

A consumer sensory study of the influence of rigor temperature on eating quality and ageing potential of beef striploin and rump

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Abstract. Few consumer data are available on the effects of high rigor temperatures on eating quality of different muscles in the beef carcass. The aim of the present study was to investigate the effect of high rigor temperature (heat-toughening) on the consumer and quality traits of two beef muscles. A dataset containing consumer eating-quality scores for 3865 striploins (*m. longissimus lumborum*) and 734 rumps (*gluteus medius*) was analysed. Temperature at pH 6 (temp@pH6) was calculated for the striploin and carcasses with a temp@pH6 of >35°C were classified as high rigor temperature (heat-toughened) carcasses. For short ageing periods (1–7 days), high rigor temperature striploins were assessed, by a consumer panel, as being more tender with higher overall liking and higher (more liked) flavour and juiciness, than were striploins entering rigor at a lower temperature. Beyond 14 days of ageing, the high rigor temperature striploins showed minimal improvement in tenderness and the other eating-quality attributes also showed minimal improvements. The consumer scores for tenderness, juiciness, flavour and overall liking for the rump decreased with increasing rigor temperature. High rigor temperature striploins were scored, by trained graders, to have a higher proportion of coarser and softer texture and paler colour. Carcasses defined as 'high rigor temperature' will show minimal ageing after extended storage and, at grading, have a higher proportion with pale colour and softer, coarser texture compared to lower rigor temperature carcasses. In conclusion, methods to reduce high rigor temperatures in beef carcasses would improve the acceptability of beef.

Additional keywords: consumer, heat-shortening, heat-toughening, rigor shortening.

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Introduction

Tenderness, juiciness and flavour of beef meat are important quality attributes for the consumer. Understanding the factors that contribute to variations in these quality traits assists in determining strategies to optimise them. The concept of a pH–temperature window was one of the initial specifications for the Meat Standards Australia (MSA) grading scheme in Australia and was designed to minimise the detrimental effects of extremes in processing, such as heat-toughening and cold-shortening (Ferguson *et al.* 1999). The MSA scheme is aimed at accurately predicting consumer satisfaction with individual beef meals, by accounting for interactive effects of all factors affecting the eating quality of individual muscles cooked by a range of methods. The pH–temperature window was developed from the published meat-science literature, which generally showed that minimal shortening in muscles occurs at ~15–20°C, resulting in optimum tenderness (Locker and Hagyard 1963; Tornberg 1996; Devine *et al.* 1999).

The negative effects of a fast pH fall at a high temperature on the water-holding capacity, colour and texture of pig muscle, resulting in the pale, soft exudative (PSE) phenomenon, have been well documented (Warner *et al.* 1997). Channon *et al.* (2000) showed that PSE pork was initially more tender, as indicated by lower shear-force values, than was normal pork. After 5 days ageing this was reversed, suggesting that PSE pork may not age as well as normal pork. This was supported in beef by Thomson *et al.* (2008) who also showed that the cross-over in shear force occurred at ~5 days postmortem.

Electrical stimulation of beef carcasses was introduced to accelerate the rate of postmortem pH fall to allow more rapid rigor onset and to prevent cold-shortening. Most of the standards set down for electrical stimulation in the 1970s were based on the assumption that electrical stimulation was the only electrical input on the slaughter-floor (Chrystall and Devine 1978; Petch 2001). While this assumption was generally true at the time, this no longer applies because due to changes in the handling and

processing of carcasses, electrical inputs can occur at the immobiliser, bleed rail and the hide puller (Warner *et al.* 2014a).

Prior to the commercial use of electrical stimulation, the pH at 8 h post-slaughter was reported to be on average 6.8, a drop of only 0.2 pH units from the pH immediately post-slaughter (Davey *et al.* 1976). Tornberg *et al.* (2000) described fast pH fall in beef carcasses as reaching pH of 5.6 in the *longissimus* at 4–5 h postmortem. Moreover, meat from carcasses that underwent a rapid pH decline was more tender than that from medium or slow pH decline carcasses (pH = 5.6 at 12 or 20 h, respectively), based on Warner–Bratzler shear force (WBSF) measurements at 24 h post-slaughter (Tornberg *et al.* 2000). Similarly, fast glycolysing beef muscle was defined by O'Halloran *et al.* (1997a) as a pH of ~6.6 in the *longissimus* at 1 h post-slaughter (estimated from graph in the paper). In a subsequent study, O'Halloran *et al.* (1997b) defined it as a *longissimus* pH of 5.9–6.2 at 3 h post-slaughter. In each case, loins that had fast rates of pH fall were rated more tender (sensory panel and WBSF). In beef-processing plants in Australia, pH values of *longissimus* at 1 h post-slaughter have been reported as low as 5.5, while the muscle temperature was as high as 40°C (Warner *et al.* 2014a). Thus, the Australian meat industry reports much faster rates of pH fall than those historically reported for beef in different countries (e.g. see Marsh *et al.* 1987; O'Halloran *et al.* 1997a). The effects of faster rates of pH fall on eating quality have not been well documented.

There have been no consumer studies examining the impact of temperature at pH 6 (rigor temperature) on eating quality with large numbers of samples, because of the difficulty and costs associated with conducting large-scale consumer taste panels and the difficulty of obtaining well controlled variation in rigor temperature. The present paper reports on an in-depth analysis of striploin data. A more limited analysis was conducted of the rump as it had far fewer numbers of carcasses with appropriate data. The aim of the present study was to investigate the effect of temperature at pH 6 on the eating quality and other quality traits of beef meat.

Materials and methods

A subset of data was obtained from the MSA database (see Watson *et al.* 2008b for a description of full dataset), based on the criteria that all carcasses that had three or more pH measurements on the day of slaughter were to be included. This resulted in a subset of data that contained eating-quality scores on 15 581 samples collected from 1997 to 2006, from 31 abattoirs across Australia and one abattoir in South Korea. The scores were generated using consumers in Sydney, Australia; Osaka and Tokyo, Japan; Suwon, South Korea; and Belfast, Northern Ireland. The data pertaining to the striploin (*m. longissimus lumborum*, $n = 3865$) and rump (*m. gluteus medius*, $n = 734$) for two cook methods (roast and grill) were extracted. For the striploin and rump, an in-depth analysis was conducted of the consumer scores for tenderness, juiciness, flavour, overall liking and the palatability score (MQ4) (see *Sensory design and cooking protocol* for definitions).

Data on the hot carcass weight, hanging method (achilles tendon or tenderstretch), sex (steer or female), days aged and cooking method (grill or roast) used were also recorded. The dataset included grain- and grass-fed cattle, cattle treated with and

without growth promotants (HGP), vealers (0 permanent incisors) and older animals (2–6 permanent incisors) and cattle that were consigned directly to the abattoir or via saleyards.

Description of pH measurement and carcass grading

After placement in the chiller, a series of pH–temperature and time measurements (between three and six) were recorded in the *m. longissimus lumborum* in the region of the 2nd to 5th lumbar vertebrae on individual carcasses. The pH, temperature and time were also recorded at grading (~20–28 h post-slaughter, called the ultimate pH). For each measurement, care was taken to place the pH meter into a fresh incision rather than using the site where the previous measurement had been recorded. A Jenco pH meter (Jenco 6009, Jenco, San Diego, California, USA), with a polypropylene spear-type gel electrode (Ionode IJ44, Brisbane, Queensland, Australia) and temperature probe allowing temperature compensation, was used to measure pH and temperature. The pH meter and electrode were calibrated at ambient temperature using buffers of 4.00 and 7.00.

At ~20 h postmortem, after quartering of the carcass between the 12th and 13th ribs, MSA graders made the following measurements: rib fat depth (mm), United States Department of Agriculture (USDA) ossification score (USDA 1997); USDA marbling score (USDA 1997), ultimate pH of the exposed *m. longissimus thoracis* (at about the 12th–13th rib), AUS-MEAT meat-colour score (AUS-MEAT 1996) (using AUS-MEAT standard meat colour chips in a range of 1A (very pale) to 7 (very dark purple)), AUS-MEAT texture/firmness score (1 = firm/fine to 7 = coarse/soft) and estimated %*Bos indicus* (estimated from hump height and confirmed with vendor declarations).

Sample preparation

At boning at ~24 h post-slaughter, the striploin and rump primals were removed from both sides of each carcass, vacuum packed and transported at 1°C for preparation of sensory samples.

The preparation of samples of *m. longissimus lumborum* (from the striploin primal, hereafter called striploin) and *m. gluteus medius* (from the rump primal, hereafter called rump) for consumer sensory analysis was performed as described by Watson *et al.* (2008a). Briefly, muscles were denuded of all fat and epimysium. Samples for different ageing periods within a carcass were either alternated between carcass sides, or positions within a muscle, to remove any effect of position within a muscle or carcass on the results. Five 25-mm-thick steaks were prepared for each grill sample and the roasting blocks were prepared with the dimensions ~60 × 60 × 150 mm long. Samples were aged at 0 to –1°C and at the completion of the ageing period the samples were frozen and stored at –20°C until required for sensory evaluation.

Sensory design and cooking protocol

The taste-panel design was as described by Watson *et al.* (2008a). Briefly, grill samples were tested using a Latin square design that comprised 108 samples, allocated to nine sessions and tasted by 180 consumers. The five steaks from each sample were tested in five separate sessions and each individual steak was cut in half and

eaten by two consumers. Grill and roast samples were served separately.

Steaks were thawed (2–5°C) for 24 h, before grilling on a Silex clamshell grill (Silex Grills Australia Pty Ltd, Marrickville, NSW, Australia) set to 225°C, for 5 min, with the grill closed, to achieve a 'medium' degree of doneness. Ten sample steaks were prepared on the grill for each cooking round. Steaks were allowed to stand for 3 min before serving. After standing, each steak was cut in half into 2 equally sized rectangular pieces and served to 2 separate preselected consumers. Untrained panellists who preferred meat cooked to a medium degree of doneness and who consumed beef at least once each week were used in the study. In total, each muscle sample was tasted by 10 different consumers.

A large commercial gas oven was used to cook all roasts for any taste panel at the one time (Watson *et al.* 2008a). The roast taste panels were a modification of the above design, where each taste panel evaluated 36 samples that were tasted by 60 consumers.

For both grill and roast panels, each consumer tested a starter sample, followed by six experimental samples. Consumers were asked to score either grill steaks or roast-slice samples for tenderness, juiciness, like flavour and overall liking by placing marks on 100-mm lines (thus, the score range was 0–100) anchored with the following definitions: tenderness: very tough to very tender; juiciness: very dry to very juicy; like flavour: dislike extremely to like extremely; overall liking: dislike extremely to like extremely. Individual sensory scores for tenderness, juiciness, like flavour and overall liking were weighted by 0.4, 0.1, 0.2 and 0.3, respectively, and summed to calculate a palatability score (MQ4, Polkinghorne *et al.* 1999; Watson *et al.* 2008a). Before calculating the mean sensory scores for each sample, the 10 individual scores for each sample were ranked and the two highest and two lowest scores were clipped to reduce the variance of the mean sensory scores (Polkinghorne *et al.* 1999; Watson *et al.* 2008a).

Statistical analysis

Temperature at pH6 (Temp@pH6) in the striploin was calculated using interpolation for temperature and pH values recorded either side of pH = 6, using the following equation:

$$\text{Temp@pH6} = \text{Temp}_A - \left[\frac{(\text{pH}_A - 6) * (\text{Temp}_A - \text{Temp}_B)}{(\text{pH}_A - \text{pH}_B)} \right]$$

where Temp_A and pH_A represent the pH and temperature measurement taken above pH 6 and Temp_B and pH_B represent the measurement taken below pH 6. High rigor temperature carcasses were defined as having a temp@pH6 of > 35°C.

For the analysis of the MQ4 for the striploin, the method of restricted maximum likelihood (REML) was used.

Terms in the REML model

The following were fitted as fixed effects:

- temperature at pH 6 (temp@pH6),
- hanging method (AT, carcass hung by the achilles tendon, *n* = 2990; TS, carcass hung by sacral ligament, *n* = 509; TX, carcass hung by obdurator foramen, *n* = 240) (as TS and TX achieved a similar effect and there was only a small number of

carcasses for each, they were combined into one trait called, hence, TS)

- sex (steer or female),
- estimated %*Bos indicus*,
- carcass weight,
- USDA ossification score (100–590),
- USDA marbling score (100–1100),
- days aged (1–35), rib fat (1–31 mm),
- cooking method (grill, roast),
- ultimate pH (pHu),
- combinations of these, up to three-way interactions,
- quadratic terms for days aged.

The following were fitted as random effects:

- abattoir,
- day of kill,
- carcass, and
- carcass side.

The terms above were all fitted in the initial model and all of the fixed terms, except temp@pH6, are included in the MSA model (Thompson *et al.* 1999; Watson *et al.* 2008a, 2008b). Forward and backward selection, along with different submodelling of all parameters, was performed. All statistical analyses were performed using GENSTAT (GENSTAT Committee 2006). This analysis was then repeated for the individual components of MQ4, including clipped tenderness score, clipped juiciness score, clipped flavour score and clipped overall liking, which are, hereafter, called tenderness, juiciness, flavour and overall liking, respectively. A subset of data was also used for analysis of MQ4 score for the rump. This dataset was subjected to the same analysis approach as used above for the striploin.

Muscle colour (Grades 4 and 5 were combined due to low numbers of Grade 5 scores) and texture/firmness scores were analysed for the effect of temperature at pH 6 by using generalised linear model with a multinomial distribution and logit link function and adjustment for kill day nested within abattoir.

Results

Description of population

The mean and range for the data for carcass, meat-quality and consumer scores is given for each primal in Table 1. The carcasses that had data available for the rump were on average heavier (carcass weight), fatter (rib fat), physiologically older (higher ossification), had lower marbling scores and had less range in days aged, relative to the data for striploins. The carcasses ranged from being suitable for the domestic trade (180–220 kg carcass weight) to heavy carcasses (>320 kg carcass weight) suitable for the export market to Japan and Korea. Of the 3865 carcasses, 2990 carcasses were hung by AT and 875 by TS. In all, 36% of the carcasses were outside the acceptable pH–temperature window (Watson *et al.* 2008b), with 33.3% having a high rigor temperature (temp@pH6 of >35°C) and 3.1% of the carcasses having a low rigor temperature (temp@pH6 of <15°C). In total, 14.8% of carcasses had a pHu > 5.7 and thus would be excluded from being eligible for MSA grading. Only 1.4% of carcasses had a pHu > 6.0.

The distribution of samples among ageing periods was as follows: 12.3% and 15.7% of samples were aged for 1–6 days for

Table 1. Mean, minimum (Min.) and maximum (Max.) for the carcass and sample data for the striploin and rump
MQ4 = palatability score

Parameter	Striploin (<i>n</i> = 3865)			Rump (<i>n</i> = 734)		
	Mean	Min.	Max.	Mean	Min.	Max.
Hot carcass weight (kg)	251	122	495	267	161	495
Rib fat (mm)	7.2	1.0	31.0	8.3	1.0	31.0
Temp@pH6 ^A (°C)	31.0	1.6	41.7	31.7	2.0	41.5
Ultimate pH	5.59	5.00	6.89	5.56	5.35	6.05
Ossification	158	100	590	169	100	590
Marbling Score	368	100	1100	276	110	1100
% <i>Bos indicus</i>	17.3	0	100	12.6	0	100
Days aged	13.6	1	35	13.8	5	28
Tenderness	59.1	4.7	96.5	59.2	17.3	92.2
Flavour	59.1	7.2	91.0	58.8	27.3	84.8
Juiciness	57.2	7.3	94.0	55.0	14.0	89.0
Overall like	58.3	8.0	95.2	57.9	18.5	85.8
MQ4	58.4	7.7	93.4	58.1	21.1	86.7

^ATemp@pH6 = temperature at pH 6 in the *longissimus* and is an indication of rigor temperature.

striploin and rump, respectively (minimum was 5 days for rump), 17.4% and 16.3% for 7–13 days, 43.3% and 36.0% for 14 days, 12.9% and 7.8% for 15–20 days and 14.2% and 24.2% for 21–35 days (maximum was 28 days for rump).

Effect of temperature at pH 6 and other factors on MQ4 score for the striploin

The final model included terms for temp@pH6, days aged, marbling score, %*Bos indicus*, ossification, rib fat, hang method, cooking method × ossification, hang × days aged, temp@pH6 × hang method, temp@pH6 × days aged and a quadratic term for days aged ($P < 0.05$ for all; Table 2). The estimates and standard errors (s.e.) and the significance of each term are presented in Table 2. This model was similar to the one previously described by Watson *et al.* (2008b) on the full dataset, except that the model of Watson *et al.* (2008b) included sex, ultimate pH (pHu), HGP and the interaction of ossification × carcass weight, but obviously did not include temp@pH6. Thus, higher days aged, marbling score and rib fat have a positive effect on the MQ4 score, whereas higher ossification and %*Bos indicus* have a negative effect on the MQ4 score. There was no effect detected of sex or ultimate pH on MQ4 score ($P > 0.05$ for both). Except for temp@pH6, these effects on the consumer MQ4 score are similar to those previously found for the MSA model (Ferguson *et al.* 1999; Polkinghorne *et al.* 1999; Thompson *et al.* 1999; Watson *et al.* 2008b) and are not discussed further except where they interact with the temp@pH6.

Significant interactions between hanging method and days aged, temp@pH6 and days aged, and temp@pH6 and hanging method were found for MQ4 ($P < 0.05$ for all; Table 2). For hanging method × temp@pH6, there was a significant linear relationship for the AT carcasses but not for the TS carcasses (Fig. 1a, b). Fig. 1a shows the interaction between temp@pH6 and days aged on the predicted MQ4 score for grilled striploin from an AT carcass, with mean values in the model for marbling score, ossification, %*Bos indicus* and rib fat. In high rigor temperature striploins (temp@pH6 = 40°C), the MQ4 score was initially higher (MQ4 = 54) than in the striploins having an 'ideal' temp@pH6 of 15°C (MQ4 = 47). After 14 days of

ageing, the high rigor temperature striploin failed to become more tender with age, whereas the lower rigor temperature striploins continued to age. After 35 days of ageing, the MQ4 score of the high rigor temperature striploin was lower (MQ4 = 63) than those of the striploins with a temp@pH6 = 15°C (estimated MQ4 = 71).

Figure 1b shows there was no effect of temp@pH6 on MQ4 scores for the TS hanging method ($P > 0.05$). However, there was a reduced range of values for days aged and also for temp@pH6 for the TS carcasses, as shown in Fig. 1b.

For tenderness, juiciness, flavour and overall liking, the significant ($P < 0.05$) predictors along with the coefficients and standard errors are listed in Table 2. The results for tenderness, flavour and overall liking were very similar to the results for MQ4. For juiciness, there was no quadratic term for days aged but the crossover point for the lines was still at ~14 days aged.

Effect of temperature at pH 6 on the MQ4 score for the rump

The final models for the rump included terms for temp@pH6, days aged, marbling score, ossification, rib fat, hang method and cooking method ($P < 0.05$ for all; Table 3). The estimates and standard errors and the significance of each term are presented in Table 3. After modelling, the predictors of the individual sensory scores as well as of the MQ4 score for the rump were determined (Table 3). In general, associations similar to those in the striploin were observed; for example, ossification had a negative effect on MQ4 score ($P < 0.001$), whereas marbling score (scored in the striploin), rib fat, ageing, cooking and hanging method had positive effects ($P < 0.05$ for all). The main differences were that there was no quadratic effect for temp@pH6 on the sensory scores; there was a negative linear relationship between temp@pH6 and each sensory score. The other differences to the striploin results were that there were no significant interactions and %*Bos indicus* content did not influence the sensory scores for the rump ($P < 0.05$ for all).

For the rump, the temp@pH6 had an effect on all sensory scores ($P < 0.001$; Table 3) but this did not interact with days

Table 2. Effect of factors in the model on the prediction of the striploin tenderness, juiciness, flavour and overall liking and palatability (MQ4) score
Values are mean $\pm$ s.e. Coeff. = coefficient, Prob = probability, s.e. = standard error

Parameter	Tenderness			Juiciness			Flavour			Overall like			Striploin MQ4 ^A		
	Coeff.	Prob		Coeff.	Prob		Coeff.	Prob		Coeff.	Prob		Coeff.	Prob	
Constant ^B	36.6 $\pm$ 4.15	<0.001		40.3 $\pm$ 3.75	0.010		41.5 $\pm$ 3.13	0.007		38.3 $\pm$ 3.52	0.003		38.7 $\pm$ 3.47	<0.001	
Temp@pH6 ^C	0.361 $\pm$ 0.1076	<0.001		0.247 $\pm$ 0.0949	<0.001		0.222 $\pm$ 0.0820	<0.001		0.273 $\pm$ 0.0918	<0.001		0.293 $\pm$ 0.0897	<0.001	
Days aged	1.45 $\pm$ 0.248	<0.001		1.08 $\pm$ 0.230	0.001		0.989 $\pm$ 0.1969	0.001		1.20 $\pm$ 0.217	<0.001		1.22 $\pm$ 0.210	<0.001	
Temp@pH6 – days aged	-0.016 $\pm$ 0.0064	0.014		-0.019 $\pm$ 0.0059	0.001		-0.012 $\pm$ 0.0050	0.017		-0.015 $\pm$ 0.0056	0.007		-0.015 $\pm$ 0.0054	0.005	
(Days aged) ²	-0.012 $\pm$ 0.0045	0.006		-0.006 $\pm$ 0.0042	0.136		-0.009 $\pm$ 0.0035	0.009		-0.010 $\pm$ 0.0039	0.012		-0.010 $\pm$ 0.0038	0.011	
Ossification	-0.033 $\pm$ 0.0101	<0.001		-0.009 $\pm$ 0.0085	0.428		-0.011 $\pm$ 0.0068	0.070		-0.017 $\pm$ 0.0080	0.045		-0.021 $\pm$ 0.0082	0.035	
Marbling score	0.028 $\pm$ 0.0039	<0.001		0.029 $\pm$ 0.0032	<0.001		0.025 $\pm$ 0.0027	<0.001		0.029 $\pm$ 0.0031	<0.001		0.027 $\pm$ 0.0031	<0.001	
Rib fat	0.167 $\pm$ 0.0926	0.072		0.051 $\pm$ 0.0752	0.500		0.169 $\pm$ 0.0653	0.010		0.164 $\pm$ 0.0752	0.029		0.164 $\pm$ 0.0750	0.029	
%Bos indicus	-0.154 $\pm$ 0.0196	<0.001		-0.111 $\pm$ 0.0175	<0.001		-0.098 $\pm$ 0.0142	<0.001		-0.116 $\pm$ 0.0162	<0.001		-0.127 $\pm$ 0.0162	<0.001	
Cook (roast) ^D	3.89 $\pm$ 4.871	0.424		7.14 $\pm$ 4.382	0.103		6.17 $\pm$ 3.717	0.097		7.53 $\pm$ 4.181	0.072		6.33 $\pm$ 4.086	0.122	
Cook (roast) – ossification ^D	-0.029 $\pm$ 0.0285	0.317		-0.117 $\pm$ 0.0258	<0.001		-0.060 $\pm$ 0.0219	0.006		-0.073 $\pm$ 0.0246	0.003		-0.060 $\pm$ 0.0240	0.012	
Hang (TS) ^E	19.4 $\pm$ 3.26	<0.001		14.5 $\pm$ 2.84	<0.001		12.6 $\pm$ 2.46	<0.001		15.8 $\pm$ 2.75	<0.001		16.5 $\pm$ 2.69	<0.001	
Hang (TS) ^E – temp@pH6	-0.202 $\pm$ 0.0945	0.032		-0.193 $\pm$ 0.0816	0.018		-0.163 $\pm$ 0.0708	0.022		-0.165 $\pm$ 0.0795	0.038		-0.183 $\pm$ 0.0779	0.019	
Hang (TS) ^E – days aged	-0.335 $\pm$ 0.0808	<0.001		-0.236 $\pm$ 0.0767	0.002		-0.166 $\pm$ 0.0652	0.011		-0.273 $\pm$ 0.0714	<0.001		-0.281 $\pm$ 0.0686	<0.001	

^AMQ4 = $0.4 \times \text{tenderness} + 0.1 \times \text{juiciness} + 0.2 \times \text{like flavour} + 0.3 \times \text{overall liking}$.

^BFor grill cooking method and AT hanging.

^CTemp@pH6 = temperature at pH 6 in the *longissimus* and is an indication of rigor temperature.

^DIn relation to the Roast Cook method, these estimates are the difference from the relevant coefficients for the Grill Cook method.

^EIn relation to Hang method TS (Tenderstretch), these estimates are the difference from the relevant coefficients for the AT hang method.

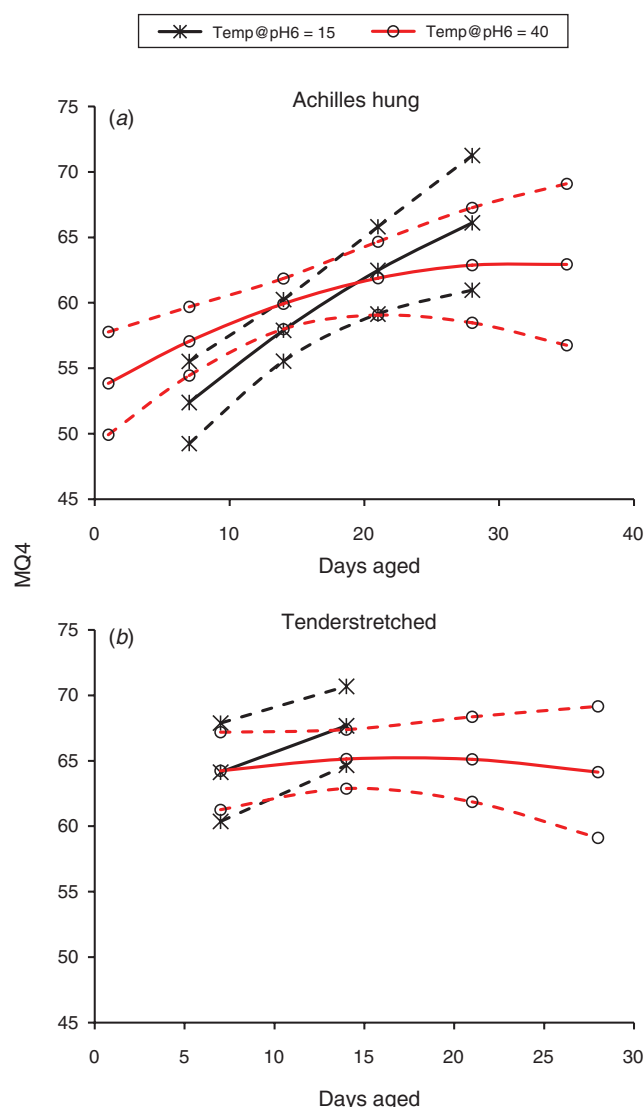


Fig. 1. Effect of temperature at pH 6 (Temp@pH6, °C) and days aged on the predicted consumer palatability (MQ4) score (combined score for juiciness, tenderness, flavour and overall liking) for grilled striploin from a carcass that had been (a) achilles hung or (b) tenderstretched and having mean values in the model for marbling score, ossification, %*Bos indicus* and rib fat. The lines show the actual range in the data because extrapolation beyond the data available is not valid. The dashed lines show the upper and lower 95% confidence intervals for each line. An MQ4 score of 48–63 is considered ‘good everyday eating quality’ (three-star), a score from 64 to 79 is considered ‘better than everyday’ (four-star) and a score of 80 and above is considered ‘premium’ (five-star).

aged. The relationship between the MQ4 score and temp@pH6 is shown in Fig. 2. Over the range of the data, as the temp@pH6 increased from 15°C to 40°C, the predicted MQ4 score dropped from 57 to 52.

Effect of temperature at pH 6 on the texture/firmness and colour scores for the striploin

Temperature at pH 6 influenced the AUS-MEAT texture/firmness and colour scores at grading for the striploin ($P < 0.05$ for both;

Figs 3 and 4, respectively). As the temp@pH6 in the striploin increased from 10°C to 40°C, there was an increase in the occurrence of coarse/soft texture scores (4 and 5) and a commensurate decrease in the occurrence of firm/fine texture scores (2 and 3). For the AUS-MEAT colour score, as the temp@pH6 in the striploin increased from 10°C to 40°C, the occurrence of colour scores 1C and 1B (pale red) increased and the occurrence of red colour scores (2 and 3) and dark red colour scores (4 and 5) decreased. Thus, for a temp@pH6 of 15°C, the striploins were predominantly graded as acceptable in colour (33% Score 1C and 32% Score 2) and texture/firmness (4%, 60% and 33% for texture/firmness Scores 5, 4 and 3, respectively). In contrast, high rigor temperature striploins (temp@pH6 = 40°C) were graded as either acceptable or pale in colour (43% for Score 1B and 50% for Score 1C) and were softer and generally less acceptable in texture/firmness (8%, 69% and 22% for texture/firmness Scores 5, 4 and 3, respectively).

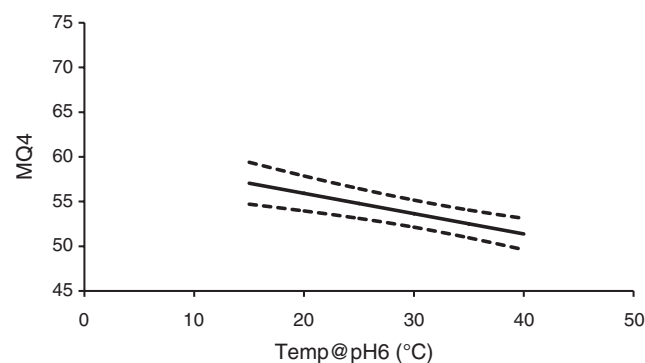
Discussion

Effect of temperature at pH 6 in the striploin

Analysis of consumer data on 3865 striploins showed a clear effect of temperature at pH 6 (rigor temperature) on eating quality (MQ4 score). The high rigor temperature striploins had higher initial tenderness at 1 day post-slaughter relative to low rigor temperature striploins, and after 14 days of ageing, low rigor temperature striploins continued to age whereas the high rigor temperature striploins showed minimal further ageing. Thus, after 35 days of ageing, the striploins entering rigor at an ‘ideal’ temperature of 15°C (estimated by temperature at pH 6) were predicted to be scored 9 MQ4 points higher than the high rigor temperature striploins entering rigor at 40°C. The analysis of consumer data on 734 rumps showed a linear negative effect of temp@pH6 on the sensory traits. Kim *et al.* (2012) also showed that high pre-rigor temperature of 38°C in excised beef striploin induced temperature-related toughness, as measured by shear force, and this was attributed to protein denaturation and subsequent attenuation of proteolysis by μ -calpain, irrespective of electrical stimulation. Other studies have used objective measures of meat tenderness (WBSF) to show a similar toughening effect for electrically stimulated beef loin held at 35°C (Marsh *et al.* 1987) and post-rigor beef loin held at 37°C (Thomson *et al.* 2008). Hopkins *et al.* (2014) compared beef carcasses going through rigor at 41°C or 33°C and found no effect of temperature on eating quality or shear force, although the range in their temp@pH6 data was much smaller than in this dataset. In lamb muscle, both *m. gluteus medius* and *m. semimembranosus* muscles in intact lamb carcasses subjected to 37°C had higher shear-force values irrespective of ageing period, than did carcasses chilled at 2°C (Warner *et al.* 2014b), which is similar to our consumer eating-quality results for the rump (*m. gluteus medius*). Although there are some studies showing no effect of high rigor temperature, there are many more studies in beef, lamb, pork and poultry showing adverse impacts of accelerated pH decline combined with high temperature on postmortem meat-tenderness development, as assessed by WBSF (see Kim *et al.* 2014a for a review). Most of the studies agree that exposing *pre-rigor* muscle to high temperature, which accompanies a rapid pH decline, results

Table 3. Effect of factors in the model on the prediction of the rump tenderness, juiciness, flavour and overall liking and palatability (MQ4) scoreValues are mean $\pm$ s.e. Coeff. = coefficient, Prob = probability, s.e. = standard error

Parameter	Tenderness		Juiciness		Flavour		Overall like		MQ4 ^A	
	Coeff.	Prob	Coeff.	Prob	Coeff.	Prob	Coeff.	Prob	Coeff.	Prob
Constant ^B	58.7 $\pm$ 2.94	<0.001	56.2 $\pm$ 2.86	<0.002	60.7 $\pm$ 2.29	<0.001	59.6 $\pm$ 2.56	<0.001	58.3 $\pm$ 2.57	<0.001
Temp@pH6 ^C	-0.256 $\pm$ 0.0697	<0.004	-0.209 $\pm$ 0.0686	<0.002	-0.215 $\pm$ 0.0567	<0.001	-0.223 $\pm$ 0.0632	<0.001	-0.227 $\pm$ 0.0601	0.067
Days aged	0.171 $\pm$ 0.060	<0.001	-0.041 $\pm$ 0.0076	<0.001	-0.016 $\pm$ 0.0061	0.010	-0.025 $\pm$ 0.0077	<0.001	0.100 $\pm$ 0.0544	<0.001
Ossification	0.010 $\pm$ 0.0048	0.038	0.010 $\pm$ 0.0048	0.046	0.010 $\pm$ 0.0038	<0.008	0.011 $\pm$ 0.0043	0.008	-0.029 $\pm$ 0.0066	0.010
Marbling score	0.462 $\pm$ 0.1243	<0.001	0.275 $\pm$ 0.1153	0.017	0.216 $\pm$ 0.0962	0.025	0.293 $\pm$ 0.1095	0.007	0.011 $\pm$ 0.0041	0.002
Rib fat	10.5 $\pm$ 0.95	<0.001	3.91 $\pm$ 0.939	<0.001	3.51 $\pm$ 0.777	<0.001	5.57 $\pm$ 0.864	<0.001	0.334 $\pm$ 0.1070	<0.001
Cook (roast) ^D	10.5 $\pm$ 1.03	<0.001	5.83 $\pm$ 1.089	<0.001	5.86 $\pm$ 0.872	<0.001	7.97 $\pm$ 0.952	<0.001	6.79 $\pm$ 4.082	<0.001
Hang (TS) ^E									8.11 $\pm$ 0.899	<0.001

^AMQ4 = $0.4 \times \text{tenderness} + 0.1 \times \text{juiciness} + 0.2 \times \text{like flavour} + 0.3 \times \text{overall liking}$.^BFor grill cooking method and AT hanging.^CTemp@pH6 = temperature at pH 6 in the *longissimus* and is an indication of rigor temperature.^DIn relation to the Roast Cook method, these estimates are the difference from the relevant coefficients for the Grill Cook method.^EIn relation to Hang method TS (Tenderstretch), these estimates are the difference from the relevant coefficients for the AT hang method.**Fig. 2.** Effect of temperature at pH 6 (Temp@pH6) on the predicted palatability (MQ4) score (combined score for juiciness, tenderness, flavour and overall liking) for grilled rump from a carcass that had been achilles hung and having mean values in the model for days aged, ossification, marbling score and rib fat. The dotted line shows the upper and lower 95% confidence intervals.

in a decrease in tenderness values, as measured by shear force (see Kim *et al.* 2014a). The novelty of our work is the reporting of the effects on consumer eating quality, using data from a large number of consumers.

When tenderness measurements were obtained between 7 and 14 days of postmortem ageing, little difference in the predicted toughness existed among carcasses. This was demonstrated by Hopkins *et al.* (2014) who reported no difference in eating quality or shear force after 14 days of ageing between carcasses entering rigor at 41°C and 33°C. This emphasises the importance of conducting studies and collecting data over a range of times postmortem, and particularly that there is a need for more data on striploins that have been aged for 35 days or longer.

The results were similar for the individual sensory traits (tenderness, flavour, overall liking) that are used to derive the MQ4 score. This was not surprising as the individual components are highly correlated (Watson *et al.* 2008a). The only minor exception was for the juiciness of the striploin, where the quadratic effect of days aged was not evident. Juiciness is a consumer trait that is predominantly determined by the intramuscular fat content and water-holding capacity of the muscle (Winger and Hagyard 1994). Thus, a consumer score for juiciness arises from the interaction between water and fat, with structural integrity of the muscle also playing a role (Winger and Hagyard 1994). In our data, the high rigor temperature striploins showed a very small (but significant) increase in the predicted juiciness score from 56 to 60 over 1–35 days of ageing. In contrast, the striploins entering rigor at an 'ideal' temperature demonstrated an increase in predicted juiciness score from 54 to 63, over 7–21 days of ageing. Muscles going through rigor at a high temperature are known to have a reduced water-holding capacity (Tarrant and Mothersill 1977) and this will influence the perceived juiciness in the product, similar to the reduced juiciness found in PSE pork (Kauffman *et al.* 1964) and also with our data.

The MSA model does not presently include or account for high rigor temperature, or temp@pH6, in the model for predicting eating quality (Watson *et al.* 2008b). The limitation to implementation of high rigor temperature into the MSA model has been the lack of a measurement that could be used at line-

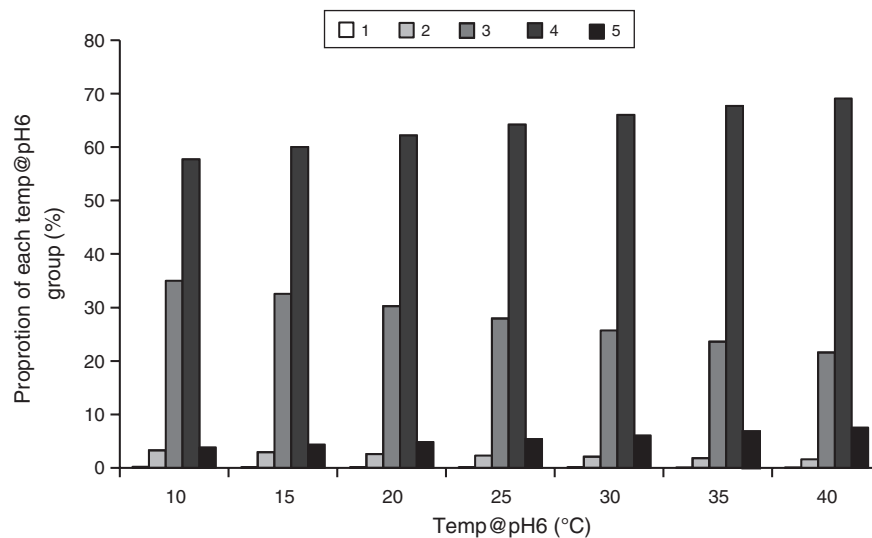


Fig. 3. Effect of temperature at pH 6 (temp@pH6) on the AUS-MEAT texture score (from 1 = firm/fine, to 5 = coarse/soft).

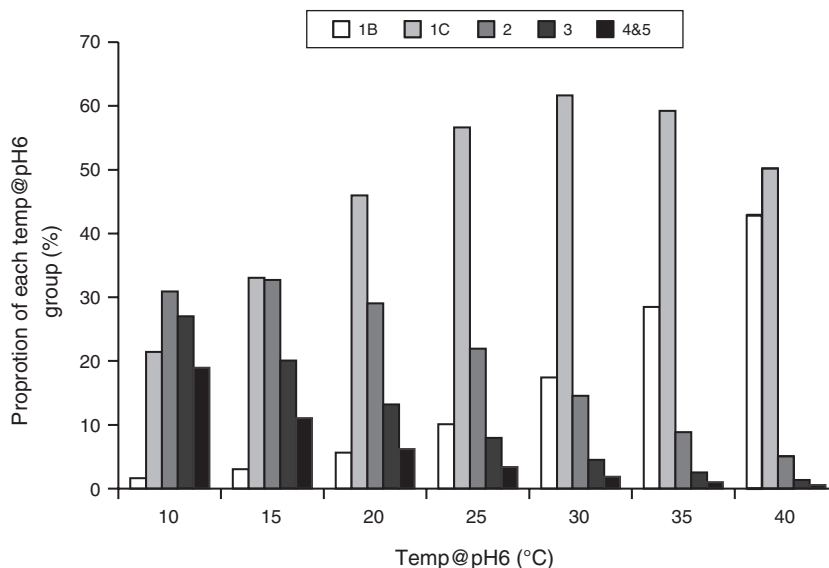


Fig. 4. Effect of temperature at pH 6 (temp@pH6) on the AUS-MEAT colour score (1B = pale, 2 = pale red, 3 = red, 4 = slightly dark red, 5 = dark red to 7 = very dark purple). A colour score >3 is considered unacceptable.

speed on individual carcasses. If such a measurement were available, the accuracy of predicting the eating quality of carcasses would be improved by incorporating a temp@pH6 term in the MSA model.

Tenderstretch

The eating quality of striploins from TS carcasses was not affected by rigor temperature, suggesting that tenderstretch may protect specific muscles in the carcass from the negative effects of high rigor temperature. The protection may be due to prevention of sarcomere shortening, although both Tornberg (1996) and Smulders *et al.* (1990) considered tenderness to be

independent of sarcomere length under conditions of rapid pH decline. Tornberg (1996) postulated that in the enzymatically active striploin, it is possible that the stretched sarcomeres are more liable to proteolysis. In PSE pork, sarcomeres are shortened due to denaturation of the myosin head causing longitudinal and transverse shrinkage, as discussed by Offer (1991). Thus, it is possible that TS prevents the shortening that occurs during myosin denaturation and shrinkage. The interaction between hang method (TS) and rigor temperature (temp@pH6) has previously been reported for sheep where stretching of muscles (e.g. tenderstretch) was found to not only prevent high rigor temperature toughening (Thompson *et al.* 2005) but also the loss in water-holding capacity (Bouton *et al.*

1975; Warner *et al.* 2014b; Kim *et al.* 2014b). As the data in our study for tenderstretched carcasses was more limited than that available for Achilles hung carcasses, the lack of effect of temp@pH6 on striploins from tenderstretched carcasses does need to be treated with some caution. Hence, further examination with sufficient data covering days aged and temp@pH6 range, similar to the AT hanging method, may be required to conclusively evaluate these associations.

Muscle differences

Clear differences between the muscles were observed. The *m. longissimus lumborum* and *m. gluteus medius* vary in sarcomere length, proteolytic activity (measured by desmin degradation), collagen content and shear force and trained-panel scores for tenderness (Rhee *et al.* 2004). Our scores for the rump were similar to those for the striploin, whereas Rhee *et al.* (2004) found that the rump was significantly lower in tenderness than was the striploin. Paradoxically, Rhee *et al.* (2004) also observed that the differences between the muscles in tenderness did not appear to be correlated with differences in sarcomere length, collagen content or proteolysis.

In our data, the interaction between days aged and temp@pH6 in the striploin consumer scores was not evident in the rump. The reduced tenderisation observed during ageing in high rigor temperature striploins was most likely a consequence of early autolysis of μ -calpain Dransfield (1993). When glycolysis is rapid, calpains are both activated and inactivated earlier; however, these processes may occur in meat before the temperature has been reduced significantly. Dransfield (1994) used models to show that inactivation of calpain occurs at high temperatures (40°C). Interestingly, he reported that the inactivation was independent of pH. Since the striploin has higher proteolytic activity than has the rump (Rhee *et al.* 2004), the rigor temperature effect on proteolysis would be more evident. Hwang and Thompson (2001a) also observed a negative effect of rapid glycolysis on beef tenderness, which appeared to be associated with an early reduction of μ -calpain concentrations. Hwang and Thompson (2001b) showed that higher rigor temperatures resulted in an earlier activation of μ -calpain, with a trend for lower WBSF values; however, as ageing time increased, this advantage was diminished by early exhaustion of μ -calpain, as suggested by Dransfield (1993). Simmons *et al.* (1996) showed that calpain activity falls commensurate with the postmortem decline in pH, but the greatest reduction was observed at a rigor temperature of 35°C, relative to rigor temperatures of 25°C or 15°C.

Effect of temperature at pH 6 on the texture/firmness and colour scores

High rigor temperature striploins had a higher proportion of pale colour and softer, coarser texture compared to lower rigor temperature striploins. This was similar to the finding that various muscles, including *m. sternomandibularis*, *m. semimembranosus*, *m. semitendinosus*, *m. adductor* and *m. biceps femoris*, when entering rigor at high temperatures have reduced water-holding capacities, paler colours and softer textures (Locker and Daines 1975; Tarrant and Mothersill 1977)

and the appearance of the muscles was described as a mild form of 'pale, soft and exudative' meat as seen in some pork.

High rigor temperature, heat-toughening or heat-shortening

Both muscle shortening and proteolytic activity affect tenderness and both are also highly affected by rigor temperatures (Devine *et al.* 1999). In the work of Devine *et al.* (1999), shortening and reduced proteolysis occurred if the rigor temperature was >15°C, but their temperatures did not exceed 35°C. PSE pork, which is essentially caused by high rigor temperature at low pH, does not have shorter sarcomeres (Van der Wal *et al.* 1988) and, in fact, the opposite has been observed (Eikelenboom and Nanni Costa 1988). Similarly, lamb muscle entering rigor at 37°C did not show evidence of sarcomere shortening, although evidence of heat-induced toughening was evident (Warner *et al.* 2014b); thus, it is probably not accurate to use the term 'heat-shortening'.

Unrestrained *pre-rigor* beef muscle can be stimulated to contract by temperature through cold-shortening at 0–8°C (Locker and Hagyard 1963), through heat-shortening at 50–100°C (Leet and Locker 1973) and through 'rigor shortening' at temperatures between ambient and 40°C (Locker and Hagyard 1963). The degree of myofibrillar contraction during rigor is clearly temperature dependent and when this occurs at temperatures of 30–40°C, rigor shortening is most prominent (Locker and Daines 1975). The weight of evidence suggests that this is rigor shortening (Locker and Daines 1975) and not heat-shortening and the two terms should perhaps not be used synonymously. Unlike cold-shortening, rigor shortening occurs at the onset of rigor mortis and the start of shortening and the loss of extensibility are very close together (Honikel Roncales and Hamm 1983); thus, the formation of irreversible actomyosin bonds at rigor onset most likely often prevent sarcomere shortening. The effect of rigor shortening at 30–40°C on the tenderness of the meat has produced quite variable results, from tenderisation (Locker and Daines 1975) to toughening (Marsh *et al.* 1987; Thomson *et al.* 2008; Kim *et al.* 2012; Warner *et al.* 2014b), and the differences can most likely be attributed to the duration of ageing and the muscle studied, as discussed above. For these reasons, the term we have used throughout this paper is high rigor temperature, rather than 'heat-toughening' or 'heat-shortening'.

Conclusions

Carcasses that are considered to be high rigor temperature, as indicated by having a temp@pH6 of >35°C, will have acceptably tender striploins at 1–7 days post-slaughter. However, after 14 days of ageing, high rigor temperature striploins minimally age, so that after 35 days of ageing they will have a MQ4 score 9 points lower than for the striploin entering rigor at an 'ideal' temperature (temp@pH6 = 15°C). Notwithstanding the limitations in the dataset, the rump does not appear to be as severely affected as the striploin. Carcasses defined as 'high rigor temperature' will show minimal ageing after extended storage and, at grading, have a higher proportion with pale colour and softer, coarser texture. In conclusion, methods to reduce

high rigor temperatures in beef carcasses would improve the acceptability of beef.

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