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Beef Carcass Chilling: Current Understanding, Future Challenges

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Introduction

Chilling freshly harvested beef carcasses is necessary for food safety and quality purposes. Before mechanical refrigeration, meat either had to be consumed immediately after slaughter or be preserved through salting, curing, and/or smoking. With the advent of mechanical refrigeration and networks of refrigerated carriers, the production, processing, and distribution of carcasses and cuts were made more convenient and practical.

The review by Savell et al. (2005) addressed what was known at the time about the chilling of beef and pork carcasses and has served as a valuable reference for those who seek to better understand the complex nature of the events occurring during the conversion of live animals to carcasses and the role of chilling throughout this process. As of May, 2012, this article had been cited in 44 scientific articles according to Thomson Reuters Web of Knowledge/Web of Science (http://wokinfo.com/), which demonstrates the importance of the information to the scientific community. This information continues to be a valuable resource for those who seek to better understand carcass chilling.

Even with the information presented in this review article, questions related to beef carcass chilling still remain. In addition, as carcass weights increase, demonstrative increases in muscle sizes and shapes present challenges to the packer/processor to ensure that these larger and heavier carcasses are being adequately chilled after the harvest process.

This review builds on the body of work first reviewed by Savell et al. (2005) with the emphasis on beef and what is currently known about the chilling process. In addition to the information presented in this review article, further research needs have been identified related to chilling beef carcasses. As with the previous review, only the meat quality aspects will be covered, but this should not diminish the importance of chilling to ensure meat is safe to consume.

The First 24 Hours

Development of rigor mortis

Rigor mortis develops in postmortem muscle when stores of adenosine triphosphate (ATP) are no longer present in sufficient quantities to break the bonds between actin and myosin. Under normal conditions, rigor begins when the pH of the muscle reaches 5.6 to 5.7 (Hannula and Puolanne, 2004). The first phase of rigor mortis is called the delay phase, and the muscle is still extensible because sufficient ATP is available to bind with magnesium (Mg^{2+}), which helps to disconnect actin/myosin cross-bridges and allows the muscle to relax. When creatine phosphate stores are depleted and adenosine diphosphate (ADP) can no longer be re-phosphorylated back to ATP, the second phase or onset phase of rigor begins. The last phase, called the completion phase, develops once the muscle becomes inextensible.

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Postmortem chilling rates can impact the development of rigor mortis. High chilling temperatures will cause rigor mortis to develop more rapidly, whereas low chilling temperatures will cause rigor mortis to develop more slowly. Electrical stimulation also has an impact on rigor development as electrically stimulated carcasses go into rigor mortis sooner than carcasses not receiving electrical stimulation.

pH decline

In postmortem muscle, pH will decline from a beginning point of 7.0 to approximately 5.6 in normal muscle. This decline occurs as a result of the need of the muscle to regenerate ATP, which is principally accomplished after death through postmortem glycolysis, and lactic acid builds up in the muscle as a consequence. The time-course of this drop in pH is greatly influenced by chilling conditions (slower chilling = more rapid drop in pH; faster chilling = less rapid drop in pH) and whether carcasses are subjected to electrical stimulation (much more rapid decline in pH in electrically stimulated carcasses). Other than the use of electrical stimulation, pH decline is not as actively managed in beef processing as it is in pork processing (i.e., rapid chilling, minimizing processing time on the slaughter floor, no electrical prods in handling, etc.).

The time-course for pH decline in beef varies, but the ultimate pH is usually achieved within 24 hours postmortem. The quality issue most often impacted by pH is dark-cutting beef (about 1 to 3% occurrence rate and greatly influenced by season). This condition occurs when limited glycogen stores in the living animal cause insufficient lactic acid buildup postmortem and results in higher rather than lower final pH values being observed (pH $\geq$ 6.0 for dark-cutting beef compared to pH = 5.6 for normal beef). No postmortem chilling or other management practices are available to use for minimizing the development of dark cutting beef.

Cold shortening/toughening

It has been known for about a half century that cold temperatures early postmortem could cause cold shortening or cold toughening of meat. An excellent evaluation of events that led to this discovery is covered by Locker (1985) in his review of cold-induced toughening and the impact technological improvements in refrigeration/freezing had on meat tenderness. In this study, improved refrigeration/freezing of New Zealand lamb carcasses destined for export actually resulted in tougher meat than when less efficient chilling technologies were used. He found that the degree of muscular contraction was related to tenderness (Locker, 1960), and that exposure to specific cold temperatures early postmortem and before rigor mortis would result in a phenomenon forevermore referred to as "cold shortening" (Locker and Hagyard, 1963). This discovery focused the meat science community on the evaluation of the myofibrillar component of meat as the primary contributor to tenderness (Locker, 1985).

More detailed descriptions of cold shortening and how to prevent it are available elsewhere, but Bendall (1973) found that muscles at less than 10°C are susceptible to cold shortening until a muscle pH of 6.2 is reached. Most strategies for preventing cold shortening applied this discovery as the basis for reducing or eliminating toughness that occurs when carcasses are chilled more rapidly than they should be.

Current Practices

Blast chilling

The initial chilling area in a beef processing plant is the blast chiller, often referred to as the "hot box," as this is where the freshly harvested beef carcasses (thus "hot" carcasses) are placed for cooling. In the United States, unlike some other countries, no specific regulatory requirements exist for how rapidly or to what extent this initial chilling is conducted. Many beef processing plants that have chilling as a critical control point in their Hazard Analysis and Critical Control Point (HACCP) plan often use the critical limit of less than or equal to 4°C surface temperature within 24 hours. This measurement is taken on or just beneath the surface of the carcass because controlling the surface temperature is key to preventing pathogen growth, which would be the biological hazard identified as reasonably likely to occur in a HACCP plan.

A couple of examples of country-specific regulatory requirements for chilling carcasses exist. An earlier document from the European Communities (The Council of the European Communities, 1964) stated this under Chapter IX, Storage: "Fresh meat intended for intra-community trade must be chilled immediately after the *post mortem* inspection and kept at a constant temperature of not more than +7°C for carcasses and cuts and +3°C for offal." More recent language from the European Union (The European Parliament and the Council of The European Union, 2004) stated this under Chapter VII: Storage and Transport, 1(a): "Unless other specific provisions provide otherwise, postmortem inspection must be followed immediately by chilling in the slaughterhouse to ensure a temperature throughout the meat of not more than 3°C for offal and 7°C for other meat along a chilling curve that ensures a continuous decrease of the temperature." Brown et al. (2009) elaborated more on this issue stating that the temperature requirement for chilling in the deep round muscles does not specify a time requirement to reach it. Bowater (2001) stated that it took a two-day chilling program using conventional carcass-chilling systems to achieve a deep leg temperature of 7°C. Regardless of a lack of a time requirement to achieve this chilled-carcass temperature, reducing the body heat from a carcass to 7°C internal temperature, especially in carcasses from cattle, can be a major task.

Strydom and Buys (1995) referred to the South African Hygiene Act and stated that "no post-chilling bone temperature is stipulated; however, a minimum post-mortem chilling time of 16 hours, under specified environmental conditions of temperature and air velocity, is as follows: While the air temperature should not be in excess of 7°C initially, the air temperature in the terminal stages of chilling shall be maintained between -1 and +2°C; average air velocity over the carcass should be maintained at about 0.75 m/sec."

For the most part, blast chilling consists of rapid air movement with temperatures around 28 to 30°F. However, temperatures may be lower than this at the start of the chilling process because once the cooler begins to fill with hot carcasses, the temperature of the cooler will increase steadily until enough heat is removed from the carcasses to cause some temperature equilibrium to occur. Beef carcass sides are placed on rails spaced at least three feet apart and often are "cross shanked," which means that sides are alternated so that the dorsal aspect of one side is aligned with the ventral aspect of the next side throughout the rail spacing. In this system, carcass sides can be placed more closely together than if they are placed in the traditional side-by-side configuration along the split vertebral column.

Although it would seem that placing hot carcasses into the blast chiller and then removing the chilled carcasses from the chiller would be on a "first in, first out" basis, this is almost never the case. The challenge beef processing plants face is that when so many freshly harvested carcasses are placed into the blast chiller, the temperature differential between the hot carcasses and the cold-chill room produces condensation, which when formed on surfaces of the ceiling, rail supports, and the rails themselves presents regulatory issues related to sanitation, especially if this condensation drips onto carcasses. The actual practice of loading the initial blast chiller may include placing freshly harvested beef carcasses throughout the blast chiller on rails that may also include some chilled carcasses as a way of balancing the heat load more appropriately. After initial chilling of the freshly harvested beef carcasses, fully chilled carcasses on the same rail are removed for sorting and further processing, which frees up rail space for additional hot carcasses to be placed.

A few large U.S. plants have incorporated a long hallway or have developed somewhat of a serpentine-powered rail system from the harvest floor to the blast-chill cooler whereby the hot beef carcasses travel distances long enough and over sufficient time to dissipate some of their initial heat. This minimizes condensation that may be created when hot carcasses are placed in the hot box. Obviously, this is a costly partial solution to condensation; therefore, only plants where space and capital improvement budgets are available have taken this kind of approach.

Spray chilling

Widespread spray chilling of beef carcasses is a relatively recent practice in the United States largely because a patented process by Swift & Company (Hansen et al., 1973) called Clor-Chil (Heitter, 1975) required royalty payments for its use and limited it to company-owned processing plants and to those willing to pay the royalties to use it. Clor-Chil was a chilled-water spray with chlorine in it, which served as an antimicrobial. The abstract of the disclosure states:

> A method of chilling carcass meat to substantially reduce the shrinkage loss attributable to the moisture evaporation from freshly killed animals so as to maintain the freshness and bloom of the meat and to substantially reduce the bacterial count.

During the 1980s, either this patent expired or the process was modified enough to avoid infringement issues and beef processors began to incorporate the use of spray chilling routinely during the initial phases of beef chilling. It should be noted that the spray chilling process evolved to discontinue the use of chlorine, which at some point was disallowed for meat products shipped to Canada. Those processors that began using spray chilling were interested primarily in using moisture to minimize carcass weight shrinkage versus in the antimicrobial properties of chlorine. As spray chilling became more widespread, the most common practice was for the intermittent spray of cold water to be applied for approximately the first 14 hours or so of chilling with the remaining time (approximately 10 hours if following a 24-hour chilling process) necessary for the surface to dry sufficiently so that a grader's ink could be applied to the carcass without becoming illegible. During the 1980s, most beef carcasses were still rolled with the grading stamps to signify U.S. Prime, U.S. Choice, etc.; however, in recent years, grade identification is mostly achieved through the grade labeling program on vacuum packages and boxed beef. Strydom and Buys (1995) reported that if spray chilling was used for 17 hours before ending the chilling process at 18 hours (only one hour of drying time), the carcasses appeared to be pale and wet, which gives further credence that the spray chilling system must be terminated at some point in the blast chiller so that sufficient surface-drying time can occur before carcasses move through further production.

For the past three decades, spray chilling has been widespread and commonplace in U.S. beef processing plants and follows the same general schedule of approximately 14 hours of intermittent sprays. Beef processors in at least two countries, the United States (U.S. Department of Agriculture, 1993) and New Zealand (New Zealand Food Safety Authority, 2007), are required to develop and implement quality control programs and meet other regulatory requirements to ensure that carcass weight gains do not occur when using spray chilling systems.

Spray chilling's impact on preventing carcass shrinkage is well documented. Hippe et al. (1991) found that spray chilling was effective in reducing carcass shrinkage in both Choice steers and lean cows. Spray chilling has been investigated on a variety of species including red deer. As would be expected, carcass weight loss during the chilling process was minimized by the use of spray chilling (Wiklund et al., 2010). In a study from Brazil, de Mesquita et al. (2003) did not observe differences in carcass weights between treatments, but did find differences in moisture content of the carcass meat. Kinsella et al. (2006) investigated the use of a "Jasca" air humidification system to provide intermittent water spraying of carcass sides and found a significant reduction in weight loss (0.19% average) without increasing the surface populations of certain bacterial populations.

Spray chilling does not always impact carcass-temperature decline significantly. Hippe et al. (1991) did not find that chill rates were increased when using spray chilling. Wiklund et al. (2010) found a significant, final, carcass-surface-temperature difference between spray-chilled and air-chilled red deer carcasses although they did not find a deep-leg-temperature difference between the two treatments. Similar results were found by Strydom and Buys (1995) in that the *M. longissimus thoracis* (ribeye) chilled more rapidly in the spray-chilled carcass-sides treatment compared to the conventionally chilled sides, but that the *M. semimembranosus* (inside round) did not.

Although no carcass or subprimal shrinkage information was reported, Hamby et al. (1987) used the spray-chilling process with lactic and acetic acids as an antimicrobial treatment and found significant reductions in spoilage microorganisms when spray chilling incorporated these organic acids as part of this process. However, it should be noted that typical spray-chill systems in the United States use only chilled water without added chlorine.

Cooler storage/staging before fabrication

Over the past three decades, as beef processing plants in the United States moved towards more fully integrated boxed-beef production facilities and away from shipping carcasses, the need to have more storage space for carcasses became apparent. Two primary reasons for this were: (1) carcasses had to be chilled more adequately when they were destined for boxed beef or the shelf life of vacuum-packaged beef would be compromised, and (2) grade and other labeling/branding programs necessitated that enough carcasses be available within each category so that during fabrication production, sufficient carcasses would be broken down into primals, subprimals, and trimmings to minimize the number of times that production would have to be halted. This break in fabrication production was designed to create a clean-out gap between programs to allow a changeover to the boxes and labels for the next category. The chilling process was broken into two different phases: (1) the initial hot box or blast-chilling phase (about 24 hours), and (2) a further chilling phase after grade sortation (12 to 24 hours) in what are referred to as sales or staging coolers. Blast chilling removed most of the heat from the carcass, but the temperature decline in the deep round took longer so the additional 12 to 24 hours was necessary to drop the temperature to 45°F or lower (this was a common temperature used by many beef processors as the point at which carcasses could be released for fabrication). With this two-step chilling/staging process, additional coolers were built by many of the U.S. beef processors because approximately twice as much space was required to accommodate the volume of carcasses from the day's harvest as well as the additional space required for the previous day's graded and sorted carcasses as they awaited fabrication.

During the 1990s, most major U.S. beef processors decided to increase the length of time carcasses were in the initial blast-chilling areas and decrease the length of time the carcasses were in the sales/staging coolers. It made sense to chill these carcasses longer before they were ribbed and presented for grading because the additional time would benefit the development of the quality-indicating characteristics related to the U.S. Department of Agriculture quality grade (Calkins et al., 1980), and it was still going to require about 36 to 48 hours from harvest to fabrication. Extending the chilling time before ribbing and grading resulted in several benefits. Without the rush to chill carcasses rapidly before they were removed from blast chillers, carcasses began to be chilled more slowly and more uniformly so that carcass chilling was conducted with greater care. Prior to this, it was not uncommon to find carcasses that had frozen shanks, plates, and flanks when they exited the blast cooler because chilling was so extreme. Now with a longer time period available, the blast coolers continue to remove the internal heat from the carcass, but without the negative effects of frozen extremities and thin meat areas that occurred when air velocities and temperatures were set to accomplish maximum heat removal in as short a time as possible. Carcasses received quality grades more indicative of their actual quality attributes and time was available to sort carcasses into the grade, brand, and weight categories necessary for fabrication. In fact, this change in chilling methodology was cited by Brooks et al. (2000) as one of the theories for improved beef tenderness ratings in the National Beef Tenderness Survey compared to the previous survey reported by Morgan et al. (1991).

Alternatives to Traditional Chilling

Delayed chilling

If cold shortening/toughening is caused by too low chilling temperatures, then it stands to reason that chilling at a temperature less conducive to cold shortening or delaying the beginning of the chilling process may provide some protection against toughness caused by the chilling process. A number of studies exist that have evaluated the impact of delayed chilling on beef tenderness and other quality factors (Aberle and Judge, 1979; Elgasim et al., 1981; Razminowicz et al., 2008; Rosenvold et al., 2008; Kim et al., 2012), and brief discussions of these studies follow.

In addition to investigating the tenderness of beef from carcasses suspended by the Achilles' tendon or by the pelvic bone, Aberle and Judge (1979) also chilled carcasses at –2.2°C, 3.3°C, and 8.9°C to determine the impact of these chilling conditions on meat tenderness. No difference in palatability traits were observed among these different temperature treatments, and the authors believed that the external fat thickness of these carcasses was sufficient to prevent cold shortening in their study.

Elgasim et al. (1981) evaluated combinations of electrical stimulation (ES versus Non-ES) and chilling methods (2°C versus 16°C) on multiple factors including tenderness. They observed that electrical stimulation had a greater impact on meat tenderness than did chilling temperature. Interestingly, Razminowicz et al. (2008) found that electrical stimulation was more effective than delayed chilling (holding carcasses at 15°C for 90 minutes before normal chilling) in increasing the tenderness of grass-fed beef. It could be that electrical stimulation more effectively prevents cold shortening than delayed chilling. Further supporting this concept is the work of Rosenvold et al. (2008) who investigated various combinations of electrical stimulation, wrapping, and pre-rigor temperature (15°C or 35°C) on different parameters of *M. longissimus lumborum* (strip loin). Time to reach rigor differed greatly for the various combinations of electrical stimulation and pre-rigor temperature: the ES, 35°C treatment reached rigor in 4.6 hours, whereas the non-ES, 15°C treatment reached rigor at 22.4 hours. However, it was the electrical stimulation treatment that offered the greatest protection against toughening as a result of either heat shortening or cold shortening.

Kim et al. (2012) followed up on the work of Rosenvold et al. (2008) with a study on various treatments involving electrical stimulation, wrapping, and chilling temperatures. Their findings indicated that storing meat at a high pre-rigor temperature of 38°C accelerated the onset of rigor, but this induced more protein denaturation as a result of the rapid pH fall while muscle temperatures were still high. These conditions also impacted μ-calpain autolysis and desmin degradation, which would interfere with postmortem tenderization of beef and may be the causative factor in heat-induced toughening rather than heat shortening.

It is clear that delayed chilling or any system designed to allow postmortem temperatures to remain high in order to prevent cold shortening/toughening may create other unintended consequences with respect to tenderness, quality, and functionality of meat.

Rapid chilling

Due to the mass of muscle and fat tissue in beef carcasses, more rapid chilling has been an area of research focus for some time (Bowling et al., 1987; Gigiel et al., 1989; Joseph, 1996; Aalhus et al., 2001; Bowater, 2001; Van Moeseke et al., 2001; Aalhus et al., 2002; Zhu et al., 2011). Key learnings from these articles follow.

Joseph (1996) described very fast chilling as meat that "is chilled to –1°C by 5 hours postmortem," and this article detailed a European Union-funded collaborative study in this area. Two interesting points were made:

(1) Very fast chilling caused the release of calcium ions, which were important in stimulating proteolysis, but (2) Very fast chilling stimulated contraction, which resulted in tougher meat. Joseph (1996) discussed some options for ways to increase chilling times without the negative tenderness effects that the very fast chilling system can cause, but noted that the increased chilling time system was not ready for full-scale adoption.

Van Moeseke et al. (2001) evaluated a system of very fast chilling on *M. semitendinosus* (eye of round) that included brine chilling or freezing. In both cases, cold shortening occurred and the sarcomere lengths were reduced by more than 30% compared to traditional chilling. Very fast chilling resulted in tougher meat than what was produced under traditional chilling.

Aalhus et al. (2002), in another study of very fast chilling, compared beef carcasses subjected to blast-chilling conditions of either –20°C or –35°C to traditional chilling of 2°C for 24 hours. Carcasses from the very fast chilling protocols were removed at different time intervals to be further chilled under the traditional chilling method. Aalhus found that regardless of the chilling system evaluated, no internal temperature of the round met the targeted temperature (approximately –1°C within 5 hours postmortem), but the *M. longissimus thoracis* (ribeye) did reach this target. The authors also found that within a shorter aging period (6 days), beef from the –35°C chilling treatment was more tender than beef from the traditional chilling regime. However, this improvement in tenderness disappeared when steaks were evaluated after 21 days of aging. Their conclusions stated that very fast chilling may be useful in reducing aging requirements for beef. Other findings comparable to what Bowling et al. (1987) found, such as decreased carcass shrinkage, slower rate of pH decline, and an increased perception of marbling were observed.

Zhu et al. (2011) explored the use of a conventional-chilled system (0-4°C, air speed 0.5 m/s for 24 hours) versus a rapid-chilled system (–14° ± 1°C, air speed 3 m/sec for 2 hours before placing carcasses into a conventional-chilled system until 24 hours postmortem) on the tenderness of beef from Chinese bulls. The researchers used low-voltage electrical stimulation on the carcasses before the sides were allocated to one of the two chilling treatments. They found an increased rate of temperature decline and a decreased rate of pH decline (both $P < 0.05$) for rapidly chilled carcasses, and the use of electrical stimulation prevented tenderness problems in rapidly chilled carcasses.

Bowling et al. (1987) investigated a novel rapid-chill system whereby carcasses were chilled at –70°C for 5 hours, held at +16°C for 4 hours, and held at 1°C for 15 hours and compared this to conventional chilling (–7°C for 24 hours). Rapid chilling resulted in less carcass shrinkage, darker lean with higher marbling scores, and steaks with longer sarcomeres, lower shear-force values, and higher sensory-panel tenderness scores. The literature review for this document revealed no other research project that subjected beef carcasses to such extreme temperatures so early in the postmortem time period, and no other rapid-chilling research project has ever resulted in such positive shrinkage and palatability ratings when compared to a conventional system. It appears this protocol has never been implemented commercially or studied again.

Aalhus et al. (2001) stated that rapid chilling had several economic advantages including reduction of cooling times, increased product turnover, and decreased shrinkage. Their study evaluated rapid chilling combined with electrical stimulation on the quality factors of the *M. semimembranosus* (inside round) and *M. longissimus lumborum* (strip loin) from beef carcasses that ranged in external fat thickness. The negative effects of rapid chilling — darker and tougher meat — were somewhat mitigated with the use of electrical stimulation. As would be expected, the negative consequences of using a rapid-chilling system would have to be addressed to realize the possible economic advantages commercially.

Gigiel et al. (1989) compared two different systems: fast chilling to reduce shrinkage and to achieve more rapid turnover and slow chilling to avoid cold shortening. The authors noted that both systems accomplished their goals, but possible tenderness problems existed in the rapidly chilled carcasses, and the slow-chilled carcasses required a much longer time period to reach the internal temperature requirements necessary for domestic or export marketing.

Bowater (2001) discussed a number of chilling systems that could be used on meat from a variety of species including beef carcasses. For one of the trials, beef carcasses were chilled with an initial air temperature of –15°C and a velocity of 3 m/sec across the hindquarter for approximately five hours before the refrigeration unit was turned off and the carcasses were allowed to equilibrate so that at the end of the 24-hour-period, the carcasses reached 7°C to meet European Union regulations. The author stated that using this system versus the traditional system resulted in a reduction of shrinkage from 1.2% to 0.6%, which represented a significant yearly savings. It should be noted that this system did not use spray chilling, which may have accomplished a similar reduction in shrinkage without the increased energy expenditures necessary to operate a rapid-chilling system.

Vascular chilling

Although not widely used in the beef industry, a few studies have investigated vascular chilling as a method to increase the chilling rate of carcasses. This system uses the vascular system as a conduit into the deep tissue so that pre-chilled water (Wang et al., 1995) or a mixture of pre-chilled water with a low concentration of salt (Brown et al., 2009) can be delivered during the early postmortem period immediately following carcass exsanguination. This patented process (Lawler, 2010) is called "Rinse & Chill™" and is marketed by MPSC, St. Paul, Minnesota (MPSC, 2012). Additional details about the process can be found at Meat Industry Services (2006).

Brown et al. (2009), using freshly slaughtered lambs as their model for the incorporation of vascular chilling, were able to reduce the time required to achieve deep leg temperatures of 20°C from 2.6 to 1.3 hours, which is a significant time reduction. Wang et al. (1995) found that vascular chilling combined with chilling in a conventional chiller resulted in a reduction ($P < 0.05$) in time to reach 10°C in the *M. longissimus thoracis* (ribeye) from 9.9 to 5.5 hours; however, no decrease in the total chilling time (21.8 versus 20.4 hours; $P > 0.05$) was observed for the deep *M. semimembranosus* (inside round) between the two treatments.

Vascular chilling may offer an innovative way for beef carcasses to be chilled; however, consumer perception and added costs are likely barriers to successful implementation.

Impact on Quality Factors

Duration of chilling before grading presentation

In the United States, beef quality is still determined by evaluating the ribeye muscle *(M. longissimus thoracis)* at the 12th rib on a chilled carcass side. Even today with the advances in instrument grading, the quality-determining factors are still evaluated on the chilled surface of the exposed muscle sometime between 24 and 48 hours postmortem.

The study by Calkins et al. (1980) on postmortem conditions affecting beef grading is addressed in other sections of this paper, but the information is vital in understanding the importance of adequate chilling before ribbing and presenting beef carcasses for grading. Several factors impact optimum quality grading: (1) rigor mortis must be fully developed in the ribeye muscle so all regions, especially on the dorsal area near the subcutaneous fat, are in full rigor, (2) the conversion of muscle glycogen to lactic acid must be complete so the muscle pH is about 5.6 with the resultant bright, cherry red color so often described in the industry as most desirable for beef, (3) the ribeye must be chilled sufficiently (probably less than 4°C) so the intramuscular fat or marbling is set and contrasts well with the lean, making it visibly evident to the human eye or instrument depending on the method of grading employed, and (4) the length of time between ribbing and grading (at least 10 minutes, but may be longer depending on meat temperature) must allow for "blooming" to occur.

Though the importance of the parameters that impact maximum quality-grade development is well recognized, research is limited in this area. Studies to investigate the impact of environmental conditions (Johnson et al., 1986), lighting type and intensity (Kropf et al., 1984), and postmortem chilling times and electrical stimulation on grading (Calkins et al., 1980) are examples of the rather limited research that has been conducted in the past. The focus of more recent studies has been on some aspect of instrument grading (Shackelford et al., 2012a; Shackelford et al., 2012b) rather than conditions that may be conducive for appraisal of traditional marbling-based visual grading.

Electrical stimulation

The discovery that the postmortem application of electrical stimulation to beef carcasses resulted in improvements in quality-indicating characteristics of the lean was truly a moment of scientific serendipity when both electrically stimulated and control ribeyes were first found to differ in quality attributes (Savell, 1985). Smith et al. (1977) were the first to report quality-indicating characteristic improvements for electrically stimulated beef (which could translate to USDA quality-grade improvements and resulting increases in beef carcass value), and the demand for actual in-plant demonstrations greatly escalated along with the implementation of electrical stimulation in the United States (Stiffler et al., 1982; Savell, 1985).

In the late 1970s, with the increased interest in implementing electrical stimulation in beef processing facilities and the recognition of the potential for improving the quality-indicating/USDA quality-grading characteristics of beef carcasses, leaders in the U.S. Department of Agriculture's Meat Grading Branch were concerned electrical stimulation might be artificially improving the marbling, color, and firmness attributes beyond the inherent grading ability of the carcass. Texas A&M University researchers conducted a study (Calkins et al., 1980) designed to better address this concern. In the industry, it was well known that beef carcasses chilled over the weekend — cattle that were harvested on Friday or Saturday and were graded on Monday — had the highest percentage of U.S. Choice and U.S. Prime versus those chilled during the week. Thus, the term, "weekend cattle," was used to describe the phenomenon of the highest carcass grades being received on Mondays. It appeared that this was exactly what was happening with electrical stimulation: Carcasses electrically stimulated and graded after a 24-hour chill were comparable in quality-grade factors to those graded after a 48-hour chill (Calkins et al., 1980), and the greatest advantage of electrical stimulation in improving quality-grade factors was for those carcasses chilled and graded at less than or equal to 24 hours postmortem.

It is important to understand the pressures on throughput and space limitations that beef processors at this time faced. It should be noted that today's beef processors face the same challenges. Before harvest could begin, the hot box had to have ample room in it for the freshly harvested hot carcasses to enter. In some processing plants, this may have meant that all of the chilled carcasses were removed from the hot box and were taken to the sales cooler where they would have been ribbed and graded either on the chain (moving past the grader who was on a well-lit stand) or placed on stationary rails where the grader would have walked by and applied the grade stamp to them. The graded carcasses would have been identified for further merchandising and marketing and would have been either shipped out in carcass form to customers who could handle such entities or would have been fabricated into some early form of vacuum-packaged boxed beef or hanging primals (chucks, ribs, loins or rounds). At the end of the production day, the sales cooler would have been emptied and readied to begin the process again the next day with the transfer of chilled carcasses from the previous day's harvest. The need to ready the hot box so that the harvest floor could begin production forced, at times, short chill times (sometimes as brief as 14 hours for those cattle slaughtered at the end of the day) so that the hot box had room to start the next day's slaughter. Electrical stimulation was especially effective in minimizing quality issues for those carcasses not sufficiently chilled, in time or temperature, before being presented for grading.

Challenges with Increasing Beef Carcass Weights and Sizes

Trends in carcass weight and size

Even casual observers of the U.S. beef industry will recognize that live cattle and carcass weights have increased substantially over the past several years. This has caused challenges for the retail and foodservice sectors related to increased sizes and weights of beef

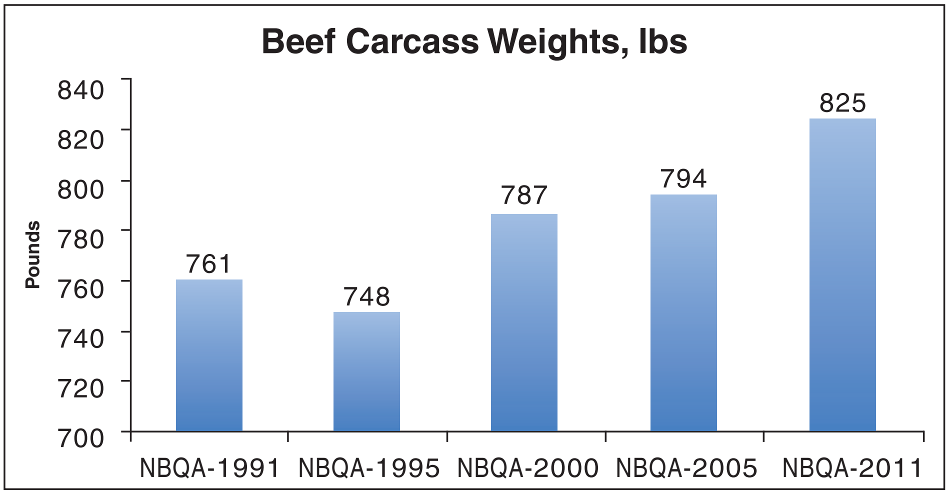

Figure 1. Beef carcass weight (pounds) increases as measured in the checkoff-funded National Beef Quality Audits

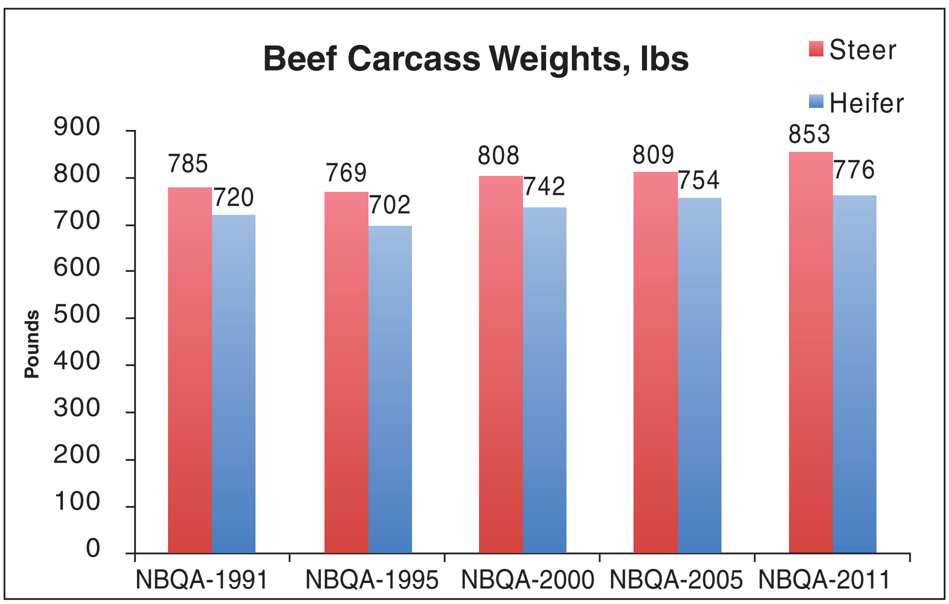

Figure 2. Beef carcass weight (pounds) increases, stratified by steers and heifers, as measured in the checkoff-funded National Beef Quality Audits

subprimals that are more difficult to merchandise to consumers. Presented in Figure 1 are overall average carcass weights for the beef carcasses sampled in all the National Beef Quality Audits (Lorenzen et al., 1993; Boleman et al., 1998; McKenna et al., 2002; Garcia et al., 2008; Moore et al., 2012). It is clear that carcass weights have increased over time and have averaged a two to three pound increase each year. Steer versus heifer carcass weights are reported in Figure 2. Lost in overall carcass averages (Figure 1) is the fact that steer carcass weights are about 60 pounds heavier than heifer carcass weights so chilling carcasses from steers can be even more challenging because of their above-average weights. Gray et al. (2012) reported that seasonal differences in carcass weights were observed. Heaviest carcass weights (steers and heifers combined) were observed in November and lightest carcass weights were observed in May. Not only do beef processors have to manage chilling requirements of increasingly heavier carcasses, but also they have to account for sex-class differences (steers versus heifers), seasonal differences (month-to-month variation), and maybe most importantly, variation within a production lot.

Increases in size are not limited to carcass weights only. As would be expected, ribeye areas have increased steadily (Figure 3) with an almost one square inch increase over 20 years. This increase in size challenges beef processors to achieve a uniform chill rate across this important value-determining muscle when presented for grading.

A very relevant factor in the 21st century in increasing carcass weights has been the development and adoption of growth enhancement technologies including implants and beta-adrenergic agonists. Delmore et al. (2010) presented a review of the recent work on cattle and carcass performance as affected by the beta-adrenergic agonist zilpaterol hydrochloride. Live animal weights were increased by about 20 pounds when cattle were fed zilpaterol hydrochloride, but carcass weights were increased by about 33 pounds, illustrating the repartitioning of nutrients between carcass and non-carcass components. How these growth enhancement technologies achieve this increase in carcass weight above that of live animal weight is still to be determined, but this additional 33 pounds of carcass weight must be chilled using the same systems that were originally designed for lighter carcasses decades ago.

The increased muscle mass appears to be focused especially in the rounds of the live animal and thus the rounds of carcasses from cattle administered beta-adrenergic agonists. These rounds appear to be larger, plumper, and thicker than their control counterparts. This is the case with feeding beta-adrenergic agonists to Holstein cattle where significant weight gains in the round (Boler et al., 2009) and size and shape changes in the loin (Lawrence et al., 2011) were observed. At this time, no known research exists related to how best to chill beef carcasses that are thicker muscled and heavier and this is a current need for the beef industry.

Addressing increased heat load with heavy carcasses

Blast-chill coolers have different numbers and lengths of rails so no set industry-wide standard exists (oftentimes, these vary even in the same plant based on original plant design and plant renovations that occurred over time). However, the following demonstrates some of the challenges with chilling heavier carcasses in blast-chill coolers designed for lighter-weight carcasses. If a blast-chill cooler had 10 rails with the capacity of 40 head per rail, then 400 beef carcasses would be in it when it was fully loaded. With a current average weight of 825 pounds per carcass, the total weight to be chilled would be 330,000 pounds. Assuming that beef carcass weights continue to increase about 2 pounds per year, in five years, this blast-chill cooler would be required to chill 334,000 pounds of beef (an additional 4,000 pounds) assuming that the same number of head could fit on the rails. For beef processors, the number of head processed per hour, per shift, per day, per week, etc., are the benchmarks they strive to meet with pounds of throughput obviously a very important factor in minimizing costs on a per-head or per-pound basis. At some point, though, increased carcass sizes and weights present operational challenges when space configuration begins to reduce capacity on a per-head basis because the sheer volume of what can be placed on a rail prevents the same number of head to be chilled in the same blast-chill cooler as before.

Conclusions and Recommendations

General

Most of the work on the impact of chilling on beef quality has been conducted over the past half century and coincides with the development of sophisticated commercial refrigeration systems designed for efficient heat removal. However, unintended consequences related to how exposure of the muscle to the cold temperatures in the time period between the death of the animal and completion of rigor mortis negatively impacted the ultimate palatability of the product. Foundational research conducted at the beginning of this time period is still very applicable to our understanding of the factors affecting the quality and palatability of beef.

Interestingly, two different research approaches on alternative chilling have evolved over the years: delayed chilling and rapid chilling. It would seem as though research would have been more targeted on either chilling carcasses more quickly or more slowly rather than having efforts in both areas. However, this dual approach to studying issues faced in the conversion of muscle to meat has yielded two very important points:

1. Proponents of delayed chilling felt this system would prevent cold shortening, but knew some product shrinkage would occur at a slower chill rate. However, they discovered that electrical stimulation would minimize the effects of cold shortening and allow more rapid chilling that would otherwise be imprudent to use without this important postmortem treatment.

2. Proponents of rapid chilling felt throughput and meeting important regulatory temperature thresholds were most important to the industry. Again, as was the case for the delayed-chilling researchers, the rapid-chilling investigators found the use of electrical stimulation would help prevent cold shortening so more rapid chilling could be employed without having negative consequences.

It may appear that electrical stimulation is an ideal solution, and it should be noted that if this technology had not been adopted to the extent that it has, beef quality and palatability would have suffered given the variation in chilling parameters used from plant to plant and country to country.

The other area of industry concern with the chilling process is the avoidance of carcass shrinkage. Since spray chilling of carcasses in the chilling process has virtually eliminated shrinkage, developing chill systems designed to reduce shrinkage is no longer necessary.

Chilling research gaps

Even with the findings listed above, it is clear that at least four research gaps on the topic of beef chilling remain. Funding projects in these areas would greatly benefit our understanding of the parameters necessary to produce high quality and safe beef. The research needs follow (in no particular order):

1. To evaluate chilling times, temperatures, and other parameters most conducive for developing beef quality/marketing/value-determining traits.

2. To develop best practices for chilling beef carcasses to ensure maximum food safety, appropriate product yield and quality, and optimized eating quality.

3. To understand how changes in compositional and dimensional aspects of beef carcasses from heavy cattle affect the chilling process.

4. To determine if a more targeted chilling system could be developed for the beef round primal.

Literature Cited

Aalhus, J. L., J. A. M. Janz, A. K. W. Tong, S. D. M. Jones, and W. M. Robertson. 2001. The influence of chilling rate and fat cover on beef quality. Can. J. Anim. Sci. 81: 321-330.

Aalhus, J. L., W. M. Robertson, M. E. R. Dugan, and D. R. Best. 2002. Very fast chilling of beef carcasses. Can. J. Anim. Sci. 82: 59-67.

Aberle, E. D., and M. D. Judge. 1979. Consumer acceptability and retail yield in beef after pelvic suspension and delayed chilling. J. Food Sci. 44: 859-861.

Bendall, J. R. 1973. The biochemistry of rigor mortis and cold-contracture. Pages 1-27 in Proc. European Meet. Meat Res. Workers, Paris, France.

Boleman, S. L., S. J. Boleman, W. W. Morgan, D. S. Hale, D. B. Griffin, J. W. Savell, R. P. Ames, M. T. Smith, J. D. Tatum, T. G. Field, G. C. Smith, B. A. Gardner, J. B. Morgan, S. L. Northcutt, H. G. Dolezal, D. R. Gill, and F. K. Ray. 1998. National Beef Quality Audit-1995: Survey of producer-related defects and carcass quality and quantity attributes. J. Anim. Sci. 76: 96-103.

Boler, D. D., S. F. Holmer, F. K. McKeith, J. Killefer, D. L. VanOverbeke, G. G. Hilton, R. J. Delmore, J. L. Beckett, J. C. Brooks, R. K. Miller, D. B. Griffin, J. W. Savell, T. E. Lawrence, N. A. Elam, M. N. Streeter, W. T. Nichols, J. P. Hutcheson, D. A. Yates, and D. M. Allen. 2009. Effects of feeding zilpaterol hydrochloride for twenty to forty days on carcass cutability and subprimal yield of calf-fed Holstein steers. J. Anim. Sci. 87: 3722-3729.

Bowater, F. J. 2001. Rapid carcass chilling plants compared to conventional systems. Accessed May 28, 2012. http://www.fjb.co.uk/wp-content/themes/fjb/publications/Rapid%20Carcass%20Chilling%20vs%20Conventional.pdf.

Bowling, R. A., T. R. Dutson, G. C. Smith, and J. W. Savell. 1987. Effects of cryogenic chilling on beef carcass grade, shrinkage and palatability characteristics. Meat Sci. 21: 67-72.

Brooks, J. C., J. B. Belew, D. B. Griffin, B. L. Gwartney, D. S. Hale, W. R. Henning, D. D. Johnson, J. B. Morgan, F. C. Parrish, Jr., J. O. Reagan, and J. W. Savell. 2000. National Beef Tenderness Survey-1998. J. Anim. Sci. 78: 1852-1860.

Brown, T., R. I. Richardson, C. A. Wilkin, and J. A. Evans. 2009. Vascular perfusion chilling of red meat carcasses – A feasibility study. Meat Sci. 83: 666-671.

Calkins, C. R., J. W. Savell, G. C. Smith, and C. E. Murphey. 1980. Quality-indicating characteristics of beef muscle as affected by electrical stimulation and postmortem chilling time. J. Food Sci. 45: 1330-1332.

de Mesquita, A. J., C. S. Prado, V. F. F. Bueno, J. R. G. Mansur, R. B. S. Neves, I. A. Nunes, M. E. Lage, and A. N. de Oliveira. 2003. The effects of spray chilling associated to conventional chilling on mass loss, bacteriologycal and physico-chemical quality of beef carcasses. Ciência Animal Brasileira 4: 145-153.

Delmore, R. J., J. M. Hodgen, and B. J. Johnson. 2010. Perspectives on the application of zilpaterol hydrochloride in the United States beef industry. J. Anim. Sci. 88: 2825-2828.

Elgasim, E. A., W. H. Kennick, L. A. McGill, D. F. Rock, and A. Soeldner. 1981. Effects of electrical stimulation and delayed chilling of beef carcasses on carcass and meat characteristics. J. Food Sci. 46: 340-343.

Garcia, L. G., K. L. Nicholson, T. W. Hoffman, T. E. Lawrence, D. S. Hale, D. B. Griffin, J. W. Savell, D. L. VanOverbeke, J. B. Morgan, K. E. Belk, T. G. Field, J. A. Scanga, J. D. Tatum, and G. C. Smith. 2008. National Beef Quality Audit-2005: Survey of targeted cattle and carcass characteristics related to quality, quantity, and value of fed steers and heifers. J. Anim. Sci. 86: 3533-3543.

Gigiel, A. J., P. Collett, and S. J. James. 1989. Fast and slow beef chilling in a commercial chiller and the effect of operational factors on weight loss. Int. J. Refrig. 12: 338-349.

Gray, G. D., D. S. Hale, C. R. Kerth, D. B. Griffin, J. W. Savell, T. E. Lawrence, K. E. Belk, D. R. Woerner, J. D. Tatum, D. L. VanOverbeke, G. G. Mafi, R. J. Delmore, Jr., S. D. Shackelford, D. A. King, and T. L. Wheeler. 2012. National Beef Quality Audit – 2011: Survey of instrument grading assessments of beef carcass characteristics. J. Anim. Sci. (Available online September 5, 2012).

Hamby, P. L., J. W. Savell, G. R. Acuff, C. Vanderzant, and H. R. Cross. 1987. Spray chilling and carcass decontamination systems using lactic and acetic acid. Meat Sci. 21: 1-14.

Hannula, T., and E. Puolanne. 2004. The effect of cooling rate on beef tenderness: The significance of pH at 7 °C. Meat Sci. 67: 403-408.

Hansen, R. R., T. A. Ray, and G. M. Reimer. 1973. Carcass chilling process. United States Patent 3,745,026.

Heitter, E. F. 1975. Clor-chil. Pages 31-32 in Proc. Meat Ind. Res. Conf., Chicago, IL. American Meat Institute Foundation, Arlington, VA.

Hippe, C. L., R. A. Field, B. Ray, and W. C. Russell. 1991. Effect of spray chilling on quality of beef from lean and fatter carcasses. J. Anim. Sci. 69: 178-183.

Johnson, D. D., J. W. Savell, C. E. Murphey, D. M. Stiffler, and H. R. Cross. 1986. Postmortem environmental factors affecting beef carcass lean maturity and marbling evaluations. J. Food Qual. 8: 253-264.

Joseph, R. L. 1996. Very fast chilling of beef and tenderness—a report from an EU concerted action. Meat Sci. 43, Supplement 1: 217-227.

Kim, Y. H. B., A. Stuart, G. Nygaard, and K. Rosenvold. 2012. High *pre rigor* temperature limits the ageing potential of beef that is not completely overcome by electrical stimulation and muscle restraining. Meat Sci. 91: 62-68.

Kinsella, K. J., J. J. Sheridan, T. A. Rowe, F. Butler, A. Delgado, A. Quispe-Ramirez, I. S. Blair, and D. A. McDowell. 2006. Impact of a novel spray chilling system on surface microflora, water activity and weight loss during beef carcass chilling. Food Micro. 23: 483-490.

Kropf, D. H., M. E. Dikeman, M. C. Hunt, and H. R. Cross. 1984. Lighting type and intensity effects on beef carcass grade factors. J. Anim. Sci. 59: 105-108.

Lawler, C. E., Jr. 2010. Meat processing. United States Patent 7,666,074 B2.

Lawrence, T. E., D. M. Allen, R. J. Delmore, J. L. Beckett, W. T. Nichols, M. N. Streeter, D. A. Yates, and J. P. Hutcheson. 2011. Technical Note: Feeding zilpaterol hydrochloride to calf-fed Holstein steers improves muscle conformation of top loin steaks. Meat Sci. 88: 209-211.

Locker, R. H. 1960. Degree of muscular contraction as a factor in tenderness of beef. J. Food Sci. 25: 304-307.

Locker, R. H. 1985. Cold-induced toughness of meat. Pages 1-44 in Advances in Meat Research: Volume 1 – Electrical Stimulation. A. M. Pearson and T. R. Dutson, eds. AVI Publishing Company, Inc., Westport, CT.

Locker, R. H., and C. J. Hagyard. 1963. A cold shortening effect in beef muscles. J. Sci. Food. Agric. 14: 787-793.

Lorenzen, C. L., D. S. Hale, D. B. Griffin, J. W. Savell, K. E. Belk, T. L. Frederick, M. F. Miller, T. H. Montgomery, and G. C. Smith. 1993. National Beef Quality Audit: Survey of producer-related defects and carcass quality and quantity attributes. J. Anim. Sci. 71: 1495-1502.

McKenna, D. R., D. L. Roeber, P. K. Bates, T. B. Schmidt, D. S. Hale, D. B. Griffin, J. W. Savell, J. C. Brooks, J. B. Morgan, T. H. Montgomery, K. E. Belk, and G. C. Smith. 2002. National Beef Quality Audit-2000: Survey of targeted cattle and carcass characteristics related to quality, quantity, and value of fed steers and heifers. J. Anim. Sci. 80: 1212-1222.

Meat Industry Services. 2006. Rinse & Chill. Food Science Australia, a joint venture of CSIRO & the Victorian Government, CSIRO Food and Nutritional Sciences. Accessed May 28, 2012. http://www.meatupdate.csiro.au/new/Rinse%20and%20Chill.pdf.

Moore, M. C., G. D. Gray, D. S. Hale, C. R. Kerth, D. B. Griffin, J. W. Savell, C. R. Raines, K. E. Belk, D. R. Woerner, J. D. Tatum, J. L. Igo, D. L. VanOverbeke, G. G. Mafi, T. E. Lawrence, R. J. Delmore, Jr., L. M. Christensen, S. D. Shackelford, D. A. King, T. L. Wheeler, L. R. Meadows, and M. E. O'Connor. 2012. National Beef Quality Audit–2011: In-plant survey of targeted carcass characteristics related to quality, quantity, value, and marketing of fed steers and heifers. J. Anim. Sci. (Available online September 5, 2012).

Morgan, J. B., J. W. Savell, D. S. Hale, R. K. Miller, D. B. Griffin, H. R. Cross, and S. D. Shackelford. 1991. National Beef Tenderness Survey. J. Anim. Sci. 69: 3274-3283.

MPSC. 2012. Rinse & Chill™: Revolutionizing the Meat Processing Industry. Accessed May 28, 2012. http://mpscinc.com/home.html.

New Zealand Food Safety Authority. 2007. Draft amended New Zealand standard for spray chilling – Large mammals and large birds. Accessed May 28, 2012. http://www.foodsafety.govt.nz/elibrary/industry/spray chilling-large-discussion-paper/2007-spray chilling-draft.pdf.

Razminowicz, R. H., M. Kreuzer, and M. R. L. Scheeder. 2008. Effect of electrical stimulation, delayed chilling and post-mortem aging on the quality of *M. longissimus dorsi* and *M. biceps femoris* of grass-fed steers. J. Sci. Food. Agric. 88: 1344-1353.

Rosenvold, K., M. North, C. Devine, E. Micklander, P. Hansen, P. Dobbie, and R. Wells. 2008. The protective effect of electrical stimulation and wrapping on beef tenderness at high *pre rigor* temperatures. Meat Sci. 79: 299-306.

Savell, J. W. 1985. Industrial applications of electrical stimulation. Pages 219-236 in Advances in Meat Research: Volume 1 – Electrical Stimulation. A. M. Pearson and T. R. Dutson, eds. AVI Publishing Company, Inc., Westport, CT.

Savell, J. W., S. L. Mueller, and B. E. Baird. 2005. The chilling of carcasses. Meat Sci. 70: 449-459.

Shackelford, S. D., T. L. Wheeler, D. A. King, and M. Koohmaraie. 2012a. Field testing of a system for online classification of beef carcasses for longissimus tenderness using visible and near-infrared reflectance spectroscopy. J. Anim. Sci. 90: 978-988.

Shackelford, S. D., T. L. Wheeler, and M. Koohmaraie. 2012b. Technical note: Validation of a model for online classification of US Select beef carcasses for longissimus tenderness using visible and near-infrared reflectance spectroscopy. J. Anim. Sci. 90: 973-977.

Smith, G. C., T. R. Dutson, Z. L. Carpenter, and R. L. Hostetler. 1977. Using electrical stimulation to tenderize meat. Pages 147-155 in Proc. Meat Ind. Res. Conf., Chicago, IL. American Meat Institute Foundation, Arlington, VA.

Stiffler, D. M., J. W. Savell, G. C. Smith, T. R. Dutson, and Z. L. Carpenter. 1982. Electrical Stimulation: Purpose, Application and Results. Texas Agric. Ext. Serv. B-1375, Texas A&M Univ., College Station.

Strydom, P. E., and E. M. Buys. 1995. The effects of spray chilling on carcass mass loss and surface associated bacteriology. Meat Sci. 39: 265-276.

The Council of the European Communities. 1964. Council Directive of 26 June 1964 on health problems affecting intra-Community trade in fresh meat (64/433/EEC). Accessed May 28, 2012. http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=DD:I:1963-1964:31964L0433:EN:PDF.

The European Parliament and the Council of The European Union. 2004. Regulation (EC) No 853/2004 of the European Parliament and of the Council of 29 April 2004: Laying down specific hygiene rules for on the hygiene of foodstuffs. Accessed May 28, 2012. http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2004:139:0055:0205:EN:PDF.

U.S. Department of Agriculture. 1993. FSIS Directive 6330.1 -- Carcass spraying during chilling. Food Safety and Inspection Service, United States Department of Agriculture, Washington, DC. Accessed May 28, 2012. http://www.fsis.usda.gov/OPPDE/rdad/FSISDirectives/6330-1.pdf.

Van Moeseke, W., S. De Smet, E. Claeys, and D. Demeyer. 2001. Very fast chilling of beef: effects on meat quality. Meat Sci. 59: 31-37.

Wang, Y., D. S. McGinnis, R. R. Segado, and S. D. M. Jones. 1995. Vascular infusion of beef carcasses: effects on chilling efficiency and weight change. Food. Res. Int. 28: 425-430.

Wiklund, E., R. M. Kemp, G. J. leRoux, Y. Li, and G. Wu. 2010. Spray chilling of deer carcasses—Effects on carcass weight, meat moisture content, purge and microbiological quality. Meat Sci. 86: 926-930.

Zhu, L., S. Gao, and X. Luo. 2011. Rapid chilling has no detrimental effect on the tenderness of low-voltage electrically stimulated *M. longissimus* in Chinese bulls. Meat Sci. 88: 597-601.

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