Meat Science 93 (2013) 201–206

Contents lists available at SciVerse ScienceDirect

Meat Science

journal homepage: www.elsevier.com/locate/meatsci

Effects of chilling methods and hot-boning on quality parameters of *M. longissimus lumborum* from *Bos indicus* Nelore steer

Manuel Pinto Neto [a,*], Nelson J. Beraquet [a], Susana Cardoso [b]

[a] ITAL, Centro de Tecnologia de Carnes, Av. Brasil 2880, CEP 13070178, Campinas, SP, Brazil
[b] UFRGS, Faculdade de Veterinária, CEPETEC, Av. Bento Gonçalves 8834, CEP 91540000, Porto Alegre, RS, Brazil

ARTICLE INFO

Article history:
Received 17 August 2011
Received in revised form 24 August 2012
Accepted 27 August 2012

Keywords:
Tenderness
Beef
Aging
Hot-boning
Fast-chilling

ABSTRACT

To study the effects of chilling methods and hot-boning on quality parameters of *M. longissimus lumborum* (LL) of Nelore steers, sixteen left-carcass sides were electrically stimulated and the LL muscles were hot-boned and chilled at −20 °C (HBVFC) or 0 °C (HBO). Eight control left-carcass sides were cold-boned (AT). All muscles were vacuum-packaged and aged at 0 °C for 14 d. Shear force and tenderness of the AT-treated muscles were not different from HBO-treated muscles. The shear force values of the HBVFC muscles were higher after 7 and 14 d *post-mortem* (*pm*) compared to those of the AT muscles, but there was no difference from the HBO muscles. Aging did not reduce the shear force values of the HBVFC muscles. The purge losses of the HBVFC muscles were higher than those of the HBO and AT muscles. The HBVFC muscles were less tender than the HBO and AT muscles at 14 d *pm*.

1. Introduction

Hot-boning is a well established process used to accelerate meat processing, and several studies have been conducted showing its economical advantages, such as reduced weight loss, lower chilling costs and enhanced functional properties of the meat like higher water-binding capacity (Cuthbertson, 1984; Kastner, 1977, 1983; Sørheim & Hildrum, 2002).

The removal of the muscle from the carcass during the pre-rigor phase allows the muscle to contract more than muscles that are conventionally chilled while attached to the skeleton, and the degree of contraction in which a muscle enters a state of rigor is highly variable among different muscles of a carcass (Locker, 1960). Such contraction can arise from either a rigor contraction of muscle fibers entering rigor above the optimum temperature of 10–18 °C or from cold contracture occurring below this temperature (Hildrum, Nilsen, & Wahlgren, 2002).

The degree of muscle contraction can be measured by the length of the sarcomeres, where shortened sarcomeres may indicate reduced myofibrillar tenderness (Sørheim & Hildrum, 2002). Some authors have found a significant correlation between meat tenderness and sarcomere length, mainly for slow glycolizing muscles (Rødbotten & Hildrum, 2000). These authors reported that the sarcomere length accounted for 62% of the variation in the Warner–Bratzler shear force of quickly chilled muscle that did not receive electrical stimulation. Bouton, Fischer, Harris, and Baxter (1973) found that the relationship between sarcomere length and tenderness was valid for some but not for all muscles.

Hot-boned and vacuum-packed meat cuts from stimulated carcasses must be cooled very quickly to prevent microbiological growth and protein degradation (Berry & Kotula, 1982; den Hertog-Meischke, Smulders, van Logtestijn, & van Knapen, 1997; Sumner & Krist, 2002). Rapid chilling, however, increases the risk of cold shortening, which adversely affects eating quality (Locker & Hagyard, 1963; Marsh & Leet, 1966). Bendall (1972) established that a safe condition for the time/temperature binomial during cooling that prevents cold shortening from occurring is 10 h/10 °C.

Electrical stimulation accelerates the decline in muscle pH to below the level that is critical for the development of cold shortening (pH<6.2) (White, O'Sullivan, Troy, & O'Neill, 2006). This enables rapid chilling or freezing of the carcass without the danger of cold shortening or toughening of the meat. Thompson (2002) reported a pH/temperature window concept in which the management of the pH decrease due to electrical stimulation be performed in such a way that the temperature of the muscle reaches less than 12 °C only if pH values are below 6.0.

Sørheim and Hildrum (2002) found that the extension of muscle contraction depends on the muscle temperature at the time of rigor, which is at least approximately 15 °C. Devine, Wahlgren, and Tornberg (1999) concluded that the rigor temperature affected the degree of muscle shortening and the activation of proteolytic enzymes and that these two factors act synergistically to give the greatest tenderness. They found that the best condition to improve meat tenderness is when muscles enter rigor between 10 and 15 °C. Hwang and Thompson (2001) concluded that the optimum pH decline required to produce the most

* Corresponding author. Tel.: +55 19 3743 1889; fax: +55 19 3743 1882.
E-mail address: manuel@ital.sp.gov.br (M. Pinto Neto).

0309-1740
http://dx.doi.org/10.1016/j.meatsci.2012.08.024

tender meat was dependent on the number of days of aging, and under their experimental conditions, an intermediate pH decline (pH 5.9–6.2 at 1.5 h *pm*), or rigor temperature (29–30 °C at pH 6.0) produced the most tender meat in strip loin after 14 d of aging.

Improvements in tenderness can be achieved by aging the meat for up to 3 weeks under chill, though aging is a highly variable process that depends on several factors such as the age and sex of the animal, muscle type, anabolic and repartitioning agents and on electrical stimulation, temperature and duration of storage (Dransfield, 1994). The extent of aging decreases with increased muscle shortening or reduction in sarcomere length (Davey, Kuttel, & Gilbert, 1967; Dransfield, 1994). When muscles are cold-shortened severely, aging does not occur (Marsh & Leet, 1966).

In Europe, an alternative chilling practice known as ultra-rapid chilling or very-fast chilling has been investigated for beef (Joseph, 1996; O'Mahony, McKenna, & Joseph, 1997) and lamb carcass processing (Redmond, McGeehin, Sheridan, & Butler, 2000). In their review, Sørheim and Hildrum (2002) described techniques to reduce muscle contraction, and the variation in meat tenderness, among which is the chilling of the muscles very quickly to form a crust on the surface. However, very-fast chilling has been shown to produce considerable muscle toughening and adverse consumer reaction (Joseph, 1996). The results of some studies indicate that there are minimal differences in tenderness between ultra-rapid and conventionally chilled products (Redmond et al., 2000), but other studies (Dransfield, 1998) have demonstrated that its commercial application would be somewhat limited.

Most of the quoted studies were conducted on muscles from pure or cross breeds of *Bos taurus*, and the results of the application of very-fast chilling to hot-boned meat were not conclusive.

Brazil is the leading beef export country in the world exporting 1635 million t in 2011 (Anuário DBO, 2012). Currently processing plants in Brazil have a low rate of technology incorporation, with limited use of electrical stimulation and no adoption of hot-boning, despite their known advantages with respect to improved quality and processing economics. In addition, limited attention has been given to *post-mortem* chilling rates in the largely produced *Bos indicus* breeds, which are known to produce tougher meat when compared to European breeds. Incorporation of some of these technologies into the Brazilian beef processing sector may increase Brazil's competitive export advantage. A further investigation of hot-boning under ultra-rapid and conventional chilling conditions compared to cold-boning under conventional chilling conditions in *Bos indicus* carcasses that had undergone low-voltage stimulation immediately *post*-exsanguination was undertaken.

2. Materials and methods

Twenty-four Nelore (*Bos indicus*) pasture-fed steers 30–36 months of age were slaughtered at 4 different times over a period of 3 months. Electrical stimulation, administered with a low-voltage electrical stimulator (LVES) (nose/rail) (model BV 80, Jarvis Argentina S.A.I.C., Argentina), was applied for 90 s to all carcasses immediately after exsanguination. The parameters used were 20 V (rms), 14 cycles/s, 0.25 A DC, alternating 5 ms on and 60 ms off. On each occasion 6 animals were slaughtered. The six left-carcass sides were randomly assigned to 3 treatments and 2 replications while the right-carcass sides were used in other studies. The *longissimus dorsi* (LD) muscles were boned and further divided into *thoracis* and *lumborum* (LL) sections.

The experiment involved three treatments those being two for hot-boned (HB) LL muscles and a control one. In the HBO treatment LL muscles were divided into 4 pieces. Three pieces of about 10 cm of length were individually vacuum-packed and immediately stored and conditioned at 0 °C for 2, 7 and 14 d. The fourth piece was divided into 6 smaller samples that were used to determine pH, R value and water-holding capacity (WHC) at 1, 2, 4, 6, 8 and 24 h *pm*. The temperature of the vacuum-packed pieces was followed by inserting the Pt 100 probes in a control sample through a silicon septum and was monitored and recorded in a data logger Field Chart Novus (model ISO 4851, Novus Produtos Eletronicos Ltda., Porto Alegre, Brazil).

In the HBVFC treatment whole vacuum-packed LL muscles were chilled very quickly in a freezing tunnel with forced circulated air (−20 °C, 2 m/s) that was completed, on average, 3 h and 30 min *pm* when the muscle surface temperature reached −1 to −2 °C as suggested by Joseph (1996). The temperature was measured near the surface (~1–2 mm) and at the geometric center of the cut with T-type thermocouples inserted through silicon septa and recorded in a data logger (model 1253, Grant Instruments Ltd., Cambridge, England). After chilling, the cuts were divided into four pieces and vacuum-packed again. One piece was taken for pH, R value and WHC samples.

For the control treatment (AT) left-carcass sides were hung by the Achilles tendon and conventionally chilled at 0 °C. The temperature of the LD muscle was followed by inserting probes at the 12th rib approximately at the center of the muscle. The temperature probes and recording instruments were the same as that used for HBO treatment. The boned LL muscles were divided into four pieces, 24 h *pm*, three of them were vacuum-packed and conditioned at 0 °C for 2, 7 and 14 d and the fourth piece was used for pH, R value and WHC determination, as described above.

The pH was determined 1, 2, 4, 6, 8 and 24 h *pm* (Kastner et al., 1993) as described by Bendall (1973). The muscle samples (25 g) were collected in plastic bags, frozen in liquid nitrogen and kept in a Revco biofreezer (model ULT10120-5D/VA, Revco Technologies Inc., Asheville, USA) at −80 °C until they were analyzed. Samples weighing 2.5 g were homogenized in a 25 mL solution with 1.04 g of sodium iodoacetate and 11.18 g of KCl, and the pH was measured with a digital pH meter (model Ingold WTW pH91, Mettler-Toledo Industria e Comercio Ltda., Brazil).

The same samples collected for pH measurements were used for R value (250/260 nm) determination with a spectrophotometer (Cary 1E UV, Visible, Varian) according to Honikel and Fischer (1977). The WHC was measured by the press-and-filter paper method described by Hoffmann, Hamm, and Bluechel (1982).

The vacuum-packed pieces were picked at random 2, 7 and 14 d *pm*. Each piece was weighed before packaging, and after the opening of the package: the weight difference was taken as the percentage lost as purge.

For shear force determination and sensory analysis the pieces were cut into 3 steaks (2.54 cm) per treatment and cooked on the 2nd, 7th and 14th d *pm*. The steaks were cooked according to adapted AMSA (1995) guidelines using an electrical contact grill (model PDL, Sirman, Italy) with heating in the bottom and in the lid (150 °C) until their internal temperature reached 74 °C. The steaks were weighed before and after cooking, when the surface temperature reached 40 °C, to determine the total cooking loss. Temperatures were monitored using a digital thermometer (model 51, Novus Produtos Eletronicos Ltda., Porto Alegre, Brazil) with a K-type probe inserted into the center of each steak. The cooked steaks were left in a refrigerator overnight and 8 cylindrical samples, with one-half inch diameter and parallel fiber orientation, were drawn from each steak. Shear forces were determined with a TA.XT2i Texture Analyzer (Stable Micro System Limited, Surrey, England) coupled with a Warner–Bratzler type blade (TA-7 USDA). The crosshead speed was set at 200 mm/min and the samples were sheared perpendicular to the longitudinal orientation of the muscle fiber.

Tenderness, juiciness and flavor were evaluated by 15 trained panelists, using the quantitative descriptive analysis method with a structured 10-point scale, where 0 was slightly tender, slightly juicy or had slightly aged flavor, 5 was tender, juicy or had aged flavor and 10 was very tender, very juicy or had intense aged flavor. Meat cube samples of 1.5 cm were taken from cooked steaks and presented in a monadic sequential scheme with random rotation to prevent the “carry over” effect.

Sarcomere length was measured immediately after boning and after 14 d *pm*. For HBVFC-treated muscles it was measured soon after very fast chilling. The method utilized was a general histological processing for the morphometric analysis of length. Muscle fragments, with their principal axes oriented along the muscle fiber were collected from the same inner LL muscle position. After washing the fragments with physiological solution, they were laid on aluminum foil containing CRYOform™ and frozen with liquid nitrogen in an n-hexane solution. Sections 6 μm in thickness were cut using a cryotome (IEC-USA). The images were captured with a microscope (Eclipse 800, Nikon, Japan) and digital camera (CoolSnap-Pro Digital Media Cybernetics, USA) and processed with the ImagePro-Plus Software Media Cybernetics, USA.

The experimental design was randomized blocks considering the slaughter as a blocking factor. Analysis of variance (ANOVA) was used to test for the significance of blocks, aging time, treatment and interaction of aging time/treatment. The Duncan's Multiple Range Test for variables was used to detect mean differences ($p<0.05$) with SAS statistical package 8.0 (SAS Institute Inc., 2000). The correlation among variables was measured with Pearson's coefficient using the Statistica 5.5 software package (StatSoft, 1999).

The sensory scores were statistically analyzed as complete balanced randomized blocks (software version Five 4.2, Compusense Inc., Guelph, Ontario, Canada) and an ANOVA test was used considering the panelist as a source of error. The significance level of 5% was considered in all tests.

3. Results and discussion

3.1. Temperature decline, pH drop and sarcomere length

The temperature of the cooling chamber during the AT treatment oscillated around 10 °C during the first 12 h and reached 5 °C at the end of chilling (Fig. 1). The temperature of the cooling chamber for HBO treatment oscillated around 2.5 °C.

The AT-treated muscles reached 10 °C around 11 h *pm* (Fig. 1) which, according to Bendall's rule of thumb (Bendall, 1972), would prevent the occurrence of cold shortening. The muscle's pH reached 6.0 (Table 1) when the temperature of the muscle was around 17 °C indicating, according to Thompson (2002), that no cold shortening occurred.

The muscle's R value for this treatment was 1.1 after 8 h *pm* indicating, according to Honikel, Roncalés, and Hamm (1983), that the muscle entered into *rigor mortis* at this time while its temperature was around 14 °C. Muscles entering *rigor mortis* at temperatures around 15 °C are considered to result in tender meat according to Devine et al. (1999). The sarcomere lengths of the AT-treated muscles immediately after boning and 14 d *pm* were respectively 2.092 and 1.986 μm (Table 2) which are in the normal range of 1.9–2.0 μm for non-shortened muscles (Smulders, Marsh, Swartz, Russel, & Hoenecke, 1990). The sum of all these conditions leads to the conclusion that the temperature decline and pH drop for this treatment were within the best conditions recommended to obtain tender meat.

The HBO-treated muscles had a much faster temperature decline than the AT ones reaching 10 °C in about 5 h *pm* which is less than half of the time required for the AT-treated muscles to reach this temperature. According to Bendall (1973), under this combination of temperature and time the HBO-treated muscles would be prone to cold shortening. However they reached pH 6.0 in about 4 h *pm* when muscle temperature was around 12 °C which, according to Thompson (2002), would not cold shorten the muscle. The muscle's R value at the same time *pm* was 1.1 indicating that the muscle also entered into rigor at this favorable temperature. Sarcomere lengths of 2.044 and 1.898 μm, respectively, immediately after boning and 14 d *pm* were not statistically different ($p>0.05$) from those of the AT treatment and were also in the normal range of non-shortened relaxed muscle.

In the case of the muscles subjected to HBVFC treatment the temperature at the center of the muscle dropped very sharply (Fig. 2): after 1 h it was below 10 °C, and after 2 h it was near 0 °C. The temperature drop became very slow at −1 °C, and this point was considered the end of the process. Tomás, Beltrán, and Roncalés (1998) and Dransfield (1998) defined very-fast chilling (VFC) as a chilling condition under which the temperature inside the muscle reaches 0 °C in less than 4 h *pm*. Joseph (1996) defined VFC as a chilling regime under which the temperature of the muscle falls to −1 °C in 5 h, whereas Honikel and Joseph (2003) stated that VFC is obtained when the muscle temperature falls to 0 °C before 5 h *pm*. The results presented in Fig. 2 show that the LL was submitted to cooling conditions that satisfy all of the quoted VFC definitions. The pH value was 6.15 after 1 h *pm* and remained above 6.0 until 4 h *pm* when its temperature was 0 °C. Hence according to Bendall (1973) and Thompson (2002) extensive cold shortening might have occurred. The HBVFC-treated muscles entered into *rigor mortis* after 4 h *pm* as

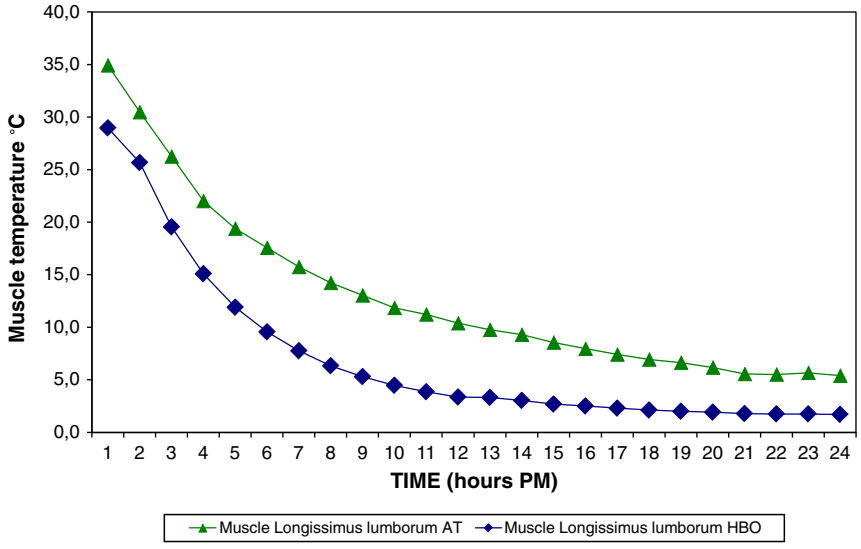

Fig. 1. Temperature decline (°C) at the center of the *M. longissimus lumborum* either attached to the carcass (AT) or hot-boned (HBO).

Table 1
pH and R values for *M. longissimus lumborum* under different treatments 1, 2, 4, 6, 8 and 24 h *pm*.

Measurement	Treatments					
	HBO		HBVFC		AT	
	Mean	SE	Mean	SE	Mean	SE
pH						
1 h *pm*	$6.27^{A,a}$	±0.10	$6.15^{A,a}$	±0.10	$6.37^{A,a}$	±0.07
2 h *pm*	$6.16^{A,ab}$	±0.13	$6.16^{A,a}$	±0.10	$6.21^{A,a}$	±0.07
4 h *pm*	$5.99^{A,abc}$	±0.10	$6.10^{A,ab}$	±0.07	$6.17^{A,ab}$	±0.09
6 h *pm*	$5.96^{A,bc}$	±0.08	$5.90^{A,bc}$	±0.05	$5.94^{A,bc}$	±0.10
8 h *pm*	$5.92^{A,bc}$	±0.09	$5.72^{A,cd}$	±0.06	$5.82^{A,c}$	±0.12
24 h *pm*	$5.71^{A,c}$	±0.04	$5.60^{AB,d}$	±0.05	$5.53^{B,d}$	±0.07
R value						
1 h *pm*	$1.01^{A,c}$	±0.02	$0.88^{B,b}$	±0.01	$0.92^{B,d}$	±0.03
2 h *pm*	$1.05^{A,c}$	±0.05	$0.93^{A,b}$	±0.02	$0.93^{A,d}$	±0.04
4 h *pm*	$1.10^{A,c}$	±0.05	$0.94^{A,b}$	±0.11	$0.97^{A,cd}$	±0.02
6 h *pm*	$1.25^{A,b}$	±0.06	$1.26^{A,a}$	±0.03	$1.07^{B,bc}$	±0.04
8 h *pm*	$1.30^{A,ab}$	±0.05	$1.15^{A,a}$	±0.12	$1.11^{A,b}$	±0.06
24 h *pm*	$1.41^{A,a}$	±0.01	$1.22^{B,a}$	±0.06	$1.32^{AB,a}$	±0.05

SE = standard error of the mean, n = 8 replications; *pm* = *post-mortem*.
Different letters means significant difference (^{A,B} rows; ^{a,b} columns) by Duncan's test ($p<0.05$), treatment and h *pm*, respectively.
HBO = hot-boning and aging at 0 °C; HBVFC = hot-boning and very fast chilling; AT = cold-boning and carcass hung by Achilles tendon.

indicated by the R values. Consequently the muscle entered *rigor mortis* at 0 °C. All these conditions favored muscle shortening. The measurement of sarcomere length, taken at 14 d *pm*, shows that it was 35% shorter than the sarcomeres of the AT and HBO treatments, confirming the assertions made above based on temperature and pH.

Van Moeseke, De Smet, Claeys, and Demeyer (2001) found that sarcomere lengths were reduced by more than 30% in the *semitendinosus* muscle after very-fast chilling compared to conventional chilling.

No significant difference ($p>0.05$) was found among the pH values of muscles from all treatments for measurements made up to 8 h *pm* (Table 1). The mean pH value of muscles subjected to HBO treatment, when measured 24 h *pm*, was higher than that of muscles subjected to AT treatment ($p<0.05$), while the mean pH value of the HBVFC treatment was intermediate to the HBO and AT.

Although no statistically significant difference was found among treatments, the pH drop between 1 and 8 h *pm* amounts to 0.35, 0.43 and 0.55 pH units for the HBO, HBVFC and AT treatments respectively. These differences in pH value could probably be related to the effect of the chilling rate on the rate of pH drop. The hot-boned muscles (HBO) had lower temperatures during the chilling period than the cold-boned AT-treated muscles (Fig. 1). White et al. (2006) found similar results with hot-boned *M. semimenbranosus* chilled at 2 °C and 10 °C.

Table 2
Sarcomere lengths for *M. longissimus lumborum* under different treatments at boning time and 14 d *pm*.

Measuring time	Treatments					
	HBO		HBVFC		AT	
	Mean µm	SE	Mean µm	SE	Mean µm	SE
Boning	$2.044^{A,a}$	±0.048	$^{a}1.712^{B,a}$	±0.200	$^{b}2.092^{A,a}$	±0.090
14 d *pm*	$1.898^{A,a}$	±0.022	$1.234^{B,b}$	±0.038	$1.986^{A,a}$	±0.056

SE = standard error of the mean, n = 4 replications; *pm* = *post-mortem*.
Different letters means significant difference (^{A,B} rows; ^{a,b} columns) by Duncan's test ($p<0.05$), treatment and aging time, respectively.
HBO = hot-boning and aging at 0 °C; HBVFC = hot-boning and very-fast chilling; AT = cold-boning and carcass hung by Achilles tendon.
[a] After very-fast chilling.
[b] After 24 h.

3.2. Water-holding capacity, purge loss and cooking loss

The WHC was affected only by the aging time and there was no significant difference ($p>0.05$) related to the time of boning (hot or cold boning) and speed of chilling (Table 3). The WHC of the LL muscle decreased significantly ($p<0.05$) with aging under the HBVFC and AT treatments from the 2nd to the 14th d *pm*. There was no significant difference ($p>0.05$) in WHC with aging for the HBO-treated muscles.

As shown in Table 4, the purge loss of muscles from all treatments increased with aging time, which has already been reported by González, Juárez, Polvillo, Contò, and Failla (2008) and followed the same trends of the WHC results. The purge loss of HBVFC-treated muscles was significantly higher ($p<0.05$) than that of muscles subjected to the other two treatments; this increase in purge loss could be mainly explained by the shortening of sarcomeres and the freezing of the muscle surface. These differences could not, however, be verified with the WHC results. The purge loss in HBO muscles was not different ($p>0.05$) from AT muscles during the aging period.

The range of average values of cooking losses of LL muscles for all treatments was 23.92% to 31.20% (Table 4). There were no significant cooking loss differences ($p>0.05$) among all treatments during aging. González et al. (2008) found cooking losses of 29.7% in thermal shrinkage and no significant differences during aging for *longissimus thoracis* muscle.

3.3. Warner–Bratzler shear force and sensory analysis

The tenderizing effect of aging was observed in the HBO and AT treatments (Table 5). Very-fast chilling of hot-boned muscle decreased the effectiveness of aging on shear force. No difference was found in the shear force among all treatments 2 d *pm* ($p>0.05$). However, in 7 and 14 d *pm* there was a significant effect on the meat shear force for the different treatments. The HBVFC-treated muscles had significantly higher shear force values than the conventionally chilled (AT) ($p<0.05$), but there was no difference from the HBO treatment.

In all treatments the muscle tenderness was significantly affected by aging ($p<0.05$; Table 6). After 7 d of aging, muscles from all treatments received scores above 5.0, which meant that they were considered by the panelists as "tender".

The HBVFC-treated muscles presented the lowest score for tenderness after 14 d of aging and are significantly different from AT and HBO-treated muscles ($p<0.05$). Van Moeseke et al. (2001) found similar results and concluded that aging was not able to counteract the initial increase in toughness due to muscle shortening.

There were no treatment or aging-induced effects on juiciness ($p<0.05$). The average score for juiciness was 6.5. Therefore, the higher purge loss in HBVFC muscles did not affect juiciness.

The flavor of aged meat was not affected by the treatments ($p>0.05$), though, as expected, aging promoted an increase in scores for all of the treatments. After 14 d *pm*, the average score was 5.0, which on the structured scale is considered the threshold for acceptable aged flavor.

The regression analysis of the data shows a significant positive correlation of the sarcomere length with tenderness ($r=0.33$), which is in accordance with the results of Locker and Hagyard (1963), Hostetler, Link, Landmann, and Fitzhugh (1972) and Van Moeseke et al. (2001). There was a significant negative correlation between sarcomere length and purge loss ($r=-0.54$). Tenderness scores showed a significant negative correlation with shear force ($r=-0.64$).

4. Conclusions

Conventionally deboned and aged (AT-treated) *M. longissimus lumborum* from *Bos indicus* Nelore steers showed shear force values

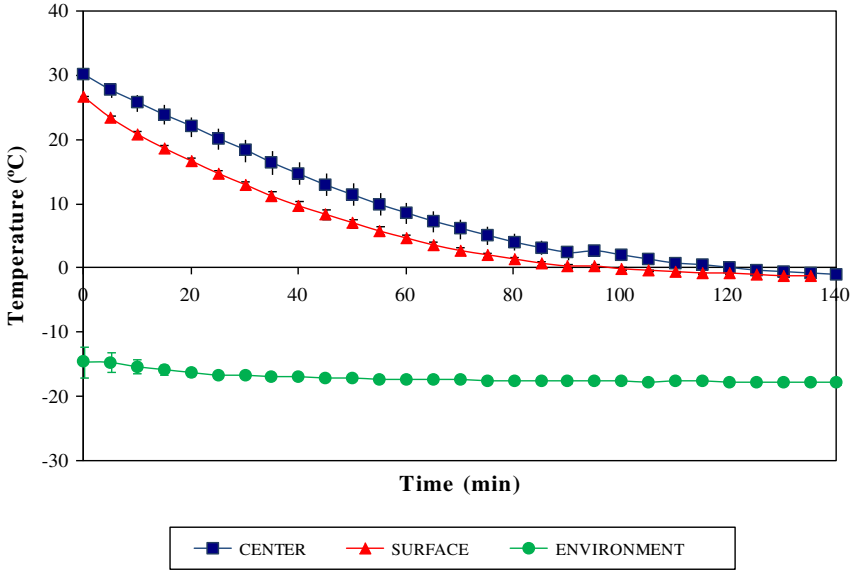

Fig. 2. Temperature decline (°C) in the center (■) and on the surface (▲) of hot-boned and very-fast chilled *M. longissimus lumborum* (HBVFC-treated) in a blast air freezing tunnel (●: air temperature).

Table 3
Water-holding capacity in the *M. longissimus lumborum* under different treatments at 2, 7 and 14 d *pm*.

Measures	Treatments					
	HBO		HBVFC		AT	
	Mean	SE	Mean	SE	Mean	SE
WHC						
2 d *pm*	$0.50^{A,a}$	±0.01	$0.50^{A,a}$	±0.03	$0.51^{A,a}$	±0.02
7 d *pm*	$0.51^{A,a}$	±0.02	$0.46^{A,ab}$	±0.01	$0.46^{A,b}$	±0.01
14 d *pm*	$0.48^{A,a}$	±0.03	$0.43^{A,b}$	±0.03	$0.43^{A,b}$	±0.01

SE = standard error of the mean, n = 8 replications; *pm* = *post-mortem*.
WHC values are dimensionless.
Different letters means significant difference (^{A,B} rows; ^{a,b} columns) by Duncan's test ($p<0.05$), treatment and aging time, respectively.
HBO = hot-boning and aging at 0 °C; HBVFC = hot-boning and very-fast chilling; AT = cold-boning and carcass hung by Achilles tendon.

Table 4
Purge and cooking losses for *M. longissimus lumborum* under different treatments 2, 7 and 14 d *pm*.

Measurement	Treatments					
	HBO		HBVFC		AT	
	Mean %	SE	Mean %	SE	Mean %	SE
Purge loss						
2 d *pm*	$0.67^{B,b}$	±0.11	$1.59^{A,b}$	±0.29	$0.53^{B,b}$	±0.15
7 d *pm*	$0.97^{B,ab}$	±0.12	$3.45^{A,ab}$	±0.87	$1.46^{B,a}$	±0.28
14 d *pm*	$1.35^{B,a}$	±0.25	$3.99^{A,a}$	±0.84	$1.77^{B,a}$	±0.36
Cooking loss						
2 d *pm*	$26.19^{A,a}$	±0.52	$28.83^{A,a}$	±1.34	$30.54^{A,a}$	±2.39
7 d *pm*	$26.03^{A,a}$	±1.77	$29.95^{A,a}$	±1.44	$28.58^{A,a}$	±0.94
14 d *pm*	$29.70^{A,a}$	±1.53	$28.51^{A,a}$	±1.29	$27.64^{A,a}$	±1.12

SE = standard error of the mean, n = 8 replications; *pm* = *post-mortem*.
Different letters means significant difference (^{A,B} rows; ^{a,b} columns) by Duncan's test ($p<0.05$), treatment and aging time, respectively.
HBO = hot-boning and aging at 0 °C; HBVFC = hot boning and very-fast chilling; AT = cold-boning and carcass hung by Achilles tendon.

that were significantly smaller than those treated by HBVFC after 7 and 14 d *pm*, though these values were not different from those of HBO-treated muscles. HBO-treated muscles, which were not expected to toughen, featured no significant difference in shear force with respect to HBVFC-treated muscles.

The sensory tenderness of AT-treated muscle was not different from HBO-treated muscle ($p<0.05$), and both treatments showed higher scores than HBVFC-treated muscles after 14 d *pm*.

There was no sarcomere shortening of muscles from AT and HBO treatments and sarcomere lengths were not significantly different ($p<0.05$) at boning and after 14 d. The sarcomere length of the HBVFC-treated muscles, taken at 14 d *pm*, was 35% shorter than the sarcomeres of the AT and HBO treatments.

Purge loss of AT-treated muscles was not different from the HBO-treated muscles ($p<0.05$) in all aging times. The purge losses of the HBVFC muscles were higher than those of the HBO and AT muscles. HBO-treated muscle showed no difference in WHC with aging.

Considering these results, hot-boning with low voltage electrical stimulation, correctly applied, with controlled chilling temperature and aging could be applied to commercial abattoirs in Brazil to accelerate the throughput and ensure the eating quality of the meat.

Table 5
Shear force values for *M. longissimus lumborum* under different treatments 2, 7 and 14 d *pm*.

Measurement	Treatments					
	HBO		HBVFC		AT	
	Mean (kgf)	SE	Mean (kgf)	SE	Mean (kgf)	SE
Shear force						
2 d *pm*	$7.39^{A,a}$	±0.50	$7.10^{A,a}$	±0.42	$6.93^{A,a}$	±0.47
7 d *pm*	$5.90^{AB,b}$	±0.34	$6.77^{A,a}$	±0.47	$5.36^{B,b}$	±0.36
14 d *pm*	$5.14^{AB,b}$	±0.32	$6.13^{A,a}$	±0.32	$4.86^{B,b}$	±0.52

SE = standard error of the mean, n = 8 replications; *pm* = *post-mortem*.
Different letters means significant difference (^{A,B} rows; ^{a,b} columns) by Duncan's test ($p<0.05$), treatment and aging time, respectively.
HBO = hot-boning and aging at 0 °C; HBVFC = hot-boning and very-fast chilling; AT = cold-boning and carcass hung by Achilles tendon.

Table 6
Means and standard errors for scores from a sensorial panel related to the attributes tenderness, juiciness and flavor for *M. longissimus lumborum* under different treatments at 2, 7 and 14 d *pm*.

Measurement	Treatments					
	HBO		HBVFC		AT	
	Mean	SE	Mean	SE	Mean	SE
Tenderness						
2 d *pm*	$5.10^{A,b}$	±0.49	$4.66^{A,b}$	±0.15	$5.44^{A,b}$	±0.27
7 d *pm*	$5.66^{A,b}$	±0.40	$5.56^{A,a}$	±0.32	$6.07^{A,ab}$	±0.32
14 d *pm*	$6.96^{A,a}$	±0.32	$5.56^{B,a}$	±0.25	$6.73^{A,a}$	±0.39
Juiciness						
2 d *pm*	$6.55^{A,a}$	±0.09	$6.37^{A,a}$	±0.18	$6.16^{A,a}$	±0.25
7 d *pm*	$6.41^{A,a}$	±0.17	$6.40^{A,a}$	±0.14	$6.30^{A,a}$	±0.19
14 d *pm*	$6.44^{A,a}$	±0.13	$6.26^{A,a}$	±0.16	$6.54^{A,a}$	±0.21
Flavor						
2 d *pm*	$2.64^{A,c}$	±0.23	$2.41^{A,c}$	±0.13	$2.91^{A,c}$	±0.22
7 d *pm*	$3.77^{A,b}$	±0.17	$3.75^{A,b}$	±0.15	$4.01^{A,b}$	±0.14
14 d *pm*	$5.05^{A,a}$	±0.18	$4.76^{A,a}$	±0.17	$4.96^{A,a}$	±0.28

SE = standard error of the mean, n = 8 replications; *pm* = *post-mortem*.
Different letters means significant difference (^{A,B} rows; ^{a,b} columns) by Duncan's test ($p<0.05$), treatment and aging time, respectively.
HBO = hot boning and aging at 0 °C; HBVFC = hot boning and very-fast chilling; AT = cold boning and carcass hung by Achilles tendon.
0 = slightly tender, slightly juicy or slightly aged flavor.
10 = very tender, very juicy or intense aged flavor.

The results also suggest that HBVFC treatment is not advisable for commercial abattoirs since it inhibits tenderization by aging and muscles are tough and more exudative.

Acknowledgments

This study has received financing from the São Paulo State Foundation for Research Support (FAPESP).

References

AMSA (1995). *Research guidelines for cookery and sensory evaluation and instrumental tenderness measurements of fresh meat.* Chicago, Illinois: AMSA/National Livestock and Meat Board.
Anuário DBO (2012). *DBO Editores Associados Limitada, Rua Dona Germaine Burchard, 229.* SP, Brazil: Sao Paulo.
Bendall, J. R. (1972). The influence of rate of chilling in the development of rigor and cold-shortening. *Meat chilling — Why and how?* (pp. 3-1–3-6). Langford, Bristol, UK: Meat research Institute.
Bendall, J. R. (1973). *Post-mortem* changes in muscle. In G. H. Bourne (Ed.), *The structure and function of muscle* (pp. 243–309). (2nd ed.). New York: Academic Press.
Berry, B. W., & Kotula, W. (1982). Effects of electrical stimulation, temperature of boning and storage time on bacterial counts and shelf-life characteristics of beef cuts. *Journal of Food Science*, *47*, 852–857.
Bouton, P. E., Fischer, A. L., Harris, P. V., & Baxter, R. I. (1973). A comparison of the effects of some post-slaughter treatments on the tenderness of beef. *Journal of Food Technology*, *8*, 39–49.
Cuthbertson, A. (1984). Processado en caliente de la carne: Revision de sus razones e implicaciones econômicas. In R. A. Lawrie (Ed.), *Avances de la ciencia de la carne* (pp. 84–118). Zaragoza: Ed. Acribia.
Davey, C. L., Kuttel, H., & Gilbert, K. V. (1967). Shortening as a factor in meat ageing. *International Journal of Food Science & Technology*, *2*, 53–56.
Devine, C. E., Wahlgren, N. M., & Tornberg, E. (1999). Effect of rigor temperature on muscle shortening and tenderization of restrained and unrestrained beef m. Longissimus thoracicus et lumborum. *Meat Science*, *51*, 61–72.
Dransfield, E. (1994). Optimization of tenderization, ageing and tenderness. *Meat Science*, *36*, 105–121.
Dransfield, E. (1998). Texture in very fast cooled beef. *Very fast chilling in beef, 2. Muscle to meat* (pp. 17–22). Bristol, UK: University of Bristol Press.
González, S. F., Juárez, M., Polvillo, O., Contò, M., & Failla, S. (2008). Changes in meat quality characteristics of two beef muscles during ageing. I: Water holding capacity and colour. *Proceedings 54th International Congress of Meat Science and Technology, Helsinki, Finland*.
den Hertog-Meischke, M. J. A., Smulders, F. J. M., van Logtestijn, J. G., & van Knapen, F. (1997). *Journal of Animal Science*, *7*, 118–124.
Hildrum, K. I., Nilsen, B. N., & Wahlgren, M. (2002). Improving the tenderness of hot boned beef muscles. *Fleischwirtschaft International*, *1*, 42–48.
Hoffmann, K., Hamm, R., & Bluechel, E. (1982). Neue uber die Bestimmung der Wasserbindung mit Hilfe der Filterpapierpressmethode. *Fleischwirtschaft*, *62*, 87–94.
Honikel, K. O., & Fischer, C. A. (1977). A rapid method for the detection of PSE and DFD porcine muscles. *Journal of Food Science*, *42*, 1633–1636.
Honikel, K. O., & Joseph, R. L. (2003). Very fast chilling. *Fleischwirtschaft International*, *3*, 57–61.
Honikel, K. O., Roncalés, P., & Hamm, R. (1983). The influence of temperature on shortening and rigor onset in beef muscle. *Meat Science*, *8*, 221–241.
Hostetler, R. L., Link, B. A., Landmann, W. A., & Fitzhugh, H. A. J. R. (1972). Effect of carcass suspension on sarcomere length and shear force of some major bovine muscles. *Journal of Food Science*, *37*, 132–135.
Hwang, I. H., & Thompson, J. M. (2001). The interaction between pH and temperature decline early *post-mortem* on the calpain system and objective tenderness in electrically stimulated beef longissimus dorsi muscle. *Meat Science*, *58*, 167–174.
Joseph, R. L. (1996). Very fast chilling of beef and tenderness — A report from an EU Concerted Action. *Meat Science*, *43*, 217–227.
Kastner, C. L. (1977). Hot processing: Update on potential energy and related economics. *Proceedings of the Meat Industry Research Conference* (pp. 43). Chicago: American Meat Institute Foundation.
Kastner, C. L. (1983). Optimal hot-processing systems for beef. *Food Technology*, 96–104 May.
Kastner, C. L., Schwenke, J. R., Kenney, P. B., Campbel, R. E., Kendall, J. A., & Milliken, G. A. (1993). Comparisons of effect of electrical stimulation methods on *post-mortem* pH decline in beef muscle. *Meat Science*, *35*, 183–190.
Locker, R. H. (1960). Degree of muscular contraction as a factor in tenderness of beef. *Food Research*, *25*, 304–307.
Locker, R. H., & Hagyard, C. J. (1963). A cold shortening effect in beef muscles. *Journal of Food Science and Agriculture*, *14*, 787.
Marsh, B. B., & Leet, N. G. (1966). Studies in meat tenderness. III. The effects of cold shortening on tenderness. *Journal of Food Science*, *31*, 450.
O'Mahony, B., McKenna, B. M., & Joseph, R. L. (1997). Very fast chilling of beef. *Proceedings 43rd International Congress of Meat Science and Technology, Auckland, New Zealand* (pp. 560–561).
Redmond, G. A., McGeehin, B., Sheridan, J. J., & Butler, F. (2000). The effect of ultra-rapid chilling and subsequent ageing on the calpain/calpastatin system and myofibrillar degradation in lamb M. longissimus thoracis et lumborum. *Meat Science*, *59*, 293–301.
Rødbotten, R., & Hildrum, K. I. (2000). Sarcomere length as indicator of tenderness in bovine M. longissimus dorsi exposed to different *post-mortem* treatments. *Proceedings 46th International Congress of Meat Science and Technology, Buenos Aires, Argentina* (pp. 480–481).
SAS (2000). *SAS 6.1.2 user's guide: statistics.* Cary, NC: SAS Inst. Inc.
Smulders, F. J. M., Marsh, B. B., Swartz, D. R., Russel, R. L., & Hoenecke, M. E. (1990). Beef tenderness and sarcomere length. *Meat Science*, *28*, 349–363.
Sørheim, O., & Hildrum, K. I. (2002). Muscle stretching techniques for improving meat tenderness. *Trends in Food Science and Technology*, *13*, 127–135.
StatSoft, Inc. (1999). *Electronic Statistics Textbook.* Tulsa, OK: StatSoft.
Sumner, J., & Krist, K. (2002). The use of predictive microbiology by the Australian meat industry. *International Journal of Food Microbiology*, *73*, 363–366.
Thompson, J. (2002). Managing meat tenderness. *Meat Science*, *62*, 295–308.
Tomás, S., Beltrán, J. A., & Roncalés, P. (1998). Very fast chilling of beef longissimus dorsi. *Very Fast Chilling in Beef, 2. Muscle to meat* (pp. 169–176). Bristol, UK: University of Bristol Press.
Van Moeseke, W., De Smet, S., Claeys, E., & Demeyer, D. (2001). Very fast chilling of beef: Effects on meat quality. *Meat Science*, *59*, 31–37.
White, A., O'Sullivan, A., Troy, D. J., & O'Neill, E. E. (2006). Effects of electrical stimulation, chilling temperature and hot-boning on tenderness of bovine muscles. *Meat Science*, *73*, 196–203.