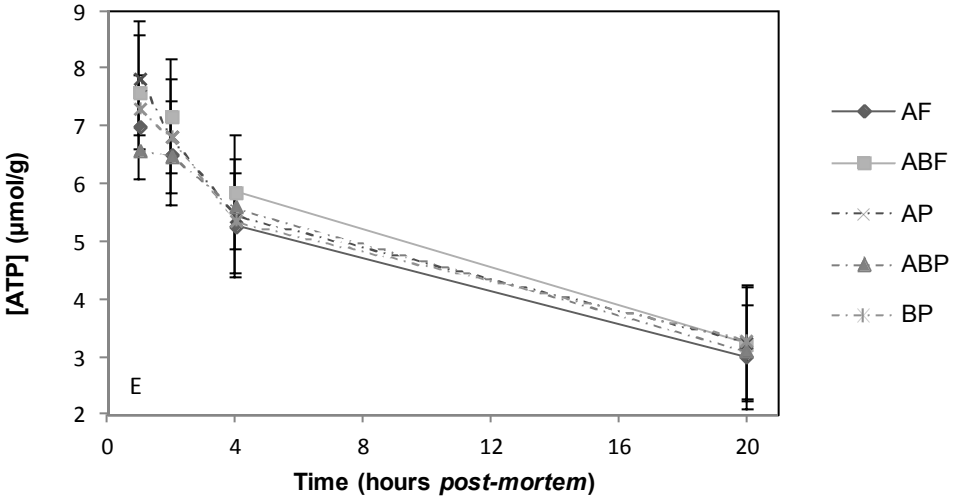
Figure 2. Effect of production system on m. longissimus dorsi glycogen (A), glucose (B), glucose-6-P (C), ATP (D), creatine-P (E), lactic acid concentrations (F) and calculated glycolytic potential (G) at 1, 2, 4 and 20 h post-mortem. The differences ($P < 0.05$) between production system groups were indicated by a's and b's.

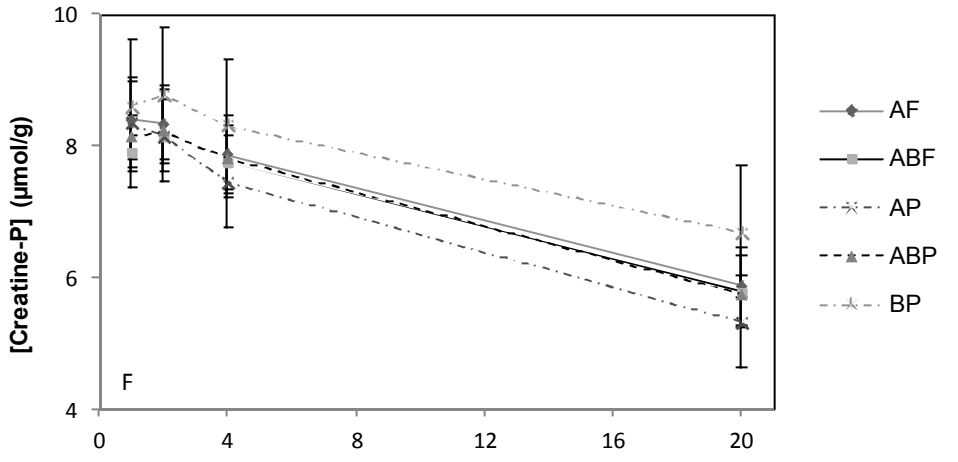




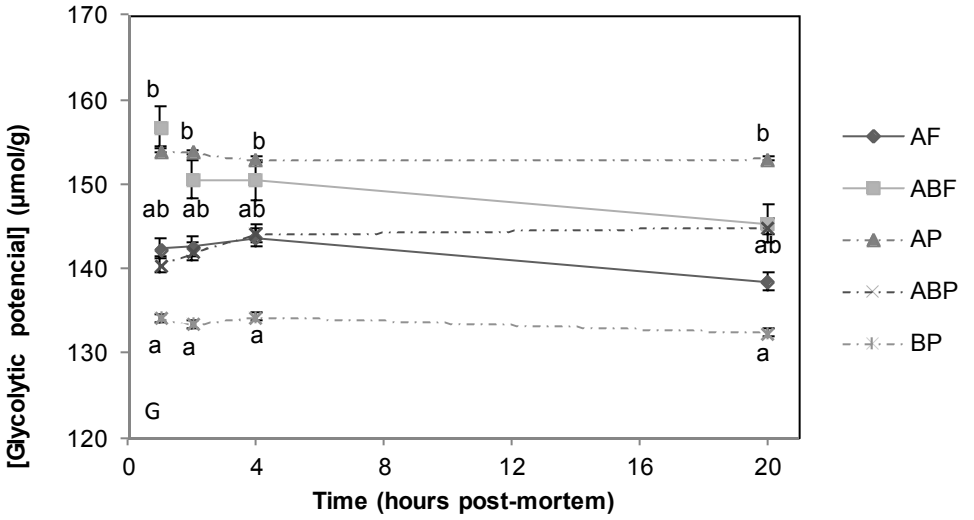



[Glucose-6-P] (µmol/g)
Time (hours post-mortem)
b
a
D
AF
ABF
AP
ABP
BP


[ATP] (µmol/g)
Time (hours post-mortem)
E
AF
ABF
AP
ABP
BP


[Creatine-P] (µmol/g)
F
AF
ABF
AP
ABP
BP

Time (hours *post-mortem*)



stimulation and therefore it is expected that glycogen levels would be lower compared to levels reported in literature of non-stimulated carcasses. Electrical stimulation accelerate glycogen metabolism (Carse, 1973; Seideman & Cross, 1982), therefore the rule cannot be applied in this study. Nevertheless the ABF and AP systems had the highest glycogen levels at 1 h *post-mortem* (~51 µmol/g, $P<0.05$) with AF, ABP and BP systems showing lower muscle glycogen concentration at this point (~44 µmol/g). Overall glycogen depletion rate was slower for the AP, ABP and BP systems while AF and ABF systems had increased glycolysis rates (Figure 2 A). At 20 h *post-mortem*, muscle from the AF system had the lowest glycogen (15.9 µmol/g) and those from the AP system had the highest glycogen concentrations (26.1 µmol/g) ($P<0.05$). Corresponding to this, the AF production system muscle lactate were higher at 4 ($P=0.05$) and 20 h *post-mortem* ($P<0.001$) than that of ABF, AP, ABP and BP with the pasture systems having the tendency to have slower lactate producing rates (Figure 2 B). This agrees with the slower pH decline rates in the AP, ABP and BP systems (Figure 1). A high energy diet, which is typical in feedlots, increased the capacity for *post-mortem* glycolysis. Monin and Sellier (1985) suggested that animals with increased capacity for *post-mortem* glycolysis would lead to an extended pH decline and lower pH_u. If this is true the high energy diet only influenced the AF carcasses (pH_u 5.48) but not the ABF carcasses that was similar to the AP, ABP and BP carcasses with pH_u around 5.65 ($P<0.05$) (Table 2).

Muscle glucose concentration at 20 h *post-mortem* ($P=0.17$) and subsequent glucose production rate were higher in the production systems using younger animals (AF and AP; ~4.3 µmol/g) than that of the systems producing older animals, ABF, ABP and BP (~3.9 µmol/g; Figure 2 C). This age effect is not so severe for the muscle glucose-6-P where only the BP system had a lower glucose-6-P production rate and lowest average muscle glucose-6-P concentrations (Figure 2 D) at 1, 2, 4, and 20 h *post-mortem* ($P<0.05$). Glucose concentrations at 1, 2, 4, and 20 h *post-mortem*

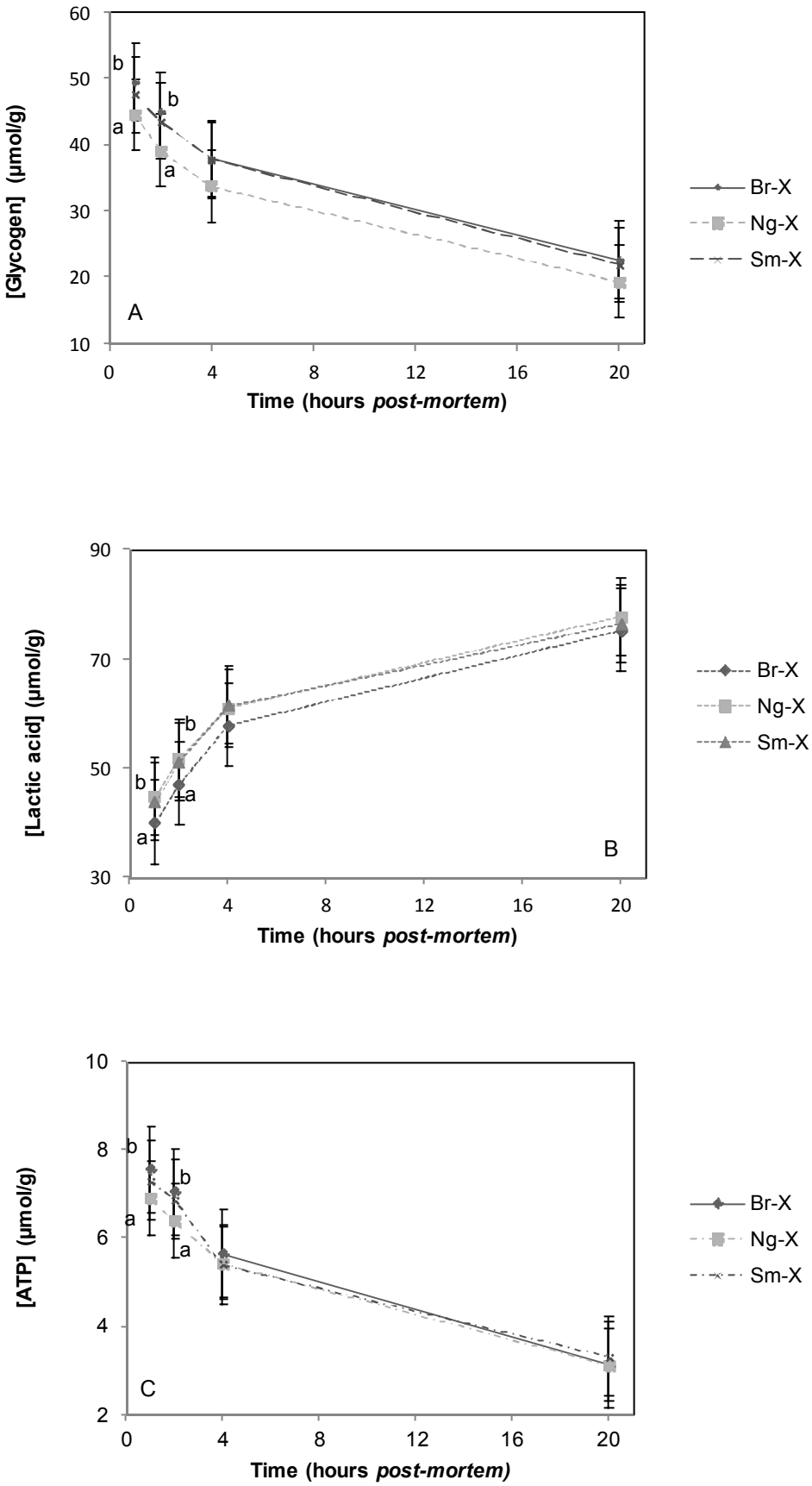
correlated negatively with pH decline at 1, 2, and 4 h *post-mortem* (-0.472 > r > -0.300) and pH_u (*r* =-0.350).

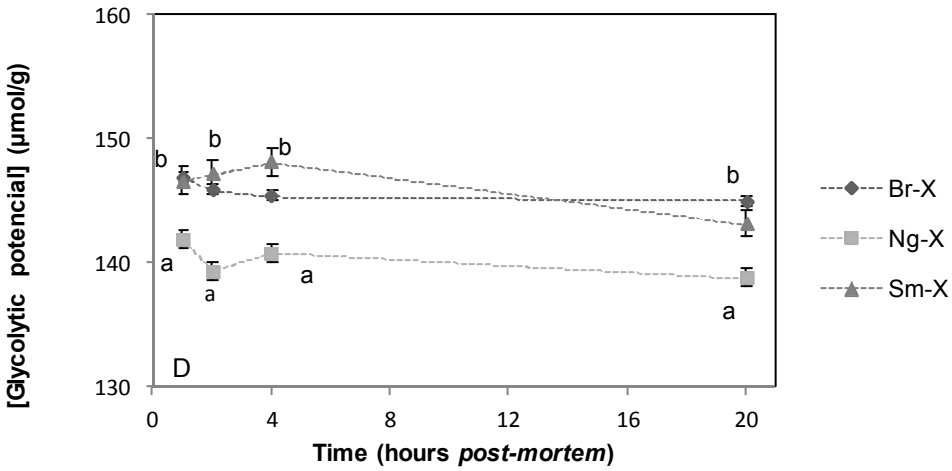
Production system had no effect on ATP reduction rate (Figure 2 E), but the BP system had the lowest creatine-P reduction rate with the corresponding highest creatine-P levels at 1, 2, 4 and significantly at 20 h *post-mortem* (6.7 μmol/g; Figure 2 F), supporting a slower glycolysis rate converting glycogen to glucose and lactate. A mathematical model of anaerobic muscle energy-metabolism was developed by Vetharanian, Thomson, Devine and Daly (2010) to predict pH and the concentrations of nine muscle metabolites over time held at 35 °C. They showed how the individual metabolites influence each other. In contrast to their results creatine-P did not reach zero with the oldest animals from the pasture (BP) having the highest muscle creatine-P concentrations compared to younger animals from the feedlot. According to Bendall (1969) *rigor mortis* is completed in muscles when all supplies of energy (ATP and creatine-P) are exhausted. Either the LD in carcasses of all production systems did not reach full *rigor mortis* at 20 h *post-mortem*, or the normal glycolytic processes were influenced by a number of pre- or post-slaughter interventions. Vestergaard, Oksbjerg, and Henckel. (2000) reported that forage-based diets fed restricted amounts might promote oxidative metabolism, rather than anaerobic muscle metabolism (slower glycolysing muscle) and glycogen storage and this phenomenon could be enhanced by the age of the animal (Powell, 1991). As a result, the restricted diets in combination of animal age led to less glycogen, lower rate of creatine-P breakdown and higher muscle pH. Vestergaard *et al*. (2000) also suggested that the increased oxidative muscle potential could decrease lactate production while increasing pyruvate oxidation within mitochondria, beta-oxidation and time to muscle exhaustion. Mancini, Hunt, Kim and Lawrence (2004) proposed that the conversion of lactate to pyruvate and NADH via lactate dehydrogenase is responsible for higher colour stability as a result of the action of NADH and metmyoglobin reduction producing more deoxymyoglobin. This metabolic reaction could result in darker muscle colour than what is typical of high energy feedlot diets (Priolo *et al.*, 2001).

With energy metabolites present in muscle *during rigor,* changes in actin/myosin interactions could still occurs leading to cold shortening. From above results it follows that the calculated glycolytic potential (GP) of the BP production system was the lowest at 1, 2, 4 and 20 h *post-mortem*, differing from the ABF and AP glycolytic potentials at 1, 2 and 4 hours *post-mortem* ($P<0.05$) (Figure 2 G). Age of the animal at slaughter seems to play a role in determining GP especially early *post-mortem* taking into account that electrical stimulation *post-mortem* could influence the unpredictability of these results. Electrical stimulation of carcasses to accelerate pH fall is considered to have a levelling effect towards muscle energy metabolism, but the acceleration may be variable (Eikelenboom, Smulders & Ruderus, 1985).

Some breed effects on glycogen and ATP depletion and lactic acid production and subsequent effects on glycolytic potential that occurred are presented in Figures 3, A - D. The Ng-X cross breed had a slower glycogen depletion and lactate production rate differing from Bh-X and Sm-X at 1 and 2 h *post-mortem* ($P<0.05$) (Figure 3 A and B). NF-X ATP levels at 1 and 2 h *post-mortem* also differed from that of Bh-X and Sm-X cross breeds ($P<0.05$; Figure 3 C). Breed effects on GP showed that the Ng-X had lower GP values at 1, 2, 4 and 20 h *post-mortem* than the Bh-X and Sm-X cross breeds ($P<0.05$; Figure 3 D). Although the average Ng-X GP values (~140 µmol/g), were on the lower side, they were still higher than that of the average BP production system GP values (~130 µmol/g) and similar to the systems, AF, ABF and AP. According to Wulf, Emnett, Leheska and Moeller (2002) higher GP is associated with increased tenderness, and low GP (less than ~100 µmol/g) at slaughter is associated with DFD meat ($pH_u>6$), which results in substantially higher shear force values and more shear force variation than those from normal carcasses. This is contradictory to studies of Purchas (1990) and others that provided that if cold-shortening was prevented, tenderness of beef tends to decrease with a rise in pH_u from 5.5 to 6.1, and then to improve with further increases up to 7.0. Studying our 17 carcasses that had pH values of 5.8 and higher, only 5 had GP values of < 120 µmol/g at 1 h *post-mortem*. The other 12 carcasses had GP

Figure 3. Effect of cross-breed on m. longissimus dorsi glycogen (A), lactic acid(B), ATP (C), and calculated glycolytic potential (D) at 1, 2, 4 and 20 h post-mortem. The differences (P<0.05) between production system groups were indicated by a's and b's.




160
150
140
130
0
4
8
12
16
20
[Glycolytic potencial] (µmol/g)
Time (hours post-mortem)
b
b
b
b
a
a
a
a
D
Br-X
Ng-X
Sm-X

values of between 120 and 182 µmol/g at 1 h *post-mortem*. In addition the highest GP values were calculated for the AP system muscle and according to Wulf *et al.* (2002) the AP carcasses should be the most tender, which was not the case (Figure 2).

In summary younger steers from the feedlot had an higher average GP, higher glycogen and lower lactic acid, glucose-6-P and ATP in muscle compared to older animals from the pasture system, giving rise to a better meat colour parameters (higher *L*, a** and *b**). Younger animals from the pasture had the highest GP, muscle glucose and glycogen concentrations *post-mortem* compared to older animals from the feedlot. The oldest animals from the pasture had higher muscle creatine-P concentrations compared to younger animals from the feedlot and pasture, resulting in darker (lower *L) coloured meat of the older animals from the pasture, although not related to DFD. The resultant beef colour could be affected by the amount of physical activity, which could influence muscle fibre type and metabolism (Thompson, 2002).

Muscle energy status at slaughter and carcass size (therefore temperature decline) only had an effect on SL of AP muscle (e.g. SL correlated with lactate at 1 h *post-mortem* measured in the AP system*; r*=0.453). All efforts were made to prevent cold shortening and the 15 s electrical stimulation could have been enough to prevent cold shortening even in the smaller carcasses, produced from pasture. The fact that the 1 d *post-mortem* WBS values of the AP, ABP, BP and AF production systems did not differ, proof that muscle contraction pre-rigor, was not a factor at the time that sarcomere lengths were measured. The lower carcass weights of the AP group coincided with shorter SL while 1 h lactate levels were positively correlated with SL in this group only (r=0.453), meaning that lower production of lactate and a slower decline in glycogen (glycolysis rate) could result in shorter SL. Considering these relationships, we could show a tendency towards tougher meat for AP LD's. Apart from the AP group where tenderness might have been affected by chilling rate, it is noteworthy that the older pasture fed LD's were not much different in tenderness than those of the AF group.

5. Conclusions

Production system affected both energy status and chilling rate of the carcass that resulted in shorter sarcomere length/cold shortening and subsequent lower meat tenderness in the lighter pasture fed carcasses of the AP system. This toughening effect could not be overcome by ageing.

Although the BP production system had significant lower glycolytic potential compared to the other systems AF, ABF and ABP systems and although the glycolytic rate of the pasture systems tended to be slower than that of feedlot systems, energy status did not affect shear force results significantly. Energy status affects the more visible attributes such as colour, drip loss and water holding capacity.

The present results show that feeding nutritional status of the animal as influenced by production system and diet and slaughter conditions influence meat tenderness more than animal age – but the latter considered to be the most important aspect in the current SABCCS classification, which does not seem justifiable based on the results of this study.

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