THE CHILLING OF CARCASSES

J.W. Savell*, S.L. Mueller, B.E. Baird
Meat Science Section, Department of Animal Science
Texas A&M University, College Station, TX, 77843-2471, USA

Abstract

Biochemical processes and structural changes that occur in muscle during the first 24 hours postmortem play a great role in the ultimate quality and palatability of meat and are influenced by the chilling processes that carcasses are subjected to after the slaughter process. For beef and lamb, employing chilling parameters that minimize cold shortening is of the greatest importance and can be best addressed by ensuring that muscle temperatures are not below 10°C before pH reaches 6.2. For pork, because of the impact of high muscle temperatures and low pH on the development of pale, soft, and exudative (PSE) pork, a more rapid chilling process is needed to reduce PSE with the recommended internal muscle temperature 10°C at 12 h and 2 to 4°C at 24 h. Spray chilling, a system whereby chilled water is applied to carcasses during the early part of postmortem cooling, is used to control carcass shrinkage and to improve chilling rates through evaporative cooling. Delayed chilling can be used to reduce or prevent the negative effects of cold shortening; however, production constraints in high-volume facilities and food safety concerns make this method less useful in commercial settings. Electrical stimulation and alternative carcass suspension programs offer processors the opportunity to negate most or all of the effects of cold shortening while still using traditional chilling systems. Rapid or blast chilling can be an effective method to reduce the incidence of PSE in pork but extreme chilling systems may cause quality problems because of the differential between the cold temperatures on the outside of the carcass compared to the warm muscle temperatures within the carcass (i.e., muscles that are darker in color externally and lighter in color internally).

Keywords: Chilling; Cold shortening; Color; Meat tenderness; Shrinkage

* Corresponding author. Tel.: +1-979-845-3957; fax: +1-979-845-9454

E-mail address: j-savell@tamu.edu

Introduction

Most postmortem chilling processes of livestock carcasses are primarily employed to ensure food safety, maximize shelf-life, and reduce shrinkage with less emphasis on maintaining tenderness and color factors of the finished product. Whether chilling conditions are being met for regulatory requirements, as part of a critical control point of a HACCP system, or as best practices, other factors may be more important than those affecting direct consumer satisfaction of the product.

Heat dissipation initially was accomplished through natural means such that animals would have been slaughtered in cooler seasons and product would have been stored in caves as a way to prolong keeping quality. Throughout the centuries, more sophisticated means were developed to reduce the heat from freshly slaughtered animals. Today, advanced refrigeration systems are used throughout most parts of the world to accomplish the task of chilling carcasses during the critical time period after slaughter and through the development of rigor mortis. The efficiency of heat removal became so great that a half century ago, it was discovered that the process of chilling could negatively affect the eating quality of beef and lamb (Lawrie, 1998). Conversely, with increases in pork carcass weights and mass over the years, the challenge oftentimes for this species is to get the product chilled more rapidly to reduce problems associated with temperature/pH relationships. These two examples reflect the importance of developing and implementing chilling systems that are neither too severe nor too mild for the particular species involved.

This is a review of past and current research on the effects of chilling systems on meat quality. Special attention is given to the impact of chilling systems on tenderness, color, and shrinkage.

The first 24 h postmortem

There are many biochemical and structural events that take place in the first 24 h period after the animal is slaughtered and the muscle is converted to meat. This period greatly impacts meat tenderness and muscle color and is species-specific in how the initial cooling process results in positive or negative consequences in meat quality.

Rigor mortis

After exsanguination, glycolysis proceeds without oxygen and produces lactic acid as a result of anaerobic glycolysis. This creates a lactic acid build-up and therefore a decrease in pH. In a normal setting, muscles begin the process of rigor mortis where permanent cross-bridges, called actomyosin, are formed between the actin and myosin filaments. Rigor begins in normal meat at pH values of 5.7 to 5.8 (Hannula and Puolanne, 2004). During the first phase of rigor, the delay phase, the muscle is still extensible because there is still ATP available to bind with Mg2+, which helps disconnect the actin/myosin cross-bridges and in turn allows the muscles to relax. Creatine phosphate is depleted during this phase, which inhibits the phosphorylation of ADP into ATP. This causes a sharp decrease in ATP production, which is the signal of the start of the onset phase of rigor. Because there is little ATP available to break down the actin and myosin bonds, muscles cannot relax and therefore become inextensible (Aberle et al*.,* 2001).

pH decline

Normally, the pH in the muscle decreases from 7.0 upon slaughter to approximately 5.3 to 5.8 (Smulders, Toldra, Flores, & Prieto, 1992). In extreme cases, this decline can take only 1 h. The typical decline for pork is in the range of 6 to 12 h, and beef usually completes its pH decline in 18 to 40 h (Smulders et al., 1992). Howard and Lawrie (1956) suggested that the rate of pH decline has an inverse relationship to tenderness. As the pH drops, it nears the iso-electric point. At this point, all of the negatively and positively charged amino acid side chains equal, which causes the maximal attraction between the two. This attraction holds the filaments closely together and does not allow any water to get in, greatly reducing the water-holding capacity (Smulders et al., 1992).

Because pork experiences a quicker pH decline than other species, it is more likely to experience elevated temperatures during the onset phase of rigor, which can be detrimental to the myoglobin pigment. This

causes the myoglobin structure to be "open" and scatter light, creating a pale colored product (Lawrie, 1998). When pork is not able to hold water, it loses color and firmness. This condition is described as pale, soft, and exudative (PSE). Quickly lowering the temperature postmortem will decrease the velocity of these chemical and biochemical reactions, therefore decreasing the rate of pH decline (Lawrie, 1998). Blast chilling will help with the reduction of this type of reaction (Meisinger, 1999). Offer (1991) reported that the effect of chilling on PSE conditions is strongly dependent on the rate of pH decline. Meisinger (1999) suggested chilling pork to muscle temperatures of less than 10°C in 12 h, and 2 to 4°C in 24 h to reduce the occurrence of PSE.

Tenderness

Koohmaraie et al. (1987) suggested that at slaughter all animals with the same pre-slaughter treatments have the same tenderness level, and that differences in tenderness are created in the first 24 h post mortem. It has been shown that there is a decrease in tenderness of muscles before the aging process begins (Koohmaraie, 1996). Koohmaraie (1995) showed that there is a large amount of variation in tenderness (shear force) after one day of postmortem storage, and that maximum toughness has been observed in the range of 9 to 24 h (Koohmaraie, 1996). After 24 h, an increase in tenderness is observed as a result of enzymatic degradation of muscle tissue. Temperature of storage can affect this enzymatic degradation, as well as other factors including: pH, muscle fiber type, amount and degree of cross-linking of connective tissue, and animal species (Smulders et al., 1992). Enzymatic degradation is caused by proteolytic enzymes such as calpains and lysomal proteases (Smulders et al., 1992). The aging process typically takes 1 to 2 d in chicken, 3 to 6 in pork, and 10 to 20 d in beef (Smulders et al., 1992).

The cause of toughening during the first 24 h has been debated, and there are numerous studies that suggest various reasons for this increase. Goll, Geesink, Taylor, and Thompson (1995) proposed that toughening was caused by the change in strength of the binding state of the actin/myosin interaction and the possibility of this change causing severe shortening in the first 24 h postmortem. Another theory is myofibril fragmentation index (MFI), which has been shown to be useful in characterizing tenderness groups (Culler, Parrish, Smith, & Cross, 1978; Parrish, Vandell, & Culler, 1979). Culler et al. (1978) found that MFI accounted for more than 50% of the variation in loin steaks, and that the MFI was a more important effecter of tenderness than collagen solubility or sarcomere length. In addition, many studies have shown that sarcomere length does not affect tenderness (Culler et al., 1978; Smith, Kastner, Hunt, Kropf, & Allen, 1979; Seideman & Koohmaraie, 1987; and Shackelford, Koohmaraie, & Savell, 1994). However, the majority of the research suggests that sarcomere shortening is the causative factor of the decrease in tenderness of muscles from the time of slaughter to 24 h postmortem. Bouton, Harris, Shorthose, and Baxter (1973) found significantly shorter sarcomere lengths in the *M. semimembranosus, M. gluteus medius*, *M. biceps femoris*, and *M. longissimus dorsi* muscles, as well as significantly tougher *M. adductor* and *M. vastus lateralis* muscles conditioned at 0 to 1ºC compared to those conditioned at 15 to 16ºC. They also found strong relationships between Warner-Bratzler shear force values and sarcomere lengths when sarcomeres were shorter than 2.0 µm. Overall, Bouton et al. (1973) found that shear force values decreased exponentially as sarcomere lengths increased. When comparing "less tender" and "more tender" steaks, Davis, Smith, Carpenter, Dutson, and Cross (1979) found that "more tender" steaks had longer sarcomeres (based on mean values) than "less tender" steaks did. Davey, Kuttel, and Gilbert (1967) found that myofibrillar contraction state affected the level of tenderness that could be achieved by aging, and specifically at 40% contraction, there was almost no effect from aging. Marsh and Leet (1966) found that decreases up to 20% of the initial excised muscle do not have a significant effect on tenderness, but toughness increases rapidly with further shortening, peaking at 40%. However, after 40%, the meat becomes progressively more tender. In addition, it was found that meat with 55 to 60% shortening had Warner-Bratzler shear force values similar to those that shortened less than 20%. Marsh and Leet (1966) concluded that the degree of rigor onset at time of cold application is inversely related to the degree of cold shortening.

Cold shortening

Cold shortening has been studied since the 1960's (Locker, 1985). Locker and Hagyard (1963) defined cold shortening as a rapid decline in muscle temperature to less than 14 to 19ºC before the onset phase of rigor mortis. When carcasses are cooled quickly, they have the potential to be affected by cold-induced shortening and/or toughening. Temperature and pH relationships at the moment of onset of rigor can be considered the decisive factor of degree of cold shortening (Hannula & Puolanne, 2004). When the muscle temperature is

reduced to 0 to 15ºC before the onset phase of rigor, the sarcoplasmic reticulin cannot function properly and is unable to bind calcium, which leaves an abundance of calcium in the sarcoplasm. Because there is still ATP left in the muscle, the muscle contracts at a maximum level, causing the filaments to slide over one another basically eliminating the I-band of the sarcomere. At internal temperatures of 1 to 2ºC, the sarcoplasmic reticulin is the least functional (Aberle et al., 2001).

The relationship of cold shortening and sarcomere length to toughness was first demonstrated clearly by Herring, Cassens, and Briskey (1965) who showed the direct relationship of sarcomere length to fiber diameter and toughness. Their theory is that the more contracted the sarcomere, the larger the fiber diameter becomes due to sliding of the filaments over one another. After cooking, meat with larger fibers is tougher.

Muscle types vary in their potential to cold shorten, with red being more susceptible than white (Bendall, 1973). Because white muscle fibers tend to have higher amounts of glycogen, they experience a more severe drop in pH earlier in the rigor process. This is especially relevant with pork. Because pork is comprised primarily of white muscle fibers, they are not as affected by cold shortening to the extent as beef and lamb. Pork takes approximately 6 h to complete the rigor mortis process, and only 15 min to 1 h to begin the onset phase of rigor. The combination of time, temperature, and pH differs between and within muscle, and also between species (Hannula & Puolanne, 2004). This indicates that all muscles are not affected by cold shortening to the same degree (Hannula & Puolanne, 2004).

Additional sarcomere shortening conditions are thaw and heat rigor. These conditions are caused when carcasses are exposed to extreme cold or hot temperatures pre-rigor. Thaw rigor is a form of rigor mortis that develops when muscle that was frozen prerigor is thawed (Aberle et al., 2001). Aberle et al. (2001) stated that when this muscle is thawed, contraction is produced by the sudden release of Ca^{2+} into the sarcoplasm resulting in a physical shortening of 60 to 80 percent of the original muscle length and a release of large quantities of meat juices and severe toughening. Heat rigor occurs when muscles are maintained at elevated temperatures up to 50°C resulting in a rapid depletion of ATP, which creates severe shortening and the early onset of rigor (Aberle et al., 2001). The severity of these two extreme conditions show the importance of designing chilling conditions that do not negatively impact meat quality.

Prevention of cold shortening

Although there is no way to prevent rigor and the shortening of sarcomeres completely, there are ways to reduce the extent and toughening effects of this process before, throughout, and after slaughter. Fat thickness can play a significant role in the reduction of cold shortening during the chilling processes of beef (Dolezal, Smith, Savell, & Carpenter, 1982) and lamb (Smith, Dutson, Hostetler, & Carpenter, 1976). Increased thicknesses of subcutaneous fat were found to improve tenderness by allowing the carcass to chill more slowly and to increase enzyme activity (Smith et al., 1976). The authors postulated that increased fatness either decreased chilling rate because of a greater amount of insulation or because of increased total mass.

Dolezal et al. (1982) found that carcasses possessing 2.54 mm of external fat received the lowest ($P < 0.05$) sensory panel ratings for myofibrillar tenderness, and had the highest ($P < 0.05$) shear force values. In addition, as fat thickness increased up to 7.61 mm, palatability also increased. Smith and Carpenter (1973) reported that a fat covering of 2.5 mm for lamb carcasses would prevent excessive postmortem shrinkage during chilling and transit. A subcutaneous fat depth of 0.62 cm at the 12th rib is suggested as the minimum level to prevent cold shortening in cattle.

Carcass weight and composition have both been deemed important factors of chilling rate (Kastner, 1981). In a study by Hippe et al. (1991), sides from thinner cows had a higher percentage of cooler shrink than sides from steers after 24 h. This is substantiated by research from Johnson, Hunt, Allen, Kastner, Danler, and Shrock (1988) that lean tissue retained less water than adipose after 20 h postmortem. More moisture loss occurs from lean than from fat tissue (Johnson et al., 1988). The major variables associated with reducing shrinkage are decreased surface area and/or increased subcutaneous fat covering (Smith & Carpenter, 1973). Increased fatness may decrease shrinkage by serving as a barrier against moisture loss (preventing evaporation from the lean), or it may act to minimize the total moisture content in the carcass (Smith & Carpenter, 1973).

Smith et al. (1976) determined that lamb carcasses with increased quantities of fat chilled more slowly, had less sarcomere shortening with less perceptible connective tissue, and were more tender. Increased levels of subcutaneous or intramuscular fat can increase lamb tenderness by altering the postmortem chilling rate, especially with little external fat (Smith et al., 1976).

Electrical stimulation helps prevent cold shortening by using up energy (ATP) before the onset stage of rigor. An electrical current is passed through the carcass during the slaughter process causing the muscles to violently contract and accelerating anaerobic glycolysis, which increases the rate of pH decline and reduces the overall time of rigor mortis. This in turn reduces the muscle's susceptibility to cold-induced shortening. Electrical stimulation of beef produces significant positive effects on lean maturity, overall maturity, and Warner-Bratzler shear force tenderness (Savell, Smith, & Carpenter, 1978; Calkins, Savell, Smith, & Murphey, 1980). Lean color also was found to be positively impacted, and heat ring (the distorted appearance of the outside edge of muscle, caused by rapid chilling and little external fat) was reduced. Also, Warner-Bratzler shear force values were significantly decreased for 21 d aged, electrically stimulated carcasses vs. control carcasses, and more interestingly, this was also true for 7 d electrically stimulated carcasses vs. 21 d controls (Savell et al., 1978). Shorthose, Powell, and Harris (1986) found this to be the case with lamb as well. Electrical stimulation had minimal (Johnson, Savell, Weatherspoon, & Smith, 1982) and even adverse (Swasdee, Terrell, Dutson, Crenwelge, & Smith, 1983) effects on quality, palatability, and weight loss in pork.

During chilling, the extent of shortening in a carcass depends on the physical restriction imposed by the attachment of the muscle to the skeleton (Hostetler, Landmann, Link, & Fitzhugh, 1970). Another method used to reduce sarcomere shortening is to alter the method of carcass suspension. Hostetler, Link, Landmann, and Fitzhugh (1972) looked at several methods including: vertical hanging (conventional hanging using suspension by the Achilles tendon), horizontal (side placed on table, with limbs tied perpendicular to the vertebra), neck-tide (side suspended from the cervical vertebra, with pelvic limb tide to thoracic limb), hip-free (side suspended from the obturator foramen and pelvic limbs free), and hip-tied (side suspended from the obturator foramen with the thoracic limb tide to the pelvic limb). The hip-free method was determined to be the most beneficial in improving sarcomere lengths and the ultimate tenderness of the muscles, especially in the loin and round. Hostetler, Carpenter, Smith, and Dutson (1975) found that carcasses suspended by the obturator foramen had muscles with 17% longer sarcomeres than those from carcasses suspended normally, and that this created less overlap of thick and thin filaments.

Times that the carcasses are placed into the cooler and temperatures at which they are held could be the most plausible way to affect cold shortening after slaughter. Bendall (1972) reported that muscles with temperatures less than 10ºC are susceptible to cold shortening until a muscle pH of less than 6.2 is reached, and at 16ºC cold shortening is less severe. Hannula and Puolanne (2004) found that the effects of aging should be more effective if the carcasses are maintained above 7 to 10ºC until the onset of rigor (pH 5.7). Olsson, Herzman, and Tornberg (1994) have set 7ºC internal muscle temperature as the upper limit for cold shortening, and Bendall (1973) recommends against cooling beef carcasses below 12ºC internally in less than 15 h, or before completion of rigor mortis. There are many different opinions on the exact temperature necessary to eliminate or reduce cold shortening. Conventional chilling allows for control of these factors that can promote or inhibit cold shortening. At the same time, there are additional techniques that can be applied during the chilling process that can alter the level of cold induced shortening.

Delay Chilling

Delay chilling has been defined by Smulders et al. (1992) as the process of keeping intact carcasses out of the chill room for some period of time. This is not to be confused with high temperature conditioning, which is subjecting primals or cuts to elevated temperatures after boning (Smulders et al., 1992). Marsh, Lochner, Takahashi, and Kragness (1980-81) indicated that beef sides delay chilled at 37°C for 3 h postmortem were more tender than conventionally chilled sides. Delayed chilling has been reported by some to have a positive influence on postmortem tenderness. In a study by Fields, Carpenter, and Smith (1976), steaks from steer and cow sides held at ambient temperatures of 14 to 19°C for 20 h were more tender than those from

normally chilled sides. Also noted was the fact that elevated temperature conditioned steaks stored for 7 d received higher panel ratings for tenderness than control steaks. In this study, pre-rigor storage at elevated temperatures improved the appearance of steaks from steer and cow carcasses (Fields et al., 1976). The authors reported that 115 out of 120 steaks from sides held at 14 to 19°C received higher ratings than control steaks for muscle color, consumer acceptability, and discoloration during 5 d of retail storage. Martin, Murray, Jeremiah, and Dutson (1983) also reported decreased toughness when carcasses were held at elevated ambient temperatures in the range to 10 to 42°C, but were unable to clearly define the mechanism responsible. Delay chilling in pork was studied by Møller and Vestergaard (1987), and *M. longissimus dorsi* with a high initial pH above 6.1 was determined to be tough, while *M. longissimus dorsi* with a low initial pH below 6.1 was not affected.

On the other hand, Will and Henrickson (1976) determined that shear force and penetration values between chill (1.1°C for 48 h) and delay chill (held 3, 5, or 7 h postmortem at 16°C) treatments were small (1.65 kg and 0.18 cm, respectively), and led them to the conclusion that there were no significant tenderness differences observed between the two regimes. Phoya and Will (1986) reported that a taste panel was able to detect differences between delay chilled steaks (16°C for 4 h, then some muscle excision and 1°C storage for another 44 h) and conventionally chilled steaks (1°C for 48 h before fabrication). Warner-Bratzler shear force values and preference and hedonic scale scores showed that delay chilling for 4 h with hot-boning did not increase beef tenderness when carcasses were suspended through the obturator foramen (Phoya & Will, 1986). In a similar study performed by Jeremiah, Martin, and Murray (1985), researchers determined that delay chilling (12.5°C for 2 h) along with electrical stimulation did not produce consistent changes in physical, cooking, or palatability traits in the *M. semimembranosus*, *M. longissimus dorsi*, or *M. triceps brachii* muscles of beef.

As noted by Smulders et al. (1992), the potential benefits of high temperature conditioning, which include prevention of cold shortening and increased proteolysis, must be weighed against the possibility of heat shortening. Also, Smulders et al. (1992) stated that the effect of increased tenderness of delay chilled muscle can disappear during storage, and could result from an increased rate of aging or accelerated start to aging because of increased temperatures. There are multiple mechanisms such as heat shortening or cold shortening prevention that can dictate the effect of delay chilling on tenderness.

4. Spray Chilling

Shrinkage represents a serious economic concern for the beef packing industry today (Hamby, Savell, Acuff, Vanderzant, & Cross, 1987). Conditions that must be kept in order to minimize shrinkage include maintaining low temperature conditions, minimal air circulation, and a high relative humidity (Smith & Carpenter, 1973). The principal purpose of spray chilling is to reduce carcass weight loss during chilling, especially during the first 24 hours postmortem (Allen, Hunt, Luchiari Filho, Danler, & Goll, 1987). Spray chilling systems are currently in use in North America, Europe, and elsewhere in the world for beef, lamb, poultry (Brown, Chourouzidis, & Gigiel, 1993), and pork (Brown & James, 1992). The process of spray chilling involves the intermittent spraying of cold water onto carcasses during the first three to eight hours post-slaughter (Hippe, Field, Ray, & Russell, 1991) to replace moisture lost by evaporation (Gigiel, Butler, & Hudson, 1989). With spray chilling, the surface remains wet allowing for maximum mass transfer and evaporative cooling without increasing carcass weight loss (Gigiel et al., 1989).

Postmortem shrinkage is the result of evaporation and drip loss of carcass wash water and loss of moisture by the carcass components (Smith & Carpenter, 1973). Evaporative weight losses of up to 2% of the hot carcass weight have been reported during the initial 24 h of conventional air chilling of beef, pork, and lamb (Greer & Jones, 1997). In a study conducted on 1,000 lamb carcasses, during the first 36 hours, 92% of the 72 h weight loss had already occurred (Smith & Carpenter, 1973). This study determined that shrinkage continues to increase with increased time in the cooler, but at a decreased rate (Smith & Carpenter, 1973). The majority of the initial carcass weight loss that was experienced in this study was due to evaporative losses of water added during washing. The approximately 39% of the weight loss remaining occurred in the next 60 h due to evaporative losses of moisture from carcass components (Smith & Carpenter, 1973). Lamb

can be considered fairly susceptible to cold shortening because of exposed musculature and high surface-to-volume ratio that leads to excessive evaporative weight loss (Brown et al., 1993).
In commercial practice, there is considerable variation in the duration of spray chilling, and the amount of water deposited on carcasses in a specified period of time is usually not known (Greer & Jones, 1997). It appears that spraying carcasses in the initial 3 to 12 h of carcass chilling is relatively common within the commercial setting (Greer & Jones, 1997).

Shrinkage
Shrouded beef carcasses chilled overnight in conventional systems typically shrink from 0.75 to 2% (Kastner, 1981). There have been numerous studies conducted on spray chilling systems that significantly reduce this inherent level of shrink. Heitter (1975) described the Chlor-Chil system used by Swift and Company as an innovative method to reduce carcass shrink while reducing the amount of spoilage bacteria normally present on carcasses in the cooler. This system involved the intermittent spraying of a mild solution of chlorine and water to achieve reductions of carcass shrink that varied from 0.5 to 1.25% (Heitter, 1975). Heitter (1975) went on to say that this shrink reduction that was realized in the chilling operation was carried through to the trimmed cuts. In one of multiple studies that compared spray chilled sides to conventionally chilled sides, Allen et al. (1987) found that after 24 h, spray-chilled beef sides shrank 1.14% less than conventionally chilled sides. In a similar study conducted by Jones, Murray, & Robertson (1988), beef sides spray chilled for 12 h and unshrouded beef sides spray chilled for 8 h had significantly lower carcass weight shrinkages to 6 d than control sides. Jones and Robertson (1988) found that shrinkage was reduced by 0.48 to 0.89 as the spray-chilling period was increased from 4 to 12 h. Hippe, Field, Ray, and Russell (1991) determined that the percentage of cooler shrink for beef sides at 2, 4, 6, and 24 h was lower for spray chilled versus conventionally chilled at all times postmortem.

Lee, Hawrysh, Jeremiah, and Hardin (1990) found that when comparing spray chilled and conventionally chilled beef sides that were both shrouded and unshrouded, unshrouded, spray chilled sides displayed the lowest percent carcass shrinkage after 24 h. They found that spray chilling unshrouded sides would result in a 1.3% savings in side weight. In a similar study by Strydom and Buys (1995), spray chilled beef sides resulted in a 1.1% savings in side weight versus conventionally chilled sides, regardless of duration of spray chilling. On a contrary note, Greer and Jones (1997) discovered a linear relationship between spray chill duration and carcass weight loss, and determined that carcass shrinkage was only reduced by 0.08 g/100 g for every hour of spray chilling.

Shrinkage of conventionally chilled pork can average from 1.85 to 100 g (Jones, Jeremiah, & Robertson, 1993). Conventional pig chilling systems work to reduce pork temperature to 4°C (Brown & James, 1992). James, Murray, and Robertson (1988) determined that a spray-chilling regime could have a significant effect on pork carcass shrinkage while increasing cooling rate of the muscles in the loin and ham. This study revealed that an average 79 kg pork carcass could receive an approximately 1.61 kg advantage in cooler shrink if spray chilling were utilized.

Quality characteristics
An additional benefit of spray chilling discovered by several researchers is an improvement in carcass quality. Allen et al. (1987) observed skeletal maturity to be significantly younger in beef sides that were spray chilled due to visual differences in skeletal ossification. This group determined that it would be advantageous to use spray chilling to improve quality grade when chilling carcasses with maturity that lies near the line drawn between younger and older classed grades. Jones and Robertson (1988) found that beef muscle color was not influenced by the spray chilling process, but fat from spray chilled sides where the spray period was 8 h or more had significantly higher Y^* values than control sides. Greer and Jones (1997) expressed similar results with no real effect of spray chilling on beef lean color, but fat L^* values that were consistently higher on spray chilled carcasses at most locations after 4, 8, 12, and 16 h of spray chill. They recovered generally lower a^* and b^* values after 12 and 16 h of spray chill, and fat developed a washed out, grey appearance after 16 h of spray chilling. It also has been reported that shear values, and therefore tenderness, are not affected by spray chilling (Hippe et al., 1991; Greer & Jones, 1997; Jones & Robertson, 1988; & Lee et al., 1990).

Purge loss

There is some evidence that the initial advantage noted in spray chilled beef sides is lost as purge during the first 15 days of vacuum storage (Allen et al., 1987). Greer and Jones (1997) demonstrated that spray chilling did not affect weight losses from the *M. longissimus thoracis* muscle in comparison to air chilled controls, after spray durations of 4, 8, 12, or 16 h, or storage temperatures of 1, 4, 8, and 12°C for up to 44 days of vacuum storage. Hippe et al. (1991) also reported that purge losses from vacuum packaged top rounds stored 5 or 10 weeks were not significantly different between spray chilled and conventionally chilled sides. Jones and Robertson (1988) determined that drip or purge losses over 6 days in vacuum packaged ribs and inside rounds were similar between spray chilled and conventionally chilled sides. Brown et al. (1993) also reported no increased drip-loss or cooking-loss from samples taken from spray chilled lamb sides. Strydom and Buys (1995) reported that 17 h of spray chilling had no effect on purge loss of vacuum packaged wholesale (7d) or retail display (3d) beef cuts. With this experiment, none of the moisture conserved during chilling was lost during vacuum packaging, retail display, or cooking. However, Allen et al. (1987) reported small (0.26%) increases in purge from inside rounds of spray chilled carcasses.

Shelf-life/microbial quality

There is some concern that the economic advantage of decreased shrinkage may be affected by a slight decrease in microbiological quality (Hippe et al., 1991). However, there is evidence that spray chilling does not affect bacterial counts (Hamby et al., 1987; Strydom & Buys, 1995; Brown et al., 1993), or may slightly reduce bacterial counts (Greer and Dilts, 1988). Greer and Jones (1997) showed that spray chilling had no effect on bacterial growth on the *M. longissimus thoracis* muscle (44 d) or retail cuts as compared to commonly chilled sides even after they were subjected to extremes in spray duration of up to 16 h and vacuum storage temperatures of up to 12°C. Dickson (1990) reported that spray chilling did not affect survival or growth of *Listeria monocytogenes* for up to 42 d of vacuum storage of beef. In a study performed by Jeremiah and Jones (1989), retail case life of chops from spray-chilled pork sides was typically shorter than those from conventionally chilled sides.

Rate of temperature decline

There are many variables influencing chilling rate including: size, shape, and fatness of the carcass, temperature, relative humidity, and flow pattern of the air (Smulders et al., 1992). It has been hypothesized by James (1996) that higher rates of heat transfer, and the heat extracted to evaporate the added water used during spray chilling, should substantially reduce carcass chilling time. Jones and Robertson (1988) indicate that spray chilling significantly affected rate of cooling in the *M. semimembranosus* (SM) and *M. longissimus dorsi* (LD) of beef. This group saw 1 to 2°C increases in the temperature declines of these muscles when sides were both shrouded and unshrouded with spray chilling duration of 8 and 12 h. This effect was most pronounced in the SM because of its position in the carcass and the fact that muscles in the round are closest to the source of water used in the spray chilling process. This effect is also enhanced by a relatively thin fat cover (Jones & Robertson, 1988).

In another study performed by Lee et al. (1990), after 8 h, LD and SM muscles from spray chilled sides had lower muscle temperatures than those that were conventionally chilled with both shrouded and unshrouded carcasses. Brown et al. (1993) also noticed small differences in chilling rate between lamb legs and loins of multiple spray chilled carcasses and those that were conventionally or double spray chilled. On a contrary note, Hippe et al. (1991) reported no differences in postmortem temperatures of *M. semitendinosus*, *M. longissimus*, or *M. serratus ventralis* muscles between sides that were spray chilled and those chilled normally.

Rapid/Blast Chilling

Systems to rapidly reduce carcass temperatures have been investigated for a variety of reasons and with a variety of results. Terms used to describe this category of chilling include but are not limited to “rapid,” “ultra-rapid,” “blast,” “very fast,” and “extreme,” with no consistent definition used by authors in defining

these systems. In this review, our focus was to maintain the terminology used by the authors rather than standardize it.

Some rapid systems are used for regulatory reasons. According to Bowater (2001), in the EU, beef and lamb carcasses must reach internal temperatures of 7°C after 24 h or before moving the carcass to the boning room (pork must reach 4°C after 24 h or before moving the carcass). In the U.S., there are no regulatory requirements for specific temperature endpoints for chilling livestock carcasses; however, the U.S. poultry industry routinely uses rapid chilling because of the United States Department of Agriculture, Food Safety and Inspection Service regulatory requirement that poultry be chilled below 4.4°C before 4 h postmortem.

All frozen poultry begins the chilling process by being immersed in chilled or ice water (Brown and James, 1992). Ultra-rapid chilling consists of two stages, the first of which is a pre-chiller, such as an air-blast tunnel (Brown and James, 1992). This pre-chiller works to quickly reduce surface temperature in order to decrease the amount of evaporative weight loss. It also helps to absorb the initial heat load of the chiller (Brown and James, 1992).

When used in beef, rapid chilling has been shown to produce considerable toughening and severe consumer reaction, and tenderness has been identified as the consumer's number one concern (Joseph, 1996). However, Bowling, Dutson, Smith, and Savell (1987) have shown that it may be possible to chill beef carcasses at extremely rapid rates with less carcass shrinkage and with no detrimental effects on quality grade or cooked beef palatability. According to McGeehin, Sheridan, and Butler (2002), rapid chilling in the lamb industry could eliminate the need for overnight chilling, allowing lambs to be shipped on the day of slaughter in order to combat the relatively short shelf life of fresh lamb.

In the study mentioned above conducted by Bowling et al. (1987), rapidly chilled sides produced beef that was more tender than conventionally chilled sides, and loin steaks from rapidly chilled sides were more juicy and desirable in overall palatability. Rapidly chilled sides experienced 0.9% less shrinkage during the first 24 h postmortem than conventionally chilled sides, and received higher marbling scores. These sides also had darker and softer lean as compared to conventional sides (Bowling et al., 1987).

Very fast chilling (VFC) has been defined as the achievement of a carcass temperature of –1°C within 5 h of postmortem chilling (Aalhus, Robertson, Dugan, & Best, 2002; Joseph, 1996). It has been proposed that toughening in lamb could be prevented by freezing in less than 4 h postmortem to cause surface hardening that restrains cold shortening (Joseph, 1996; Davey & Garnett, 1980). A study by Brown and James (1992) revealed that pork loin chops from ultra-rapidly chilled sides stored for 2 d were tougher than those from conventionally chilled sides. Joseph (1996) also identified the problem of variability in VFC meat because of storage temperature gradients produced in muscle during the VFC process. The practice of freezing lamb carcasses pre-rigor was researched by Watt and Herring (1974). These authors determined that pre-rigor freezing is known to produce toughening, and this type of rapid chilling can result in crust frozen carcasses that require extensive thawing time before fabrication can begin (Watt and Herring, 1974).

In the study by Watt and Herring (1974) on lamb carcasses, those that were chilled more rapidly had brighter lean and whiter fat, and experienced shrink savings that were maintained through shipping. This method of chilling resulted in a toughening of the *M. longissimus* up to 16%, and up to 7% in the *M. semimembranosus*, *M. semitendinosus,* and *M. biceps femoris*. Rapid chilling results in toughening in pork, but that can be improved using electrical stimulation (Gigiel et al., 1989). Chilling pork to internal temperatures of 20 to 25°C within 2 to 3 h postmortem can reduce pale, soft, and exudative characteristics, but muscle should not be chilled below 10°C in the first 5 h postmortem (Reagan & Honikel, 1985). Kerth et al. (2001) reported a reduced incidence of PSE meat from pigs carrying the Halothane gene when pork was cooled using accelerated chilling. Liquid nitrogen chilling was shown by Borchert and Briskey (1964) to prevent PSE conditions without affecting 24 h pH. Accelerated air chilling has been shown by some to improve water-holding capacity (WHC) in pork (Kerth et al., 2001; Taylor, 1971; Taylor & Dant, 1971), and to have no effect on WHC by others (Gigiel & James, 1984; Jones, Jeremiah, & Roberts, 1993). Bertram, Donstrup, Karlsson, Anderson, and Stodkilde-Jorgensen (2001) found increased WHC when using rapid tunnel chilling versus conventional chilling.

Sheridan (1990) reported that an ultra-rapid lamb chilling system was capable of producing tender loins after 7 d of storage by chilling at air temperatures of -20ºC for 3 to 5 h with an air speed of 1.5 m/s. This work led to the recommendation that lamb carcasses should not be chilled less than 12 to 14 h at 3 to 4ºC in order to prevent cold shortening (Sheridan, 1990).

Some studies paired the use of electrical stimulation with blast chilling in order to further prevent cold shortening, and therefore ensure more tenderness. In a study conducted by Aalhus, Janz, Tong, Jones, and Robertson (2001) that employed blast chilling and electrical stimulation in combination, shear force values in the *M. longissimus lumborum* (LL) of beef sides were decreased by 9.5% when compared to conventionally chilled sides. The proportion of extremely tough LL steaks also was reduced by 1.3%. The authors reported that blast chilling had no effect on marbling score, and blast chilled/electrically stimulated carcasses had brighter lean color when compared to conventionally chilled carcasses. Also, leaner carcasses experienced approximately 0.3% less cooler shrink when blast chilling was applied, and blast chilling was able to reduce the increased drip losses normally associated with electrical stimulation. As a result of these findings, Aalhus et al. (2001) was able to recommend to the industry the combination of blast chilling and electrical stimulation in order to reduce postmortem chilling times and shrink losses while continuing to produce meat quality.

Rapid chilling regimes produced significantly lower percentages of cooler shrink (Bowater, 1997; Aalhus et al., 2002) along with an increased perception of marbling, darker meat color, and increased drip loss in research conducted by Aalhus et al. (2002). Aalhus et al. (2002) found that for –20°C and –35°C blast chilling temperatures, shrink losses in beef decreased as time in the blast chill tunnel increased. After 7 h of –35°C blast chilling, cooler shrink was totally eliminated, and sides began to gain weight after 10 h of this treatment. Very fast chilling in this experiment was achieved in the *M. longissimus thoracis* after 7 and 10 h of –35°C blast chilling. The best combination they found was 10 h blast chilling with 6 d aging to produce low shear values and a high proportion of tender and probably tender steaks. Aalhus et al. (2002) identified the advantage of VFC as a reduction in the aging time necessary to achieve an acceptable product. Blast chilling of pork before the start of conventional chilling is reported to decrease shrinkage and give pork a darker and firmer lean (Jones et al., 1988).

Conclusions

Methods of chilling carcasses greatly impact the quality and palatability of meat with the results of these methods being very species-specific. In beef and lamb, employing chilling systems that minimize cold shortening should be a goal. Processes such as delayed chilling can successfully prevent or reduce the negative influence of cold shortening, however, food safety concerns and the need for maximum throughput in commercial facilities makes this system less applicable today. Commercial uses of electrical stimulation and alternative carcass suspension programs offer meat processors the opportunity to negate most or all of the effects of cold shortening when traditional chilling systems are used.

For pork, because of the role of elevated muscle temperature and low pH on the development of PSE, more rapid chilling systems have been employed to remove heat and slow the pH decline in an attempt to reduce the incidence of PSE. However, there still can be quality issues as a result of the differential between the extreme cold temperatures on the outside of the carcass and warm muscle temperatures in the deep regions of the carcass causing two-toned muscles (i.e., muscles that are darker in color externally and lighter in color internally).

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