THESIS

MAPPING TEMPERATURE DECLINE IN BEEF CATTLE DURING CONVENTIONAL CHILLING

Submitted by

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ABSTRACT

MAPPING TEMPERATURE DECLINE IN BEEF CATTLE DURING CONVENTIONAL CHILLING

A continued increase in beef carcass weights has caused a need to adjust chilling practices in order to chill carcasses appropriately to follow food safety and beef quality recommendations. The objectives of this study were to track continuous temperature decline of beef carcasses of varying size, gain insight on how fat thickness and carcass size affect overall chilling rate, and model the temperature decline of 6 muscles and one surface location on beef carcasses. Temperature recorders were placed in 7 carcass locations and temperature was measured every 30 seconds from post electrical stimulation until the carcasses left the hot boxes to be graded. Carcass temperatures were measured at 1) brisket/plate (deep pectoral), 2) deep chuck (medial side of scapula/ clod heart), 3) deep tissue (*Semimembranosus),* 4) *Gluteus medius* (Sirloin)*,* 5) *Longissimus dorsi* at the 12th rib, 6) surface (5mm under the fascia) at the 11th rib, 7) *Psoas major* (Tenderloin), and 8) ambient per group of carcasses. Carcasses were blocked by weight as 1) light (650- 750 pounds), 2) medium (850-950 pounds), and 3) heavy (1050 to 1150 pounds). Surface temperatures from all weight categories reached below 4˚C within 24 hours of chilling, following food safety recommendations and meeting critical limits set as critical control point in common HACCP (Hazard Analysis Critical Control Points) plans. In the deep tissue (SM), *Gluteus medius,* and *Longissimus dorsi* carcass locations*,* differences ($P < 0.05$) were found between the light versus medium and heavy weight ranges at the final hour of chilling (hour 28). At hour 28, no differences ($P \geq 0.05$) were found in the surface, deep pectoral, *Psoas*

major, and deep chuck locations. At hour 28, light weight carcasses in the deep tissue location reached below the recommended chilling target of 7˚C, however the medium and heavy range carcasses did not reach below 7˚C. When larger carcasses are not chilled adequately, potential quality implications exist including quality grading loss, increased carcass shrink, and fabrication issues. Therefore, beef processing facilities should consider sorting cattle before chilling in order to maximize the quality and safety of the products being processed.

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INTRODUCTION

From 2002 to 2015 cattle herd numbers were drastically deceasing, with US cattle herd numbers being at an all-time low in 2012 (USDA 2017). The decrease in cattle available for harvest has caused a need for more pounds of beef to be produced with less animals. This economic pull has caused producers to raise larger and heavier cattle to meet consumer demands. Cattle weights have been increasing on average 6.67 pounds every year since 1991, making beef carcasses 13 % larger in 2016 than in 1991 in the United States (Boykin et al., 2016). With this large increase in cattle weights, chilling times need to be extended for a in order to lower heavier carcasses to acceptable temperature limits outlined in common food safety and quality programs.

Though average hot carcass weight have been considerably increasing over the last 20 years, most all beef plants are operating in facilities that have not been renovated to accommodate for these larger sized carcasses, causing not only fabrication issues, but also cooler space issues. In order for larger facilities (4500 or more head per day) to operate efficiently, carcasses must be chilled quickly in the hot boxes typically within 30 hours of slaughter, so the carcasses can then be graded by USDA personnel, fabricated, boxed, and sent to the customer as quickly as possible. However, these larger carcasses typically have more fat covering due to longer, more intensive feeding plans along with genetic improvements. The increased fat cover along with the overall muscle size dimension increases causes larger carcasses to take longer to chill compared to smaller carcasses that have been produced in years past. Although overall average yield grade differences have not changed as drastically over the years, the incidences of USDA Yield Grade 4 and 5's has significantly increased (Boykin et al., 2016). This greater amount of fat cover may insulate the carcasses, causing an increase in chilling times. Other

issues have arose from an increase in hot carcass weights from the retailer side of the industry. Meat purveyors are struggling to buy products of consistent sizes that meet consumer specifications and retail price points, and consumers are found to dislike thinner cut steaks that often are cut due to larger muscle sizes in heavier carcasses (Maples et al., 2017).

The beef industry has responded to the large increase in hot carcass weights from both an economical and consumer driven standpoint. The US beef industry has decreased discounts on hot carcass weights of heavier carcasses and widening the range of acceptability for hot carcass weights to be from 600 to 900 pounds (USDA 2018) Branded beef programs, including Certified Angus Beef (CAB), have increased both the maximum ribeye area and the maximum hot carcass weights accepted into the branded programs (Suther 2006). These changes made by the beef industry have increased the incentive for packers to process larger cattle. Though larger cattle cause issues in terms of processing, many positives have also arose from an increase in average hot carcass weights. There has been an increase in percent of cattle that grade USDA Choice or higher that correlates with the increase in hot carcass weights (Dykstra 2013).

Most all beef processing facilities abide by Hazard Analysis Critical Control Point (HACCP) plans as a main food safety program. Often times facilities require chilling to be a critical control point (CCP) on their HACCP plan, and set the critical limit at 4˚C (39.2˚F) at the surface of the carcass within 24 hours post mortem (Savell 2013). This ensures that carcasses are chilled quickly enough and to low enough temperatures to decrease the risk of foodborne pathogens contaminating beef carcasses. Other guidelines that some facilities follow are based off the Tompkin paper that sets limits at less than 7˚C at the surface of the carcass in less than 24 hours postmortem. These limits are based off of the minimum growth requirements being above

7˚C for both *Salmonella spp.* and *E. Coli* O157:H7 (Tompkin Paper). Both guidelines are used for analysis and discussion in this study.

CHAPTER 1

REVIEW OF LITERATURE

Carcass/ Cattle Size Increases

A continuing trend in the beef industry is the increase in cattle weights, thus an increase in hot carcass weights at processing facilities. Many advancements in the beef industry has made this possible, including improved genetics, more efficient nutrition plans, and the use the growth promoting technologies (i.g. hormonal implants) (Maples et al., 2017). Additionally, there has been a drop in cow herd numbers in the last decade, however the demand for beef has stayed level, causing a need for the beef supply to stay constant (USDA 2016). This consistent supply of beef has been accomplished by increasing the number of pounds of beef each animal can produce. All of these reasons have contributed to the yearly increase in cattle size. Heavier weight cattle take longer to chill, however, packers have not adjusted chilling practices accordingly for this increase in carcass weights, causing some carcasses to be fabricated without reaching the correct ultimate deep tissue internal temperature, potentially violating HACCP critical limits set and creating additional quality defects (i.g. bone sour).

An increase in hot carcass weights have caused beef production facilities to alter the way they process these larger carcasses. Facilities are continuously tying up the fore leg of large carcasses that would otherwise drag on the production floor ground, condemn heads that touched production floor grounds, or sending live animals back to producers and feedlots whose frame sized would not be accommodating to plant facilities. Since 1991, cattle weight have increased an average of over 6 pounds per year, with the average in 1991 being 760.1 pounds and the

average in 2016 being 860.5 pounds (Boykin et al., 2016). The increase of 100 pounds per carcass has helped the supply for beef stay in line with the demand, however, the carcasses are often much heavier than the average weight of 860 pounds. In 2016, 25.7% of carcasses weighed more than 950 pounds (Boykin et al., 2016). This increased occurrence of larger carcasses being processed has changed the market grid for beef. As of May, 28th 2018, carcasses with hot carcass weights between 600 and 900 pounds would not receive a weight discount, carcasses weighing 900 to 1000 pounds averaged a $2/cwt discount, and carcasses weighing 1000-1050 pounds received an average discount of $7/cwt (USDA AMS). Using the 2016 average hot carcass weights, this would result in 44.1% of carcasses receiving a weight discount (Boykin et al., 2016). Due to the frequency of heavier weight cattle being so common, some boxed beef programs have even changed their carcass parameters to include heaver weight cattle, including Certified Angus Beef (CAB), that now includes carcasses up to 1000 pounds (Suther 2006).

Both the increase in carcass size and the resulting increase in backfat thickness contribute to difficulties in chilling beef carcasses. Along with the technical difficulties processing facilities are having in harvesting larger beef animals, these larger animals have affected the overall makeup of the beef carcasses being processed. The average yield grade of beef carcasses has increased slightly from 2.9 to 3.1 from the 2011 to 2016 National Beef Quality Audits, respectively (Boykin et al., 2016). Moreover, the incidence of yield grade four's and five's drastically increased from the 2011 to 2016 National Beef Quality Audits (Boykin et al., 2016). In 2011, 9.4% of beef animals slaughtered were yield grade four or five, compared to 14.5% in 2016 (Boykin et al., 2016). Carcasses with a greater amount of backfat have a slower temperature decline and pH drop in the *Longissimus dorsi* muscle (Aalhus et al., 2001).

Therefore, the changing makeup of fatter carcasses being processed can cause slower chilling rates if adjustments are not made to accommodate these larger, fatter carcasses. Some positives occurring within the beef industry is more carcasses are grading USDA Choice or higher. An increase in hot carcass weights correlates to the occurrence of USDA Choice or higher carcasses as shown in Figure 1.1 from Certified Angus Beef LLC (Dykstra 2013).

Faster chilled carcasses have less cooler shrink, or drip loss, which can affect the overall profitability of the production plants. Bowater reported that faster chilled carcass can have up to half as much (0.6%) carcass shrink as those carcasses that were conventionally chilled (1.2%) (Bowater 2001). Therefore, the faster the carcasses are chilled, the more profitable the production facility is, as less water is expelling from the carcass.

One method of chilling utilized frequently in the pork industry is blast chilling. Dr. Savell from Texas A&M noted in 2005 that there was no exact definition for blast chilling, but can often described as “rapid”, “ultra-rapid”, “blast”, “very fast” or “extreme” (Savell et al., 2005). Others have described blast chilling as chilling carcasses to -1˚C within 5 hours of chilling (Joseph 1996) or chilling carcasses in hotboxes with temperatures ranging from -20 to -35˚C (Aalhus et al., 2002). When utilizing a blast chilling system compared to conventional chilling, multiple studies have found, that leaner carcasses typically result in less cooler shrink (Aalhus et al., 2001, Bowling et al. 1987, Ortner 1989). These results indicate that the faster carcasses are chilled, the more profitable the production facility can be due to less cooler shrink. When comparing thinner versus fatter carcasses, James and Bailey cited that thinner carcasses (20 percent below the average set in 1977) experienced more evaporative weight loss then fatter carcasses (20 percent above the average set in 1977) when being chilled in at 0˚c for 18 hours (James and Bailey 1989). Chilling carcasses faster and chilling carcasses with a greater amount

of backfat can decrease the amount of cooler shrink of evaporative loss in beef carcasses. Due to the large quantity of beef being produced at a single large processing facility, even a small percent of cooler shrink savings can be beneficial.

Larger beef carcasses can affect the final product for consumers. As overall carcass size increases, so does individual muscle size. There has been an increase in ribeye area of over one square inch from 1991 to 2016 (Boykin et al., 2016). This increase in muscle size has changed the way that meat purveyors market meat, and how meat is further fabricated into retail cuts. In order to keep appropriate steak and roast sizes that align with nutritional guidelines for intake of protein, retailers and food service operators are forced to cut steaks thinner due to the increase in surface area of each muscle cut. These thinner steaks can result in undesirable eating characteristics by the consumer, especially because thinner steaks can be easily overcooked.

A general consensus found in 2017 by Maples et al. was consumers shared a general dislike for thin cut steaks but were not willing to pay the higher package price for a thicker cut steak (Maples et al., 2017). This can pose a problem for beef facilities down the production line, as larger carcasses can make it more challenging to meet final customer specifications for weight, thickness and retail price.

Looking historically, "weight" has been declared a top quality challenge in every National Beef Quality Audit since 1995 (Hasty et al., 2016). Thus, 66% of further processors from the 2016 National Beef Quality Audit were willing to pay a premium for guaranteed weight and size of muscle cuts (Hasty et al., 2016). Nevertheless, some comments being made by beef producers in favor of the increasing cattle weight trend is that large carcasses cost the same to process compared to smaller carcasses (Hasty et al., 2016). Moreover, Maples et al. mentioned

that lower cattle numbers is a positive for the environment as less cattle are being utilized more efficiently to meet beef demands (Maples et al., 2017).

Regulatory Temperature Growth Requirements/ HACCP

Appropriately chilling beef carcasses is an important processing step to stop the growth of harmful pathogens. If a beef carcass is not chilled quickly after exsanguination, the potential for harmful pathogens to grow and multiple increases. If a beef carcass never reaches a final chilling temperature that is low enough to stop pathogen growth, then the risk of the carcass spoiling faster or the pathogens making it to the end consumer are increased. Two of the pathogens of greatest concern in beef carcasses are *Salmonella spp.* and pathogenic strains of *E. Coli* (Tompkin paper). It has been found that these two pathogens are reasonably likely to occur in beef processing facilities, and should thus be addressed in processing HACCP plans (FSIS 2017).

The minimum growth temperature for *Salmonella spp.* is 7˚C (44.6˚F) and the minimum growth requirements for pathogenic *E. Coli* is 7-8˚C (44.6- 46.4˚F) (Tompkin paper). Hot boxes typically operate at less than 10˚C for this reason. This helps to control the growth the pathogenic organisms especially pertaining to *Salmonella spp*. as it would take 107 hours at 10˚C to increase from 10 to 100 CFU/ml (Tompkin paper). To increase *E. Coli* O157:H7 1 log at 10˚C it would take 2-5 days depending on if the environment was aerobic or anaerobic (Tompkin paper). It is important to monitor the environmental temperature of hotboxes and cooling units to maintain any microbial reduction that occurred from a previous critical control point on the slaughter floor (FSIS 2017). Prior to the carcasses being chilled, many processing facilities use a multiple hurdle approach to stop the growth the pathogens, including steam

pasteurization, lactic acid and hot water washes, and overall good manufacturing practices (GMP's) by plant personnel.

Due to these minimum temperature growth parameters, the European Union (EU) requires beef and sheep carcasses to leaves the chilling rooms at no more than 7˚C, though no location is specified (Bowater 2001 papers). Furthermore, many processing facilities in the EU require a deep leg tissue temperature of 7˚C before fabrication can take place with no time limitations (Bowater 2001, Brown et al., 2009). In the United States, beef processing facilities often set the critical limit for surface temperature within 24 hours post exsanguination at 4˚C as a critical control point (CCP) as part of their HACCP plans (FSIS 1996). Four degrees Celsius is often used as a standard in the United States due to it being under the minimum growth temperature for many foodborne pathogens, and its ease of conversion to degrees Fahrenheit (4˚C = 39.2˚F) for plant personnel. An example of Critical Control Points for chilling as a biological hazard can be found in Table 1.2 (FSIS 1996).

Food safety inspection service cited in 2017 that chilling beef carcasses is a critical step in controlling the growth of pathogens and services as a microbial load reduction step (FSIS 2017). In the 'FSIS Compliance for Minimizing the Risk of Shiga Toxin-Producing Escherichia Coli (STEC) and Salmonella in Beef (including Veal) Slaughter Operations', several chilling recommendation are outlined to ensure appropriate carcass chilling. These recommendations include starting the chilling process of the carcasses within one hour of exsanguination, monitoring temperature and sanitation processes through the chilling process to reduce microbial load reductions, and chilling carcasses to below 40˚F within 24 hours of slaughter (FSIS 2017). To ensure carcasses are chilling below 40˚F, surface temperatures are taken in 5 randomly spaced locations 5 mm under the fascia on the beef carcass inside round (FSIS 2017). Surface

temperature is one of most importance points on a carcass to monitor due to the increased risk of contamination compared to the inner muscles of the beef carcasses (Harris et al., 2009). During hide removal of the beef carcasses the risk of contaminating the outer surface of the carcass is drastically increased due to the microbial load maintained on hides, and the high likelihood of multiple knife strokes cross contaminating the hide to the outer surface of the carcass. Furthermore, the recommendations include cooler operational functions such as ensuring efficient air flow to carcasses by allowing space between carcasses, placing rails at least two feet from fixed facility infrastructure and minimizing cooler condensation (FSIS 2017).

Multiple studies have tested the ease of chilling beef carcasses to the recommended chilling requirements outlined in the last couple of decades. However, these recommendations have been altered little when taking into consideration of immense change in beef carcass characteristics that have occurred since the recommendations where outlines. James and Bailey conducted a study in 1989 that tested the efficiency of chilling beef carcasses of differing weigh classification and fat depositions. The study concluded that beef carcass sides can reach 7˚C within 24 hours when applied to light, relatively thin carcasses (James and Bailey, 1989). The study tracked deep tissue temperatures in the leg primal of beef carcasses and found that 220kg carcass sides took longer to chill compared to smaller carcass sides at 100, 140, and 180 kg. The larger carcass sides in the James and Bailey study that weighed 220kg would not account for the top 12% of beef carcasses slaughtered in the United States in 2016 (James and Bailey, 1989, Boykin et al., 2016). The small carcass sides that weighed 140 kg used in the James and Bailey study would today be consistent with carcasses that were in the lightest 1 percentage of carcasses slaughtered in the 2016 National Beef Quality Audit (James and Bailey, 1989, Boykin et al., 2016).

Postmortem Glycolysis: 0-24 Hours:

In order for the first phase of rigor mortis to start, actin and myosin must bind together. After exsanguination, most all oxygen is depleted from the body and the muscles continue to generate ATP in an anaerobic environment (Matarneh et al., 2017). Due to the generation of ATP being much less efficient in an anaerobic environment, the muscles use up all available ATP and rigor mortis begins, typically lasting around 12 hours in beef carcasses (Matarneh et al., 2017). Due to no energy in the form of ATP being stored in the muscles, actin binds to myosin to form permanent cross bridges and muscles loose ability to move and be extensible (England et al., 2017). Furthermore, after death, pyruvate is reduced to lactate and hydrogen ions (H^+) can no longer be removed from muscle tissues due to the anaerobic state, acidifying the muscles and thus dropping the pH of the tissue from around 7.2 down to the ideal level of about 5.6 (Matarneh et al., England et al., 2017, Savell 2013). Much of this decline in pH happens within the first 8 hours postmortem (decline to 5.8), and the final drop in pH occurs within 24 hours postmortem (Matarneh et al., 2017). Rate of chilling is one mechanism that can alter this rate of pH decline.

The rate of rigor mortis occurring in beef carcasses can greatly be influenced by the rate as which carcasses are chilled. The warmer the chilling conditions within the hot boxes, the faster the carcasses will go into the onset phase of rigor mortis as muscles will be depleted of adenosine triphosphate (ATP) and actin and myosin bonds will no longer able to be broken apart (Savell 2013). Opposingly, the colder the chilling conditions in the hot box, the slower the carcasses will enter the onset phase of rigor mortis as ATP will not be depleted as quickly (Savell 2013). The use of electrical stimulation depletes ATP more quickly, causing carcasses

that have been electrically stimulated to go into rigor mortis faster than those carcasses not electrically stimulated (Savell 2013).

The drop of pH in beef muscle is partially controlled by the rate of chilling. In living tissue the pH is around 7.0 (Savell et al., 2005). Once beef carcasses have gone through the completion phase of rigor mortis the final pH should be around 5.3- 5.8 which typically occurs 18-40 hours after exsanguination (Smulders, Toldra, Flores, and Prieto et al., 1992). This decline in pH can be quickened by chilling carcasses slower and by using electrical stimulation, whereas pH decline can be slowed down by chilling carcasses more rapidly (Savell 2013). As the pH declines and reaches the isoelectric point, water holding capacity is reduced due to the strong attraction between negative and positive charged amino acids not allowing for water to enter the filaments (Smulders et al., 1992).

In pork production, the rate at which pH drops is closely managed through low stress animal handling (no electrical prods used), the use the blast chilling as a main method of chilling, and by a faster chain speed resulting in pork carcasses being exposed to warmer conditions on the slaughter floor for a shorter period of time (Savell 2013). Furthermore, the pH decline in pork is naturally faster due to the onset phase of rigor mortis is only 50 minutes (Lopez-Bote 2017)

In beef production, the use of electrical stimulation is the only management practice widely used to control the decline of pH. Electrical stimulation depletes ATP energy stores before the onset phase of rigor mortis, causing a quicker decline in pH (Savell et al., 2005). One study in 2006 measured the temperature decline of seven muscles that were both electrically stimulated and non-electrically stimulated (Stolowski et al. 2006). Temperature was taken at hours 1,3,6,9, and 21 and it was found that electrically stimulated sides had higher temperatures

early on due to faster rate of glycolysis postmortem, then the non-electrically stimulated sides (Stolowski et al. 2006). This would mean that carcasses that were electrically stimulated have a faster initial pH decline but will have similar final pH values to carcasses that were not electrically stimulated.

Quality Effects of Chilling

Color

Chilling is a vital step to ensure the final consumer a safe product, but chilling is also a very important process step that can greatly affect the final quality of the meat product for the consumer. Thus, consumers often choose their beef products in the retail market based off color and general appearance of the product. The final color of beef is directly correlated to ultimate pH (Matarneh et al., 2017). Carcasses that have an higher pH than the ideal range of pH of 5.6 can result in dark firm and dry (DFD) lean that appears dark in color and is undesirable to consumers (Matarneh et al., 2017). Dark firm and dry condition typically occur from the incidence of stressful environments pre-slaughter due to the depletion of glycogen stores (England et al. 2017). However, chilling rates can play a role in the final color of meat. If the final pH of beef carcasses remains above 6.0 after 24 hours of chilling when being graded by USDA AMS the lean would be very dark and be deemed a dark cutter (Savell 2013). Dark cutters account for about 1-3% of the beef supply, depending on season (Savell, 2013). Carcass that are deemed dark cutters can be dropped one full quality grade depending on the severity of the color of the lean for A and B maturity carcasses (USDA AMS, 2017), or given a grading discount that averaged $35.83/cwt the week of May, 14th (USDA AMS). It has been noted that improper chilling of poultry can result in meat that has a lower than normal pH and be at risk for being pale, soft, and exudative (PSE) (Matarneh et al., 2017).

A study was conducted in 1989 that found that heavier carcasses (318 kg) had almost half as many occurrences of dark colored meat (2.6%) compared to lighter (272 kg) carcasses that resulted in dark meat 5.1% of the time (Murray 1989). The occurrence of dark meat was more prevalent in carcasses exhibiting less muscle mass, which may be confounded with size of carcass, while heavier muscled carcasses exhibited a higher frequency of lighter than normal muscle color (Murray 1989). However, the carcasses in this study were exposed to adequate chilling conditions and reached a correct final temperature at the time of grading.

If pH does not decline to appropriate levels by the time of grading then any carcass, no matter the hot carcass weight, are susceptible to dark cutting conditions. Additionally, fat cover was found to have an inverse relationship with color, as fat covered increase the occurrence of dark meat was drastically decreased (Murray 1989). Fortunately, with the increase in hot carcass weights, an increase in back fat thickness is also occurring, thus heavier, fatter carcasses are less likely to result in dark cutting beef.

Tenderness

Beef tenderness is a quality aspect that greatly influencing consumers overall eating experience. Tenderness can often be one of the most important factors when rating overall acceptability, going as far as some consumers willing to pay more for guaranteed tenderness (Aalyng 2017). Chilling is a processing step that can greatly influence the final tenderness of meat. Beef is at its toughest point 9-24 hours post slaughter (Koohmaraie 1996). After 24 hours of chilling, tenderness increases due to the enzymatic degradation occurring within the muscles (Savell et al., 2005) and continues to increase as the carcass ages until enzymatic activity slows to an insignificant level.

In extreme cases, cold shortening can occur in beef carcasses resulting in extremely tough meat. After slaughter, if carcasses are chilled too rapidly before the pH drops to an ideal limit, then the carcass are at risk for a cold shortening. Cold shortening happens when sarcomere length is severely shortened within the muscle bundles (Savell 2013). Cold shortening was defined in 1963 as a rapid temperature decline to less than 14-19˚C in muscle before the onset phase of rigor mortis is finished (Locker and Hagyard 1963). The risk of cold shortening in beef is much lower than compared to smaller lamb carcasses, although beef can become cold shortened if muscles are chilled to less than 10˚C while muscle pH is above 6.2 (Savell et al., 2005). Pork is not as susceptible to cold shortening due to the high abundance of white muscle fibers compared to red muscle fibers (Savell et al., 2005). White muscle fibers are less likely to become cold shortened (Bendall 1973) because they contain higher amount of glycogen that cause an earlier drop in pH during the rigor mortis process (Savell et al., 2005). Additionally, the onset phase for rigor mortis in pork carcasses is much faster, so the pH of the muscles will begin to decline quicker than in beef and lamb carcasses. Common practice in beef is to avoid carcasses being chilled below 10˚C within the first 10 hours of chilling to prevent cold shortening (Bendall 1980, Davey and Gilbert 1974).

Carcasses with greater backfat thickness are less likely to result in cold shortened beef. A study in 2001 found that carcasses with a minimum of 25mm of backfat prevented the *Longissimus dorsi* muscle from reaching cold shortening conditions in both blast chilled (3 hours at -20˚C followed by 2˚C for 21 hours) and conventional chilled systems (2˚C for 24 hours) (Aalhus et al., 2001). Beef carcasses that have higher back fat levels insulate the muscles during the chilling process and help to prevent cold shortening (Dolezal et al., 1982). Another mechanism to reduce the occurrence of cold shortening is through the use of electrical

stimulation (Savell et al., 2005). Anaerobic glycolysis is quickened during electrical stimulation due to the depletion of energy stores caused by muscles contracting when an electric current is passed through the carcass (Savell et al., 2005). This causes a quicker drop in pH in the carcasses. Carcasses can be chilled quicker without the concern of muscle temperatures dropping too low before the onset phase of rigor mortis is completed. Shortening of sarcomeres is known to have a negative effect on tenderness. When carcass go through normal rigor processes, sarcomeres are shortened 10-15%, whereas in cold shortening muscles sarcomeres can be shortened upwards of 50% (Bruce and Aalhus, 2017).

Thaw rigor is another tenderness issue that can arise from the improper chilling of meat. Thaw rigor occurs when muscle is frozen before entering rigor mortis, when thawed the final phases of rigor mortis are completed (Matarneh et al., 2017). When muscles are frozen, *sarcoplasmic reticulum's* become damages, and the subsequent thawing results in a large release of Ca^{+} that can shorten muscle bundles by up to 60-80% in severe cases (Matarneh et al., 2017). With these current chilling conditions applied at beef processing facilities, the occurrence of thaw rigor would be extremely rare.

Bone Sour

Another quality issues that improper chilling of beef carcasses can also be attributed to is the incidence of bone sour or bone taint. Bone sour is defined by the University of Nebraska, Lincoln, as the sour odors found in the beef round or pork ham near the femur bone, often caused by anaerobic bacterial contaminations of the synovial fluid of the bone joints (UNL). Research has shown that when beef carcasses are exposed to unideal cooling conditions such as deep tissue temperatures dropping to only 20˚C within 20 hours postmortem, the frequency of psychotropic *Clostridium spp.* that cause offensive odors are present in the joints of the hind legs

of beef carcasses being present increases (Lacy et al, 1998). Chilling the deep tissue location in the hind leg of beef carcasses is challenging because that primal is the deepest and has the highest volume. Some processing facilities are having increasing occurrences of bone sour, therefore, better controlling the chilling of beef carcasses, specifically focusing on adequate deep tissue temperature decline, can help to combat the quality issue of bone sour.

USDA Quality Grading

Carcasses that are chilled for a longer period of time typically will result in higher marbling scores, and thus a more valuable USDA quality grade. A study was conducted in 1980 that found that carcasses held as control carcasses that were not electrically stimulated graded better and had higher USDA quality grades when chilled for 48 hours compared to the treatment group that were electrically stimulated and chilled for 24 hours (Calkins 1980). There was no evidence in the study that suggested the greater amount of marbling in the control carcasses was due to not being electrically stimulated. The industry has termed cattle that chill for a longer period of time as "weekend cattle" (Stiffler 1982). Cattle slaughtered on a Friday will be left to chill over the weekend and be graded the following Monday, thus the chilling time for these cattle will be longer than those cattle harvested earlier in the week. Carcasses graded on a Monday compared to a other days of the week will have a slightly higher percentage of being USDA Choice or higher (Stiffler et al., 1982). Due to these findings, processing facilities could create more value by chilling carcasses for a longer period of time in order to have a higher percentage of premium quality grading cattle.

Table 1.1: Correlation between increasing cattle weight and increasing USDA Choice and Prime quality grades (USDA).

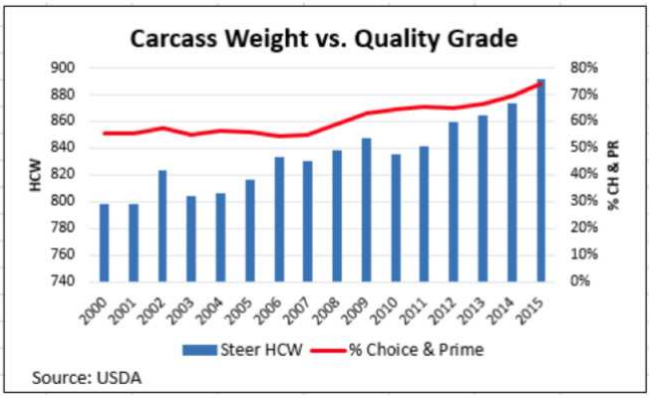

Table 1.2: Example beef slaughter HACCP model with chilling as a critical control point (CCP) (USDA FSIS 1996).

Beef Slaughter Model

Ingredient/Process Step	Potential hazard introduced, controlled or enhanced at this step	Is the potential food safety hazard significant? Risk:Severity	Justification for decision	What control measures can be applied to prevent the significant hazards?	Is this step a critical control point (CCP)?
Spinal Cord Removal	C: Not applicable P: Not applicable B: Microbiological	Unknown at this time.	Not enough scientific evidence to sufficiently address this issue.		No
Interventions (Scientifically proven anti-microbial interventions)	C: Chemical P: Not applicable B: Microbiological	C: No B: Yes	C: Must use only approved sources of chemical intervention(s). B: Potential for residual microbiological contamination.	Proper operation of the intervention technology (i.e., heat, chemical, etc.) to reduce the presence of vegetative foodborne pathogens.	Yes CCP 1-B
Chill Load Hold Unload Grade/sort/store	P: Not applicable C: Not applicable B: Microbiological - bacterial pathogens	B -Yes	Improper chilling may allow for growth of bacterial pathogens.	Proper chilling in an appropriate time period to reduce likelihood of pathogen growth.	Yes CCP - 2-B

Beef Slaughter Model

Process Step	CCP/ Hazard Number	CCP Description	Critical Limits	Establishment Monitoring	Corrective Action	HACCP Records	HACCP System Verification
Carcass Chill	CCP - 2B	Chilling of carcass	Establish refrigeration parameters for suction pressure, coil temp., equipment operations, etc. to reach a carcass surface temperature of 40°F or less within 24 hours. Carcasses cannot touch each other. *Note: Insufficient scientific data exist regarding the growth of pathogens during carcass chilling. However, the chilling parameters provided above will control quality and limit the growth rates of even psychotrophic spoilage organisms. Therefore, these parameters are more than sufficient to prevent growth of mesophilic enteric bacterial pathogens.*	Monitor defined refrigeration parameters: a. suction pressure and coil temperature, etc. b. equipment operations, i.e. fans. c. carcass spacing d. continuous spray chill temperature and intervals OR Carcass surface temperature. Measure 5 randomly spaced/day/hot box and check carcass spacing. Temperature taken 1 mm under faschia on the inside round. **All monitoring procedures must be completed by personnel responsible for the function.	Hold product, evaluate significance of deviation, determine product disposition (i.e., reprocessing, cook, condemn, etc.) Notify plant designee. Identify cause and prevent reoccurrence. If needed, notify maintenance to adjust refrigeration parameters to bring temperature into compliance. If needed, adjust carcass spacing and retrain employees.	Carcass chill log. Calibration log. Deviation/corrective action log. Verification log. Hold summary log.	HACCP coordinator or trained designated employee must daily review HACCP records prior to shipping product. Periodic calibration of thermometers (i.e. weekly) Quarterly documentation of refrigeration parameters to achieve established limits. Daily carcass temperature checks should be taken to verify that 40°F is reached.

CHAPTER 2

MAPPING TEMPERATURE DECLINE IN BEEF CATTLE DURING CONVENTIONAL CHILLING

Institutional Animal Care and Use Committee approval was not required for this study as samples were obtained from federally inspected beef harvest facilities.

Introduction

Beef cattle have continued to increase in size consistently over the last 20 years in the United States. Due to an average increase in hot carcass weights of over 6 pounds per year, carcasses in 2016 were 13% larger than then the average carcasses in 1991 (Boykin et al., 2016). The increase in carcass weights, along with a change in carcass characteristics (i.e. back fat measurements, ribeye areas, and USDA Calculated Yield Grades) have affected the rate of chilling of beef carcasses. Savell (2013) noted four key research gaps related to beef carcasses chilling, this study addressed: "3) To understand how changes in compositional and dimensional aspects of beef carcasses from heavy cattle affect the chilling process " and "4) To determine if a more targeted chilling system could be developed for the beef round primal". Since the change in chilling rates caused by substantially larger beef carcasses is largely unstudied, the objectives of this study were to track continuous temperature decline of beef carcasses of varying size, gain insight on how fat thickness and carcass size affect overall chilling rate, and model the temperature decline of 6 muscles and one surface location on beef carcasses.

Materials and Methods

Experimental Design

A total of 145 beef carcasses (N=145) were selected in three weight ranges at a single conventional beef processing facility in Northeast Colorado. The carcasses selected were of beef cattle type (excluding dairy type carcasses), under 30 months to ensure no pre-hot box sorting, and free of major trimming defects to help standardize the rate of chilling for all locations of focus. The experiment was a blocked, nested, repeated measure design. All carcasses were blocked by weight range with the light range carcasses weighing between 650 and 750 pounds (n=49), the medium range carcasses weighing between 850 and 950 pounds (n=49), and the heavy range carcasses weighing between 1050 and 1153 pounds (n=47). The medium weight ranges were chosen based of the 2016 National Beef Quality Audit hot carcass weight average for steers and heifers (Boykin et al., 2016). The medium weight range would incorporate 51.3% of the cattle harvested in 2016 (Boykin et al., 2016). The light and heavy weight ranges were chosen based off of specific beef plant and national average trends for fed cattle. The light weight ranges would incorporate cattle weighing around the bottom 6% of cattle harvested in 2016, and the heavy weight class would include cattle weighing around the top 5% of cattle harvested in 2016 (Boykin et al., 2016). Carcasses were nested by carcass location (6 muscles and 1 surface location) and a repeated measure was utilized at 20 differing time points ranging from 30 minutes post electrical stimulation to 28 hours post electrical stimulation (30 minutes, hours 1, 2, 3, 4, 5, 6, 7, 8 10, 12, 14, 16, 18, 20, 22, 24, 26, and 28).

Post Electrical Stimulation

Three to five carcasses were collected per sampling period over 6 months. Temperature recorders; LogTag model TRED30-7R (Global Sensors, LLC. Belmont, North Carloina) and

Temprecord General Multi-Use Temperature Logger (Global Sensors, LLC. Belmont, North Carolina); were inserted in carcasses within 7 minutes after the electrical stimulator and placed in the following anatomical location on one side of each carcass: 1)brisket/ plate (deep pectoral), 2) deep chuck (medial side of scapula, clod heart, 3) deep tissue location (*Semimembranosous),* 4) *Gluteus medius* (sirloin), 5) *Longissimus dorsi* at 12th rib, 6) surface of carcass (5mm under the fascia) at the 11th rib 7) *Psoas major* (tenderloin) and 8) ambient temperature located at top of hind quarter with probe facing distal from the carcass. Ambient temperature was tracked per group of carcasses that were located in the same area of each hot box. Surface temperature locations are commonly taken in beef processing facilities from the inside round, however, during this study, surface temperature was taken at the 11th rib for ease of insertion.

Temperature probes were inserted fully (5 inches) into the muscles of the deep tissue (SM), deep chuck, *Gluteus medius* (sirloin), *Psoas major* (tenderloin) at an upward angle parallel to the length of the muscle, and brisket/ plate locations. Probes were inserted 3 inches into the *Longissimus dorsi* muscle to be approximate with the geometric center of the muscle. The surface location probe was inserted parallel to the outer surface fat layer approximately 5 inches at the 11th rib. Temperature probe locations can be seen visually in Appendix C. All temperature recorders were set to record temperature every 30 seconds for the length of the hot box chilling period (approximately 30 hours) from post electrical stimulator until the carcasses left the hot boxes for the sales cooler.

The five digit carcass identification number listed on carcass tag, time at electrical stimulator, if electrical stimulator was being utilized (yes or no), and carcass side (left versus right) was recorded. Carcasses side differed (left versus right) when lead (right) side was not utilized due to major trimming defects in carcass locations of interest. To track immediate

surface temperature, an infrared thermometer (RYOBI, model IR002) held 6 to 8 inches from the carcass at the surface of the 10th rib was recorded immediately post electrical stimulator. The use of the infrared thermometer was not consistent due to faults with the thermometer, and will not be used for further analysis in this study. To better evaluate overall carcass size and dimension, carcass length was measured. Carcass length (in.) was measured using a traditional measuring tape from the bottom of the first rib to the tip of the aitch bone in the un-ribbed beef carcass. Time (minutes) from electrical stimulation to final rail location in hot boxes (time the rail was completely filled) was calculated, and the time (minutes) from final rail location in hot boxes to the time the spray chill started on that rail was calculated.

Hot Box Chilling

Carcasses chilled in one of six hot boxes located at the beef processing facility. Hot box number, rail the carcasses were located on, and the section within each rail (one through five, with one being the carcasses entering last on the rail and 5 being the first carcasses to enter the rail) were recorded. Hot boxes are designed in that hot boxes 1-2, hot boxes 3-4, and hot boxes 5-6 share the same air flow system. Therefore, temperature of a given hotbox may affect the temperature and air flow of the attached hot box. Carcasses selected were distributed amongst all 6 hotboxes at varying rail locations within each hot box . Furthermore, hot box activity including cleaning schedules, spray chilling faults, and carcass rail crowding was visually evaluated by trained personnel.

Carcasses chilled in hotboxes for approximately 30 hours until moving into the sales cooler to be ribbed and graded. Hour 28 is used as the final chilling temperature time due to all carcasses reaching a minimum chilling time of 28 hours. Cattle slaughtered on Friday's were then held until production re-started on Monday's, resulting in an overall chilling time of around

78 hours, however, hour 28 was still utilized as the final chilling hour to standardize chilling times.

Sales Cooler

Immediately prior to carcasses being graded, temperature recorders were removed. Carcasses were ribbed by plant personnel, allowed time to bloom for approximately 25 minutes, then then graded by USDA AMS (Agricultural Marketing Service) personnel. Yield and quality data was recorded by trained CSU personnel that included ribeye area (in^2.), back fat thickness in the form of a preliminary yield grade (PYG), adjusted back fat thickness (aPYG), kidney pelvic and heart fat percentages (KPH), color maturity scores on the *Longissimus dorsi* at the 12^{th} rib, and marbling score on the *Longissimus dorsi* at the 12^{th} rib. Carcasses were also evaluated using the Carcase Classification Scheme from the European Commission (EUROP Scale) for carcass confirmation and carcass fat cover (Appendix A and B) (RPA L&M 2011).

Color was evaluated on the *Longissimus dorsi* at the 12^{th} rib using a calibrated portable spectrophotometer (Hunterlab Associates Laboratory, Inc., Reston, Virginia) and recorded as L* a* and b* values. Additionally, a slice of the *Longissimus dorsi* muscle at the 13^{th} rib was collected by plant personnel to test ultimate pH. After being brought to the Colorado State University Center for Meat Safety and Quality, pH tissue samples were stored at -80˚C. Tissue samples were mixed using a mortar and pestle and then diluted in a 1 to 10 ratio with distilled water. Tissue samples were then vortexed for 30 seconds, allowed time to settle for a minimum of five minutes and vortexed for an additional 30 seconds. Following, pH measurements were taken using a calibrated pH reader with glass electrode (Denver Instruments, Arvada, Colorado).

Statistical Analysis

Temperature recorders were downloaded by date and temperature recorder identification number and evaluated by trained personnel for accuracy. Not all temperature data was utilized in the study due to faults in the temperature recording devices. Using MATLAB R2017b (9.3.0.713579) by MathWorks, a custom code selected data points from each temperature recording from start of logging at: 30 minutes, hour 1, hour 2, hour 3, hour 4, hour 5, hour 6, hour 7, hour 8, hour 10, hour 12, hour 14, hour 16, hour 18, hour 20, hour 22, hour 24, hour 26, hour 28, and hour 30. Temperature data by time was then compiled with additional data collected at time of evaluation.

Statistical analysis was completed using RStudio, Version 1.0.136. Alpha level was set at 0.05. Least square means were calculated for the 20 time points using the 'emmeans' package. Least square means for all time points, location, and weight category were calculated from a model using temperature (˚C) as the response variable; the interaction between weight category, carcass location, and temperature time as fixed variables to account for the repeated measures of location and time, and individual carcass identification number as a random effect.

Additional analysis was conducted be setting time ranges by time points of similar slopes and a change in temperature (˚C) per hour were calculated for each time range. The chilling ranges post electrical stimulation were ranges: 1-3 hours, 4-6 hours, 6-12 hours, 13-18 hours, 19-24 hours, and 24-28 hours. Least square means were calculated for all weight categories and carcass locations for each temperature range.

Temperature decline charts were made using Microsoft Excel Version 16.13.1 (180523). Least square means from each weight category and carcass location were plotted and a polynomial line was drawn from each point on the graph for each weight category and carcass

location. Deep tissue (SM) and surface locations were used an anchors for these figures and were plotted in every graph, with the five other carcass locations being plotted in separate graphs along with the deep tissue (SM) and surface locations.

An additional model was created for USDA grading and EUROP classification grading standard variables for the effect on Temperature (˚C) without the effect of weight category. Least square means were calculated for variables of significance ($P < 0.05$) and trending values ($P < 0.10$) on temperature (˚C) for hours 1, 3, 6, 12, 18, 24, and 28.

Correlation values were calculated in RStudio using the 'cor' package for each muscles individually. The correlation matrix's for each of the seven carcass locations can be found in Appendix D. Correlation values were calculated for: Temperature (˚C) for hours 1, 3, 6, 12, 18, 24, and 28, USDA calculated yield grade (2-4), ribeye area (in^2.), adjusted preliminary yield grade, kidney pelvic and heart fat, EUROP fat cover score, EUROP confirmation score, color in the forms of L*, a*, and b*. Besides high correlation values between temperature ranges and L*a*b* values, which was to be expected, no other strong (>0.80) correlation values occurred. 'NA' values occurred in the correlation graphs when the standard deviation value was too low to calculate a correlation between variables. 'NA' values also appeared for ultimate pH levels, thus pH was not included in the correlation matrix.

Results and Discussion

Summary Results

Summary results can be found in Table 2.1. Carcass characteristics differed for the three differing weight categories due to the weight being the treatment of this study. The average weight was 707 pounds for the light weight carcasses, 897 pounds for the medium weight carcasses and 1081 pounds for the heavy weight category carcasses. Additionally, yield characteristics differed for each weight category ($P < 0.05$) for ribeye area (in^2) and adjusted preliminary yield grade (aPYG) for each weight category. As expected, the larger carcasses had a larger ribeye area, and tended to have a greater amount of back fat, likely to do being on feed for a longer period of time, resulting in a larger weight and greater fat deposits. Yield grade differed ($P < 0.05$) between the heavy versus medium and light weight categories, with the heavy weight carcasses being lower yielding and thus having a higher yield grade. Kidney, pelvic and heart fat percentages differed ($P < 0.05$) between the light versus medium and heavy weight ranges, with the light weight carcasses having a higher percentage of kidney, pelvic and heart fat. These results were expected, as heavier weight carcasses typically have a lower percentage of KPH fat relative to overall hot carcass weight. Differences were found ($P < 0.05$) for carcass length (inches) between all three weight categories. The heavy weight cattle were the longest from aitch bone to first rib, followed by the medium then light weight cattle, showing that overall frame size also increases as cattle get bigger. Therefore, the differences in weight between the three categories were a combination of muscle size differences, fat deposition differences, and overall frame size differences. A relatively strong correlation value (0.495) was found between carcass length and ribeye area (Appendix D), further showing a relationship between overall carcass dimension size and muscling amount.

When grading carcasses with the European Carcass class grading scale, differences ($P < 0.05$) were found for light versus medium and heavy weight ranges for confirmation score, with the light weight ranges having lower confirmation scores, indicating lesser amount of fat deposits, which agrees with the results for adjusted PYG and USDA calculated yield grade from this study (RPA L&M 2011) (Table 2.1). Furthermore, there were differences ($P < 0.05$) between the light and heavy weight ranges in EUROP muscle scores, showing heavier carcasses to be more muscular (RPA L&M 2011). Since dairy type carcasses were excluded from this study, the muscle differences from ribeye area size and the EUROP muscle score values are from an increase in hot carcass weight rather than cattle type. There were no differences ($P \geq 0.05$) for ultimate pH in the *Longissimus dorsi* muscle taken at the 13th rib. The pH ranges were almost all in the optimum pH range (Matarneh et al., 2017), with the range for final pH ranges between 5.4 to 5.5 for all weight categories (Table 2.1). There were two carcasses that were dark cutters with pH measurements being above 6.0 (Matarneh et al., 2017) and one carcass that showed visual color characteristics of being a dark cutter, and also had a final ultimate pH of 5.8.

From a quality grading perspective, marbling scores differed ($P < 0.05$) between all weight ranges, with larger weight carcasses having a greater amount of marbling (Table 2.1). These increases in marbling score can be partially explained by the abundance of large weight category carcasses being from a certified natural program. Natural cattle that have not received hormone implants have been proven to have higher degrees of marbling when compared to conventionally raised cattle that did receive hormone implants (Platter et al, 2002). Additionally, as hot carcass weight increases, percentage of carcasses grading USDA Choice or higher increases, partially explaining why the heavier weight cattle have a greater amount of marbling (Dkystra 2013) Moreover, the differences in marbling score of 40 degrees were not meaningful

enough to cause an increase in overall quality grade, meaning that all carcasses that were 'A' maturity would be graded USDA Low Choice, independent of weight category. There were color differences ($P < 0.05$) for L* values between the light versus medium and heavy carcasses, and differences ($P < 0.05$) between the light and heavy weight carcasses for a* and b* values (Table 2.1). Carcasses that weighed more generally had a better overall brighter, more cherry-red color when viewed from a three dimensional space, as indicated by higher tendencies of L*a* and b* values. Differences ($P < 0.05$) amongst weight categories were present for the time it took carcasses to go from electrical stimulator to final hot box location, although this differences should not be explained by differences in hot carcass weights but rather by days of week and times of the day the carcass data was collected. No differences ($P \geq 0.05$) were found for the time it took the spray chill to activate from when the carcasses reached their final rail location (Table 2.1).

Carcass Weight Categories

Least square means for all weight categories (i.e. light, medium, and heavy) at all carcass locations (i.e. *Longissimus dorsi* at 12th rib, surface of carcass (5mm under the fascia) at the 11th rib, deep tissue location (*Semimembranosous),Gluteus medius* (sirloin), *Psoas major* (tenderloin), deep chuck (medial side of scapula, clod heart), brisket/ plate (deep pectoral)) at all time points (30 minutes to 28 hours post electrical stimulation) can be found in Tables 2.2, 2.3, and 2.4. Deep tissue (SM) and surface locations were used as benchmarks in this study due to the importance of these locations for beef processing facilitates for food safety (i.g. HACCP, BRC) and quality (i.g. Quality Assurance) programs. Beef processing facilities monitor deep tissue temperatures from random carcass samples in hot boxes and the sales coolers because the round has the largest mass size of all primals and the second highest primal weight (NCBA

2013), and can thus can have difficulties in being adequately chilling. The surface is a location that beef processing facilities monitor closely, and most often, is included as part of the critical limits of a critical control point (CCP) in HACCP plans. This limit is most often set at 40˚F within 24 hours of chilling (Figure 1.2). As expected, the heavy weight carcasses within each carcass location had the highest overall temperatures, followed by the medium and then the light weight carcasses for most all the carcass locations.

In the deep tissue (SM) location, no differences ($P \geq 0.05$) were found among all three weight categories through hour 10 of chilling (Tables 2.2, 2.3 and 2.4). However, the heavy weight category consistently had the highest numeric temperature, followed by the medium weight category, then the light weight category. Starting at hour 12, the light versus heavy deep tissue (SM) weight categories differed ($P < 0.05$), although no differences ($P \geq 0.05$) were present between the medium and heavy weight categories and the medium and light weight categories. This trend of differences ($P < 0.05$) continued between the light versus heavy weight carcasses in the deep tissue (SM) location until the final hour of chilling (Hour 28). At hour 28 the light weight carcasses were 2.88˚C lower than the heavy weight carcasses in the deep tissue (SM) location. No differences ($P \geq 0.05$) were found between the medium and heavy weight carcasses during the all chilling times in the deep tissue (SM) location. Thus, the heavy and medium weight cattle did not have different temperature declines in the deep tissue (SM) location, though the light weight carcasses did chill faster in the deep tissue (SM) location.

From a regulatory standpoint, no carcass weight categories in the deep tissue (SM) location met the stricter recommendation of 4˚C by the final hour (hour 28) of chilling, and only the light weight carcasses met the 7˚C recommendation by the final hour of chilling (Figure 2.1). There are opportunities within the round primal to improve quality characteristics, like reducing

the incidence of bone sour, by improving rate of chill within the deeper tissue of the round primal (De Lacey et al., 1998). The weight categories in the deep tissue (SM) location did not have differences ($P \geq 0.05$) in decrease of temperature (˚C) per hour, as shown in Table 2.5. The differences in weight did not cause heavier nor lighter carcasses to decrease in temperature (˚C) per hour at differing speeds.

At the surface location, no differences ($P \geq 0.05$) were found between the three weight categories during any portion of the chilling process from 30 minutes post electrical stimulation until 28 hours post electrical stimulation (Tables 2.2, 2.3, 2.4). Therefore, weight category does not affect the surface temperature at the 11th rib during the chilling process. The surface location of the light and medium weight carcasses met the 4˚C guideline after 24 hours of chilling, satisfying common HACCP critical control limits. The heavy weight range was very close to the 4˚C guideline at hour 24 and still fell below 40˚F. Heavy weight carcasses at the surface location met the 4˚C recommendation at hour 26. Weight category does not affect the chilling rate at the surface location for facilities following critical control limits of less than 40˚F within 24 hours of chilling.

In the *Longissimus dorsi* (LD) muscle, no statistical differences ($P \geq 0.05$) were found between the weight categories 30 minutes and 1 hour post electrical stimulation (Table 2.2). In hours 2 through 6 and 12 through 14, the light weight carcasses differed ($P < 0.05$) from the medium weight carcasses in the LD location (Table 2.3 and 2.4). In hours 2 through 26, the light weight carcasses differed ($P < 0.05$) from the heavy weight carcasses in the LD location, with a maximum difference of the light weight carcasses being 5.02˚C lower than the heavy weight carcasses at hour 5. As shown on the bottom graph in Figure 2.1, in the LD location, the light weight carcasses had a large difference in temperature as compared to the medium and heavy

weight carcasses that were much more similar in temperature decline. During the chilling process, the heavy and medium weight carcass did not differ ($P \geq 0.05$) in the LD location, similar to results shown in from the deep tissue (SM) location. When differences did occur in the LD location, the light weight carcasses were always lower in temperature (˚C) then the medium and heavy weight carcasses. Thus, the light weight carcasses chilled faster than the medium carcasses at several hours of the chilling process and faster than the heavy weight carcasses during most all time points during the chilling process.

All weight categories within the *Longissimus dorsi* location met the guideline of being less than 7˚C within 24 hours of chilling. Only the light weight carcasses met the recommendation of less than 4˚C within 24 hours of chilling; the medium weight LD location was very close to 4˚C at the final hour (Hour 28) of chilling while the heavy weight LD location never met the 4˚C guideline at the final hour of chilling. Weight classification did effect the decrease in temperature (˚C) per hour until hour 26 at the *Longissimus dorsi* location between carcasses weighing 650-750 pounds versus carcasses that weighed 1050-1150 pounds (Table 2.5).

The chuck has the highest weight percentage of any primal in the carcass (NCBA 2013), thus it was expected to have similar differences in weight category temperature decline as the deep tissue (SM). However, few differences were found among weight categories in the deep chuck location, with no differences ($P \geq 0.05$) found among any weight category in the last 18 hours of chilling. The temperature probe was located at the geometric center of the primal, though this primal has a much larger surface area when compared to the round primal, which may explain why there are fewer differences among weight category temperature decline in the chuck. At hours 2-7 the medium weight carcasses had a higher numeric temperature than the

heavy weight carcasses, though these differences were not meaningful ($P \geq 0.05$). These results were not consistent with other carcass locations because in almost all other locations at all time points, the heavy weight carcasses had the highest numeric temperature value. Figure 2.1 maps the temperature decline of the deep chuck in the center graph. From visual appraisal, the light weight deep chuck had a faster decline in the initial hours of chilling. Table 2.5 shows that the light weight carcasses in the deep chuck location had a faster temperature (˚C) decline per hour ($P < 0.05$) per hour compared to the medium and heavy weight carcasses for hours 1-3 and differences ($P < 0.05$) in light and heavy versus medium in hours 4-6.

At hour 24, no weight categories in the deep chuck location met the 4˚C recommendation for chilling, and only the light weight carcasses met the recommendation for 7˚C during hour 24. At the final hour of chilling (hour 28), the deep tissue location still did not meet the 4˚C guideline. These results show that there are opportunities to more adequately chill the chuck primal.

Similar to the muscles of the chuck primal, the *Gluteus medius*, or sirloin, location did not show major changes in temperature decline between the three weight categories (Table 2.2, 2.3, and 2.4). Minor differences ($P < 0.05$) occurred at a few hours earlier in the chilling process among the light and heavy weight carcasses, though these trends did not hold consistent during any time during chilling. The sirloin location was expected to show differences amongst weight categories due to the deepness of the *Gluteus medius* situated within the carcass. Comparable to trends seen with other locations, the heavy weight carcasses did have a higher temperature at each time point followed by the medium then the light weight carcasses, although these results do not show meaningful ($P \geq 0.05$) differences. The weight of the carcasses did not play a meaningful role in the overall decline of the sirloin sub primal.

In the first temperature range of 1-3 hours post electrical stimulation, the light weight carcasses in the sirloin location had a larger drop ($P < 0.05$) in temperature (˚C) per hour than the other weight categories, however, as chilling continued no differences ($P \geq 0.05$) in rate of temperature decline per hour appeared amongst the weight categories (Table 2.5). The sirloin location needs to be chilled at a faster rate in order to meet recommendations of being less than 4˚C within 24 hours of chilling, as only the light weight carcasses numerically met the recommendation at the final time of chilling at hour 28.

Immediate differences ($P < 0.05$) in the brisket/ plate location were seen in the chilling process between the light and medium versus heavy carcasses (Table 2.2), with the light carcasses being almost 5˚C lower than the heavy carcasses. The brisket/plate location had a very rapid decline in the first half of the chilling process, with the light carcasses being lower in temperature ($P < 0.05$) than the heavy weight carcasses through hour 7. Starting at hour 8, no differences ($P \geq 0.05$) were observed through the final hour of chilling (hour 28) amongst all three weight categories (Table 2.3 and 2.4). Therefore, chilling rate was effected in the brisket/ plate location in the beginning of chilling, but temperatures between weight categories equilibrated during the later hours of the chilling process. As shown in both Figure 2.2 on the top graph and in Table 2.5, the starting ranges of hours 1-3 and hours 4-7 had a much larger decline in temperature (˚C) per hour, with temperature drop becoming lesser at the ending hours of chilling. The brisket is a portion of the carcass that is composed of thinner muscles with a large surface area. As expected, the brisket had a larger decline in temperature during the opening hours of chilling, similar to the surface location, the slowed down as the muscles of the brisket sub primal became more equal with those temperatures in the hot boxes.

The brisket/ plate location met all guidelines for chilling recommendations by reaching 4˚C within 4 hours of chilling among all weight categories. The hot carcass weight of beef animals did not play a role in the temperature decline of muscles within the brisket sub primal.

The *Psoas major*, or tenderloin, is a very important muscle to track temperature in, to ensure high quality characteristics of such a valuable cut, specifically relating to color inconsistency. Though color was not scored on the *Psoas major* in this study, chilling rate can still be used an influencer to final color. Weight category did not have an effect on the temperature of the tenderloin at any time point during chilling (30 minutes to 28 hours post electrical stimulation), as shown in Tables 2.2, 2.3 and 2.4.

Differences in the temperature decline per hour for the tenderloin were atypical of results from other carcass locations. The rate of change of temperature (˚C) decline per hour was different ($P < 0.05$) in the light versus medium weight carcasses in hours 1-3, although the light and heavy weight carcasses were the same ($P \geq 0.05$) (Table 2.5). Though these results were statistically significant, they differences were not in high enough quantities to make major conclusions about rate of chilling within the tenderloin. Difference in kidney, pelvic, and heart fat (KPH) percentages may have played a role in the temperature decline of the tenderloin due to the KPH covering the muscle and potentially providing a greater amount of insulation for the muscle in terms of temperature decline postmortem. There were differences ($P < 0.05$) in KPH percentages between weight categories. Thus, lighter carcasses may have more insulation around the tenderloin due to greater amounts of KPH percentages (Table 2.1). This does not explain the greater temperature decline. Moreover, these results do not help explain why the medium weight carcasses within the tenderloin location had a lower drop in temperature (˚C) per hour in hour 1-3 post electrical stimulation than the heavy weight carcasses.

Carcass Location Comparison

The muscles that were larger in mass were generally slower chilling than muscles and locations of thinner, more distal areas to the carcass. These results can be seen in Tables 2.2, 2.3, and 2.4. The deep tissue (SM) location had the slowest rate of chill, beginning and ending with the highest temperature (˚C), and the surface location had the fastest rate of chill, beginning and ending with the lowest temperature (˚C), as expected. All carcass locations experienced a faster decline in temperature (˚F) per hour (Table 2.5 and Figures 1.1 and 1.2) during the initial hours of chilling, then leveled off more during the second half of the chilling process. The carcasses had larger decreases in temperature per hours initially because the difference between the carcass temperature and the hot box ambient temperature was very large. Heat from the carcass could be more quickly dissipates when the difference between ambient and carcass temperature are higher.

Muscles that were located more internal of the carcass and that represented larger primals of beef carcasses (i.e. deep tissue (SM), deep chuck, and sirloin) had more similar rates of temperature decline (Figure 1.1 and 1.2) and had an overall slower rate of chill compared to other carcass locations. Muscles that were located in areas of the carcass with thinner muscle cuts, larger surface areas, and being more distal to the carcass (i.e. brisket/ plate, and surface) had the fastest rate of chill and began and ended the chilling process at lower temperatures then other carcass locations. Two muscles, the LD and the *Psoas major* (tenderloin), had rates of chill that were in between the deeper, larger carcass locations and the thinner, more distal carcass locations.

The deep tissue location started at 30 minutes post electrical stimulation around 40˚C, and ended at 28 hours post electrical stimulation around 6.5 to 9˚C. The surface temperature

started 30 minutes post electrical stimulation at 26.5 to 28 ˚C and ended at hour 28 at 2 to 3˚C. There was a difference of around 6˚C between the deep tissue (SM) and the surface locations at the final hour of chilling, and that 6˚C spread crossed both food safety recommendations of carcasses chilling at either 4˚C or 7˚C within 24 hours of chilling. Ultimately, the surface temperature satisfied both food safety chilling recommendations, however, the deep tissue (SM) location did not reach the 4˚C limit, with only the light weight carcasses in the deep tissue (SM) location reaching below the 7˚C limit at the final hour of chilling. In the time range between 1 and 3 hours, the surface temperature had larger drops in temperature per hour as compared to the deep tissue (SM) location. This is due to the fact that the surface location has less insulation, and can drop quicker in temperature to become more level with the ambient temperatures in the hot boxes. Moreover, the surface location was the only carcass location not located directly inside muscle tissue, thus it is the only carcass location that was not going through the rigor mortis and glycolysis process. In the initial hours of chilling, the surface location has larger decreases ($P<0.05$) in temperature decline per hour as compared to the deep tissue (SM) location. The deep tissue (SM) location did not drop as quickly in the initial hours of chilling compared to the surface location, due to the fact that the deep tissue (SM) location is a much larger muscle mass and took a longer period of time for the higher temperatures deeper within the muscle of the round to decrease. The deep tissue (SM) location did still experience the largest decrease in temperature per hour in the first half of the chilling process. Overall, the deep tissue and the surface locations had similar shapes in temperature decline (Figure 2.1), with the greatest difference being that the surface location was 6-14˚C lower in temperature throughout the entire chilling process.

The deep chuck and the deep tissue (SM) locations had the most similar temperature declines during the chilling process (Figure 2.1). This is to be expected, as the chuck and the round primals are the largest primals on the carcass, comprising of over 50% of carcass weight (NCBA 2013). Therefore, these primals have the slowest rate of chill while also being the most similar in temperature decline corresponds well carcass primal size. Weight categories between the deep tissue (SM), and the deep chuck had similar temperatures (˚C) during the chilling process (Tables 2.2, 2.3, and 2.4), with only the light weight deep chuck differing ($P < 0.05$) from the deep tissue locations at hours 1-8, and both light categories differing ($P < 0.05$) from medium and heavy carcasses at hours 10-28 for both the deep tissue (SM) and deep chuck locations. The two locations also started and ended the chilling process at similar temperatures, with both locations starting 30 minutes post electrical stimulation around 37.5-40˚C and ending at 28 hours post electrical stimulation at 5-9˚C. When looking at temperature decline per hour (Table 2.5), the deep tissue (SM) and deep chuck locations showed no differences ($P \geq 0.05$) in rate of decline in hours 13-18, 19-24 and 25-28, with on the light deep chuck location being different ($P < 0.05$) from the other weight categories and location in hours 7-12. During temperature (˚C) decline per hour, ranges 1-3 and 4-6 some smaller differences ($P < 0.05$) occurred between weight categories and locations, however these differences were not meaningful enough to impact over slope of rate of chill amongst the two carcass locations.

The *Gluteus medius* (sirloin) location was similar to the deep tissue (SM) temperature decline slope (Figure 2.2). Statistical differences ($P < 0.05$) amongst weight categories occurred between the two carcass locations, however the beginning and final temperature range between the two locations was of comparable ranges. The sirloin started at 30 minutes post electrical stimulation around 38-39˚C, whereas the deep tissue (SM) location started around 40˚C. The

sirloin location ended at 28 hours post electrical stimulation at 4.5-7˚C, and the deep tissue (SM) location ended the chilling process at 6-9˚C. At the final hour of chilling (hour 28) the only difference ($P < 0.05$) was that the light weight sirloin location had a lower temperature than the other weight categories within the sirloin and deep tissue (SM) location. The sirloin also had very similar decreases in temperature (˚C) per hour compared to the deep tissue (SM) location (Table 2.5), with only the light sirloin location differing ($P < 0.05$) from the other weight categories and locations in hours 1-3 and 4-6. This can be visually seen by the similarities in shape of temperature decline shown in Figure 2.2. Due to the close proximity of the sirloin and round primal to each other, along with having more similar size masses, the temperature decline of these two primals being similar is easily explained.

The brisket/plate location had the most similar temperature decline to the surface location. Though these locations were not in close proximity to each other on the carcass, both locations are of similar shape and size. The brisket location is located farther away from other subprimals of the carcass that would have larger muscle masses, and is even further separated by the rib cage of the animal. Therefore, the brisket/ plate region would decline in temperature more independently than other muscles. The brisket/ plate location did start off at a higher initial temperature ($P < 0.05$) 30 minutes post electrical stimulation (33-37˚C) compared to the surface location that started at 26-28˚C, but both locations ended at more similar temperatures 28 hours post electrical stimulation (2-3.5˚C) and showed no statistical differences ($P \geq 0.05$) at the final hour of chilling. It was expected that the brisket/plate location would have a higher initial temperature during chilling because the temperature probe was located within the deep pectoral muscle. The muscle would have a greater amount of glycolysis occurring, caused an increase in heat (López-Bote 2017) as compared to just fat tissue being sampled within the surface location.

The brisket/plate location had a faster decline in temperature (˚C) per hour (Table 2.5) than the surface location, and even had the highest numeric temperature decline per hour during the range of 1-3 hours postmortem , declining around 3˚C per hour. However, starting at hours 7-12 the brisket/plate location became more similar in temperature decline per hour to the surface location, along with the other carcass locations. This can also be seen in Figure 2.2; the brisket/plate location had the steepest slope of temperature decline during the first couple hours of chilling then leveled off more similar to the other carcass locations.

The LD and *Psoas major* locations were very similar to each other in rate of temperature decline, which is to be expected as they are very close in proximity to each other on the carcass and also hold more similar muscle masses. The LD and the *Psoas major* are muscles that are in the middle of the size representation of the larger and thinner cuts, thus it was expected that they would have a rate of chill that was in between the deeper versus thinner muscle cuts of the deep tissue (SM) and surface locations. The LD and *Psoas major* represent the middle cuts of the carcass that have the highest retail value (Tatum 2015), therefore, it is very important to ensure these subprimals are being chilled adequately to produce the highest quality product possible. Moreover, the LD location is the muscle that USDA AMS graders use to grade the carcasses for USDA Quality grades. Therefore, if the LD does not reach a low enough temperature by time of grading, then potential grading loss can occur due to the carcasses not having adequate time to chill and for the marbling to contrast with the lean color (Stiller et al., 1982). This may result in lower potential quality grades for the carcasses then if the LD was adequately chilled.

The LD and the tenderloin location started at more similar temperatures to the deep tissue location, being between 37 and 39˚C 30 minutes post electrical stimulation compared to the deep tissue being 40˚C 30 minutes post electrical stimulation (Figure 2.2). After 28 hours of chilling

the LD and tenderloin were between 2-6˚C, which is in between the range of the surface and the deep tissue (SM) locations after 28 hours of chilling. Minor statistical differences ($P < 0.05$) occurred between the light weight *Psoas major* and LD locations versus the other weight categories within the LD and *Psoas major* locations, although no trends held throughout the entire chilling process. During the range of hours 1-3, the LD and the tenderloin had a faster decline in temperature (˚C) per hour then the deep tissue (SM) and the surface locations, being more similar to the rate of temperature (˚C) decline per hour of the deep chuck and brisket/plate locations (Table 2.5).

Other variables influencing rate of chill

Along with hot carcass weight, this study aimed to determine if other grading characteristics effected the chilling rate of beef carcasses. Other variables that were collected at time of slaughter were tested for effects on temperature decline independent of weight range. These included factors required to calculate USDA yield grade (i.e. ribeye area, adjusted preliminary yield grade, and kidney pelvic and heart fat percentages), factors utilized in the European Union grading system (i.e. EUROP confirmation and fat cover scores), and the use of electrical stimulation. For this analysis, differences in temperatures at time points and locations was analyzed without the influence of carcass weight. Carcass length (inches) was not calculated in this model due to its high correlation (0.529) with hot carcass weights. As shown in Table 2.1, other factors (i.e marbling score, final pH of the *Longissimus dorsi* muscle) did not show meaningful enough differences for beef processing facilities to consider when looking at changes in carcass chilling processes.

When running an analysis of variance (ANOVA) for USDA yield grading variables, USDA calculated yield grade had an effect($P < 0.05$) on temperature (˚C) at hours 1, 3, 6, 12, 18,

24 and 28 for all seven carcass locations. Least square means for USDA calculated yield grades can be found in Tables 2.6 and 2.7. Least square means were not calculated for yield grades 1 and 5 due to small sample size within those yield grades. The carcasses that were calculated as yield grade 1's were incorporated into yield grade 2's. The carcasses that were calculated as yield grade 5's were incorporated into yield grade 4's. Ribeye area was trending ($P = 0.0891$) for effect on temperature (˚C), and least square means for ribeye area (in^2) can be found in Table 2.9. Generally, the larger the ribeye area (in2), the higher the numeric temperature at on all time points. Adjusted preliminary yield grade (aPYG) and kidney pelvic and heart fat (KPH) did not have an effect ($P \geq 0.05$) on temperature (˚C) at hours 1, 3, 6, 12, 18, 24 and 28 for any of the all seven carcass locations, although these variables are used to calculate final USDA Yield Grade and thus should still be considered if sorting cattle based on yielding characteristics. Adjusted preliminary yield grade was trending ($P = 0.1092$), showing some effect on temperature (˚C) in all carcass locations at the given time points.

As shown in Table 2.6 and 2.7, carcasses that were yield grade two had lower ($P < 0.05$) temperatures (˚C) in all seven carcass locations than the carcasses that were yield grade three. However, carcasses that were yield grade four showed no differences ($P \geq 0.05$) from carcasses that were yield grade two and three. These results are surprising in that yield grade four carcasses did not chill faster than yield grade two, unlike the yield grade three carcasses that did chill faster than yield grade two carcasses. Higher yielding carcasses (Yield Grade 2) chilled quicker than intermediate yielding carcasses (Yield Grade 3) and resulted in lower final temperatures (hour 28) throughout the entire beef carcass. Therefore, beef processing facilities should take into consideration the yield characteristics of beef carcasses when trying to determine the temperature decline of beef carcasses. However, at this time, USDA calculated

yield grade and ribeye areas are not determined at all beef processing facilities, and if they are determined, would not occur until after 28 hours of chilling by exposing the *Longissimus dorsi* muscle at the 12th rib during the ribbing process. Thus, this would require a change in grading to implement.

After running an ANOVA by the Carcase Classification Scheme (EUROP Scale), Confirmation Score did have an effect ($P < 0.05$) on temperature (˚C) for all carcass locations at hours 1, 3, 6, 12, 18, 24 and 28. Least square means for temperature (˚C) on EUROP Confirmation Score can be found in Table 2.8. Table 2.8 shows no statistical significances ($P \geq 0.05$) between muscle scores in temperature, though heavier muscling scores had higher numeric values than lower muscle scores at all tested time points. Furthermore, the effect for Fat Cover Score on temperature was trending ($P = 0.1039$), thus Confirmation Score may be an influencer to temperature decline. It should be noted, however, that the grading of cattle by the EUROP system was performed by one individual. Results may differ from this study if visual assessment of the EUROP grading system is performed by another individual. For this study, visually accessing carcasses before ribbing using the EUROP scale would be beneficial when estimating temperature decline, especially when pertaining to confirmation score. Both ribeye area and muscle score did have an effect ($P < 0.05$) on temperature in all carcass locations, thus the heavier muscles the carcass the slower the carcass chills.

The use of electrical stimulation did not have an effect ($P \geq 0.05$) on temperature (˚C) at hours 1, 3, 6, 12, 18, 24 and 28 for any of the seven carcass locations. These results disagree with studies showing that electrical stimulation has an effect on temperature decline (Stolowski et al., 2006). Electrical stimulation was not used as a treatment variable for this study and was

not collected as a fixed effect, and therefore, this study should not be used to draw conclusions about the effects of electrical stimulation on temperature decline in beef carcasses.

Conclusions and Industry Implications

In this study, the weight of the carcasses did affect the chilling rate of beef carcasses. Larger, heavier carcasses generally chilled more slowly, especially in deeper, more inner portions of the carcass than did smaller, lighter carcasses. Carcasses that were in the light (650 to 750 pounds) weight category chilled the quickest and generally resulted in the lowest final temperatures in almost all carcass locations. Carcasses that were in the heavy (1050 to 1150 pounds) weight category chilled the slowest and generally had the highest final temperatures in most carcass locations. Medium (850 to 950 pounds) weight carcasses chilled slower than light carcasses, but faster than heavier carcasses, as expected. Lighter carcasses were more likely to meet recommended rates of chilling of 7˚C or 4˚C after 24 hours of chilling. Surface temperatures of all weight categories reached 4˚C within 24 hours of chilling to satisfy food safety programs (i.e. HACCP).

Muscles locations that represented larger carcass primals (i.e. chuck, round and sirloin) chilled the slowest and locations that were of the smallest size and more distal to the carcass (i.e. surface and brisket/ plate) chilled the quickest and reached the lowest final temperatures. Carcass locations that represented the 'middle meats' of the carcass chilled intermediately of the larger versus smaller primals. Furthermore, higher yielding carcasses chilled more quickly and resulted in lower final temperatures throughout the entire beef carcass than those carcasses that are of intermediate yield type.

Beef processing facilities need to adjust the way that beef carcasses are chilled in order to ensure the highest quality product that is safe for consumers. This can be accomplished in

several ways. Beef processing facilities should pre-sort carcasses before they enter the hot boxes and allow larger and/or lower yielding carcasses to chill for a longer period of time. Facilities could also decrease the temperature of hot boxes and allow larger and or lower yielding carcasses to chill more quickly as long as care is taken to not drop carcass temperatures too quickly.

Table 2.1: Summary Statistics for grading and hotbox variables.

Variable	Weight Category			SEM[2]	*P-Value*[3]
	Light (n=49)	Medium (n=49)	Heavy (n=47)		
Carcass Weight, lbs	707.3[c]	896.6[b]	1081.4[a]	4.6	<0.0001
Calculated USDA Yield Grade	2.66[b]	3.16[b]	3.53[a]	0.19	<0.0001
Ribeye Area, in^2	13.16[c]	14.89[b]	16.29[a]	0.32	<0.0001
Adjusted Preliminary Yield Grade	3.28[c]	3.63[b]	3.81[a]	0.09	0.0001
Kidney, Pelvic, Heart, %	2.04[a]	1.94[b]	1.61[b]	0.05	<0.0001
EUROP Fat Cover Score	2.75[b]	3.33[a]	3.52[a]	0.16	0.002
EUROP Confirmation Score[4]	325[a]	294[ab]	285[b]	0.15	0.022
Carcass Length, in	49.47[c]	52.36[b]	56.74[a]	0.51	<0.0001
pH	5.46	5.44	5.42	0.02	0.4056
L*	35.99[b]	37.84[a]	38.26[a]	0.57	0.0002
a*	18.88[b]	19.63[ab]	20.55[a]	0.40	0.016
b*	13.76[b]	14.32[ab]	15.04[a]	0.31	0.017
Marbling Score[5]	458[a]	468[b]	496[c]	13.11	0.106
Time from electrical stimulator to hot box, minutes	25.43[a]	22.04[b]	24.04[ab]	0.9238	0.035
Time from hot box to spray chill starting, minutes	1.667	3.49	7.917	2.132	0.105

[a-c]: Values that do not share a common superscript in row differ (P < 0.05).
[2]SEM is the pooled standard error (largest) of least square means.
[3]Observed significance levels for treatment effect.
[4] 200-299 =R, 300-399 = O.
[5] 400-499 = Small.

Table 2.2: Least Square means of Temperature (˚C) for carcass locations at 30 minutes, hours 1, 2, 3, 4, and 5

Weight Category	Location	30 Minutes	Hour 1	Hour 2	Hour 3	Hour 4	Hour 5
Light	Brisket/ Plate	32.99^{f}	29.35^{f}	23.93^{hi}	20.19^{j}	17.29^{j}	15.16^{j}
Medium	Brisket/ Plate	33.98^{ef}	30.84^{f}	25.28^{h}	21.22^{j}	18.27^{j}	16.19^{ij}
Heavy	Brisket/ Plate	37.2^{cde}	34.16^{e}	29.08^{g}	25.04^{i}	21.84^{i}	19.24^{hi}
Light	Deep Chuck	37.45^{cd}	35.61^{de}	32.32^{defg}	29.08^{efgh}	26.51^{fgh}	24.4^{ef}
Medium	Deep Chuck	38.96^{acd}	37.71^{acd}	35.64^{acd}	32.9^{cd}	30.39^{cd}	28.67^{cd}
Heavy	Deep Chuck	38.9^{acd}	37.83^{acd}	35.03^{cd}	32.35^{cde}	30.04^{cde}	27.87^{cd}
Light	Deep Tissue (SM)	40.34^{ac}	39.49^{ac}	37.17^{ac}	34.61^{ac}	32.13^{ac}	29.87^{ac}
Medium	Deep Tissue (SM)	40.22^{ac}	39.43^{ac}	37.33^{ac}	34.93^{ac}	32.65^{ac}	30.56^{ac}
Heavy	Deep Tissue (SM)	40.84^{a}	40.29^{a}	38.53^{a}	36.2^{a}	33.91^{a}	31.83^{a}
Light	*Longissimus dorsi*	37.78^{acd}	35.41^{de}	30.67^{fg}	26.74^{hi}	23.26^{hi}	20.58^{gh}
Medium	*Longissimus dorsi*	39.36^{acd}	37.9^{acd}	34.08^{cde}	30.24^{defg}	27.01^{efg}	24.15^{f}
Heavy	*Longissimus dorsi*	39.21^{acd}	37.93^{acd}	34.59^{cde}	31.22^{cdef}	28.2^{cdefg}	25.6^{def}
Light	*Gluteus medius*	39.41^{acd}	38.31^{acd}	35.19^{cd}	31.96^{cde}	28.93^{cdef}	26.35^{cdef}
Medium	*Gluteus medius*	38.64^{acd}	37.85^{acd}	35.29^{cd}	32.47^{cd}	29.6^{cdef}	27.5^{cde}
Heavy	*Gluteus medius*	39.76^{acd}	39.03^{ac}	36.84^{ac}	33.97^{ac}	31.32^{ac}	29^{ac}
Light	Surface	26.53^{g}	23.88^{g}	20.51^{j}	18.48^{j}	16.76^{j}	15.18^{j}
Medium	Surface	26.97^{g}	23.78^{g}	20.47^{j}	18.48^{j}	16.94^{j}	15.36^{j}
Heavy	Surface	28.15^{g}	25.16^{g}	21.69^{hj}	19.34^{j}	17.64^{j}	15.8^{j}
Light	*Psoas major*	38.69^{acd}	35.85^{de}	31.5^{efg}	28.16^{fghi}	25.55^{gh}	23.29^{fg}
Medium	*Psoas major*	38.85^{acd}	36.67^{cde}	32.92^{def}	29.97^{defgh}	27.32^{defg}	25.63^{def}
Heavy	*Psoas major*	36.9^{ce}	34.33^{e}	30.42^{fg}	27.66^{ghi}	25.51^{gh}	23.38^{fg}
SEM[2]		0.678	0.678	0.678	0.678	0.678	0.678
P-Value[3]		<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

a-k: Values that do not share a common superscript in column differ (P > 0.05).

[2]SEM is the pooled standard error (largest) of least square means.

[3]Observed significance levels for treatment effect

Table 2.3: Least Square means of Temperature (˚C) for carcass locations at hours 6, 7, 8, 9, 10, 12, 14, and 16

Weight Category	Location	Hour 6	Hour 7	Hour 8	Hour 10	Hour 12	Hour 14	Hour 16
Light	Brisket/ Plate	13.66^{j}	12.37^{j}	11.34^{k}	9.38^{i}	7.66^{h}	6.2^{h}	4.99^{g}
Medium	Brisket/ Plate	14.53^{ij}	13.25^{ij}	12.08^{jk}	10.26^{i}	8.58^{h}	7.08^{h}	5.74^{g}
Heavy	Brisket/ Plate	17.22^{hi}	15.56^{ij}	14.22^{jk}	12.14^{i}	10.44^{gh}	8.95^{fgh}	7.58^{fg}
Light	Deep Chuck	22.68^{ef}	21.21^{efg}	19.9^{efgh}	18.12^{cdefg}	15.96^{cdef}	14.03^{cde}	12.11^{cde}
Medium	Deep Chuck	26.8^{abcd}	24.59^{bcde}	23.38^{bcd}	20.82^{abc}	18.73^{abc}	16.8^{abc}	14.82^{abc}
Heavy	Deep Chuck	25.83^{bcde}	24.08^{bcdef}	22.53^{bcdef}	19.98^{bcde}	18.09^{bcd}	16.59^{abc}	15.2^{abc}
Light	Deep Tissue (SM)	27.78^{abc}	25.87^{abc}	24.11^{abc}	20.94^{abc}	18.17^{bc}	15.79^{bcd}	13.73^{bcd}
Medium	Deep Tissue (SM)	28.83^{ab}	27.07^{ab}	25.45^{ab}	22.78^{ab}	19.88^{ab}	17.56^{ab}	15.51^{ab}
Heavy	Deep Tissue (SM)	29.95^{a}	28.23^{a}	26.64^{a}	23.83^{a}	21.3^{a}	19.05^{a}	17.01^{a}
Light	*Longissimus dorsi*	18.3^{gh}	16.53^{hi}	14.98^{ij}	12.55^{hi}	10.21^{gh}	8.24^{gh}	6.64^{fg}
Medium	*Longissimus dorsi*	21.94^{f}	19.86^{gh}	18.24^{hi}	15.58^{gh}	13.67^{ef}	11.76^{ef}	9.66^{ef}
Heavy	*Longissimus dorsi*	23.23^{ef}	21.22^{fg}	19.54^{fgh}	16.86^{efg}	14.65^{ef}	12.72^{e}	11.08^{de}
Light	*Gluteus medius*	23.99^{def}	21.91^{defg}	20.17^{defgh}	17.3^{defg}	14.99^{def}	12.9^{de}	10.92^{de}
Medium	*Gluteus medius*	25.43^{cde}	23.52^{cdef}	21.83^{cdefg}	18.96^{cdef}	16.7^{cde}	14.62^{cbde}	12.83^{bcde}
Heavy	*Gluteus medius*	26.81^{bcd}	24.9^{bcd}	23.2^{bcde}	20.33^{bcd}	17.98^{bcd}	15.93^{bcd}	14.1^{abcd}
Light	Surface	13.65^{j}	12.5^{j}	11.54^{k}	9.52^{i}	7.77^{h}	6.37^{h}	5.24^{g}
Medium	Surface	14.03^{j}	12.75^{j}	11.77^{jk}	9.94^{i}	8.28^{h}	6.78^{h}	5.61^{g}
Heavy	Surface	14.65^{ij}	13.8^{ij}	13.01^{jk}	11.03^{i}	9.49^{h}	8.21^{h}	7.06^{fg}
Light	*Psoas major*	21.39^{fg}	19.73^{gh}	18.09^{hi}	15.6^{gh}	13.32^{fg}	11.48^{efg}	9.88^{ef}
Medium	*Psoas major*	23.82^{def}	22.11^{defg}	20.62^{defgh}	18.04^{cdefg}	15.9^{cdef}	14.03^{cde}	12.33^{cde}
Heavy	*Psoas major*	21.53^{f}	20.11^{g}	18.84^{gh}	16.56^{fg}	14.6^{ef}	12.85^{de}	11.26^{de}
SEM[2]		0.678	0.678	0.678	0.678	0.678	0.678	0.678
P-Value[3]		<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

[a-k]: Values that do not share a common superscript in column differ (P >0.05).
[2]SEM is the pooled standard error (largest) of least square means.
[3]Observed significance levels for treatment effect.

Table 2.4: Least Square means of Temperature (˚C) for carcass locations at hours 18, 20, 22, 24, 26, and 28

Weight Category	Location	Hour 18	Hour 20	Hour 22	Hour 24	Hour 26	Hour 28
Light	Brisket/ Plate	4.03^{i}	3.37^{i}	2.9^{h}	2.52^{h}	2.26^{h}	2.1^{g}
Medium	Brisket/ Plate	4.82^{i}	3.99^{hi}	3.46^{h}	2.04^{h}	2.54^{gh}	2.27^{fg}
Heavy	Brisket/ Plate	6.49^{fgi}	5.51^{fghi}	4.74^{fgh}	4.15^{fgh}	3.67^{efgh}	3.3^{efg}
Light	Deep Chuck	10.46^{cdef}	8.91^{cde}	7.77^{bcdef}	6.76^{bcdef}	5.86^{bcdefg}	5.14^{bcdefg}
Medium	Deep Chuck	13.02^{abcd}	11.28^{abc}	9.47^{abcd}	8.25^{abcde}	7.2^{abcd}	6.33^{abcde}
Heavy	Deep Chuck	13.77^{abc}	12.35^{ab}	10.94^{ab}	9.67^{abc}	8.56^{ab}	7.55^{abc}
Light	Deep Tissue (SM)	11.96^{bcde}	10.47^{bcd}	9.17^{bcd}	8.03^{bcde}	7.06^{bcd}	6.21^{bcd}
Medium	Deep Tissue (SM)	13.79^{ab}	12.15^{ab}	10.79^{ab}	9.64^{ab}	8.63^{ab}	7.72^{ab}
Heavy	Deep Tissue (SM)	15.19^{a}	13.61^{a}	12.25^{a}	11.07^{a}	10.03^{a}	9.09^{a}
Light	*Longissimus dorsi*	5.58^{hi}	4.61^{ghi}	3.81^{gh}	3.17^{gh}	2.66^{fgh}	2.28^{fg}
Medium	*Longissimus dorsi*	8.47^{fgh}	7.17^{efgh}	6.14^{defgh}	5.39^{efgh}	4.61^{defgh}	4.07^{cdefg}
Heavy	*Longissimus dorsi*	9.74^{ef}	8.52^{cdef}	7.48^{cdef}	6.58^{cdef}	5.89^{bcdef}	5.3^{bcdefg}
Light	*Gluteus medius*	9.43^{efg}	7.9^{cdefg}	7.03^{cdefg}	5.95^{defg}	5.08^{cdefgh}	4.37^{cdefg}
Medium	*Gluteus medius*	11.3^{bcdef}	9.95^{bcde}	8.81^{bcde}	7.76^{bcde}	6.97^{abcd}	6.28^{abcde}
Heavy	*Gluteus medius*	12.48^{abcde}	11.05^{abcd}	9.89^{abc}	8.84^{abcd}	7.95^{abc}	7.21^{abcd}
Light	Surface	4.52^{i}	3.76^{i}	3.31^{h}	2.93^{gh}	2.62^{gh}	2.34^{fg}
Medium	Surface	4.81^{i}	4.07^{hi}	3.5^{h}	2.98^{gh}	2.67^{gh}	2.42^{fg}
Heavy	Surface	5.86^{hi}	5.25^{ghi}	4.6^{fgh}	4.11^{fgh}	3.6^{efgh}	3.32^{efg}
Light	*Psoas major*	8.38^{fgh}	7.22^{efgh}	6.03^{defh}	5.26^{efgh}	4.47^{defgh}	3.91^{efg}
Medium	*Psoas major*	10.86^{bcdef}	9.58^{bcde}	8.36^{bcde}	7.5^{bcde}	6.68^{bcde}	5.94^{bcde}
Heavy	*Psoas major*	9.89^{def}	8.81^{cde}	7.67^{cdef}	6.79^{bcdef}	6.04^{bcde}	5.37^{bcdef}
SEM[2]		0.678	0.678	0.678	0.678	0.678	0.678
P-Value[3]		<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

[a-i]: Values that do not share a common superscript in column differ (P > 0.05).
[2]SEM is the pooled standard error (largest) of least square means.
[3]Observed significance levels for treatment effect.

Table 2.5: Least square means for temperature change per hour (˚C) for each weight category and carcass location for the following ranges: Hours 1-3, Hours 4-6, Hours 7-12, Hours 13-18, Hours 18-24, Hours 24-28

Weight Category	Location	Hours 1-3	Hours 4-6	Hours 7-12	Hours 13-18	Hours 18-24	Hours 25-28
Light	Brisket/ Plate	3.05^{a}	1.66^{a}	1.28^{a}	0.77^{a}	0.56^{ab}	0.25
Medium	Brisket/ Plate	2.87^{ba}	1.52^{dcba}	1.12^{dcba}	0.69^{abc}	0.5^{ab}	0.21
Heavy	Brisket/ Plate	3.03^{a}	1.65^{ba}	1.2^{ba}	0.77^{a}	0.54^{ab}	0.23
Light	Deep Chuck	2.12^{ed}	1.39^{fedcba}	1.05^{edcba}	0.61^{abc}	0.4^{ab}	0.15
Medium	Deep Chuck	1.44^{ji}	0.99^{hg}	0.7^{fe}	0.37^{c}	0.17^{b}	0.02
Heavy	Deep Chuck	1.83^{hgfe}	1.27^{gfedc}	0.92^{fedcb}	0.57^{abc}	0.35^{ab}	0.13
Light	Deep Tissue (SM)	1.63^{jihg}	1.07^{hgf}	0.79^{fed}	0.47^{abc}	0.26^{ab}	0.07
Medium	Deep Tissue (SM)	1.5^{jih}	1.04^{hgf}	0.72^{fe}	0.4^{bc}	0.17^{b}	0.04
Heavy	Deep Tissue (SM)	1.36^{j}	0.85^{h}	0.66^{f}	0.35^{c}	0.17^{b}	0.01
Light	*Longissimus dorsi*	2.89^{ba}	1.6^{cba}	1.16^{cba}	0.75^{ab}	0.51^{ab}	0.23
Medium	*Longissimus dorsi*	2.3^{dc}	1.47^{edcba}	1.09^{dcba}	0.68^{abc}	0.43^{ab}	0.17
Heavy	*Longissimus dorsi*	2.24^{dc}	1.45^{edcba}	1.07^{edcba}	0.67^{abc}	0.41^{ab}	0.17
Light	*Gluteus medius*	2.06^{ed}	1.33^{gfedcba}	1^{fedcba}	0.6^{abc}	0.39^{ab}	0.15
Medium	*Gluteus medius*	1.66^{jihgf}	1.12^{hgfe}	0.83^{fedc}	0.48^{abc}	0.29^{ab}	0.07
Heavy	*Gluteus medius*	1.68^{jihgf}	1.21^{hgfed}	0.85^{fedcb}	0.53^{abc}	0.29^{ab}	0.08
Light	Surface	1.8^{ihgfe}	1.24^{gfedc}	0.88^{fedcb}	0.56^{abc}	0.33^{ab}	0.09
Medium	Surface	1.57^{jih}	1.05^{hgf}	0.78^{fed}	0.43^{abc}	0.23^{ab}	0.06
Heavy	Surface	1.94^{gfed}	1.29^{gfedcb}	0.93^{fedcb}	0.59^{abc}	0.37^{ab}	0.14
Light	*Psoas major*	2.56^{cb}	1.5^{dcba}	1.12^{dcba}	0.68^{abc}	0.49^{ab}	0.18
Medium	*Psoas major*	2.02^{fed}	1.32^{gfedcba}	0.93^{fedcb}	0.59^{abc}	0.39^{ab}	0.14
Heavy	*Psoas major*	2.22^{dc}	1.4^{fedcba}	1.05^{edcba}	0.62^{abc}	0.4^{ab}	0.16
SEM[2]		0.0773	0.0773	0.0773	0.0773	0.0773	0.0773
P-Value[3]		0.0197	0.0197	0.0197	0.0197	0.0197	0.0197

[a-j]: Values that do not share a common superscript in column differ (P > 0.05).
[2]SEM is the pooled standard error (largest) of least square means.
[3]Observed significance levels for treatment effect.

Table 2.6: Least square means for USDA Calculated yield grades (YG 2, YG3, YG4) on Temperature (˚C) on brisket/ plate, deep chuck, deep tissue (SM), and *Longissmus dorsi* for time points: Hours 1, 3, 6, 12, 18, 24 and 28

Yield Grade[4]	Time						
	Hour 1	Hour 3	Hour 6	Hour 12	Hour 18	Hour 24	Hour 28
Brisket/ Plate							
2	29.527[a]	23.152[a]	16.536[a]	8.878[a]	4.002[a]	0.865[a]	-0.438[a]
3	30.905[b]	24.53[b]	17.914[b]	10.257[b]	5.38[b]	2.243[b]	0.94[b]
4	30.878[ab]	24.503[ab]	17.887[ab]	10.229[ab]	5.353[ab]	2.216[ab]	0.913[ab]
SEM[2]	0.552	0.552	0.552	0.552	0.552	0.552	0.552
P-Value[3]	0.0035	0.0035	0.0035	0.0035	0.0035	0.0035	0.0035
Deep Chuck							
2	36.65[a]	30.274[a]	23.658[a]	16.001[a]	11.124[a]	7.987[a]	6.684[a]
3	38.028[b]	31.652[b]	25.036[b]	17.379[b]	12.502[b]	9.365[b]	8.062[b]
4	38.001[ab]	31.625[ab]	25.009[ab]	17.352[ab]	12.475[ab]	9.338[ab]	8.035[ab]
SEM[2]	0.558	0.558	0.558	0.558	0.558	0.558	0.558
P-Value[3]	0.0035	0.0035	0.0035	0.0035	0.0035	0.0035	0.0035
Deep Tissue (SM)							
2	38.964[a]	32.588[a]	25.972[a]	18.315[a]	13.438[a]	10.301[a]	8.998[a]
3	40.342[b]	33.967[b]	27.351[b]	19.693[b]	14.816[b]	11.679[b]	10.376[b]
4	40.315[ab]	33.939[ab]	27.323[ab]	19.666[ab]	14.789[ab]	11.652[ab]	10.349[ab]
SEM[2]	0.524	0.524	0.524	0.524	0.524	0.524	0.524
P-Value[3]	0.0035	0.0035	0.0035	0.0035	0.0035	0.0035	0.0035
Longissimus dorsi							
2	33.686[a]	27.311[a]	20.695[a]	13.037[a]	8.16[a]	5.024[a]	3.72[a]
3	35.064[b]	28.689[b]	22.073[b]	14.415[b]	9.538[b]	6.402[b]	5.099[b]
4	35.037[ab]	28.662[ab]	22.046[ab]	14.388[ab]	9.511[ab]	6.375[ab]	5.071[ab]
SEM[2]	0.548	0.548	0.548	0.548	0.548	0.548	0.548
P-Value[3]	0.0035	0.0035	0.0035	0.0035	0.0035	0.0035	0.0035

[a-b]: Values that do not share a common superscript in column differ (P > 0.05).
[2]SEM is the pooled standard error (largest) of least square means.
[3]Observed significance levels for treatment effect.
[4]Yield Grades 2-4 were used due to lack of samples within Yield Grade 1 and 5. Yield Grade 1's was incorporated into Yield Grade 2's and Yield Grade 5's were incorporated into Yield Grade 4's for this table.

Table 2.7: Least square means for USDA Calculated yield grades (YG 2, YG3, YG4) on Temperature (˚C) on *Gluteus medius*, surface, and *Psoas major* for time points: Hours 1, 3, 6, 12, 18, 24 and 28

Yield Grade[4]	Time						
	Hour 1	Hour 3	Hour 6	Hour 12	Hour 18	Hour 24	Hour 28
Gluteus medius (Sirloin)							
2	36.521[a]	30.145[a]	23.529[a]	15.872[a]	10.995[a]	7.858[a]	6.555[a]
3	37.899[b]	31.523[b]	24.907[b]	17.25[b]	12.373[b]	9.236[b]	7.933[b]
4	37.871[a b]	31.496[ab]	24.88[ab]	17.222[ab]	12.346[ab]	9.209[ab]	7.906[ab]
SEM[2]	0.547	0.547	0.547	0.547	0.547	0.547	0.547
P-Value[3]	0.0035	0.0035	0.0035	0.0035	0.0035	0.0035	0.0035
Surface							
2	27.811[a]	21.436[a]	14.82[a]	7.162[a]	2.285[a]	-0.851[a]	-2.155[a]
3	29.189[b]	22.814[b]	16.198[b]	8.54[b]	3.663[b]	0.527[b]	-0.776[b]
4	29.162[a b]	22.787[ab]	16.171[a b]	8.513[ab]	3.636[ab]	0.5[ab]	-0.804[ab]
SEM[2]	0.544	0.544	0.544	0.544	0.544	0.544	0.544
P-Value[3]	0.0035	0.0035	0.0035	0.0035	0.0035	0.0035	0.0035
Psoas major (Tenderloin)							
2	34.29[a]	27.914[a]	21.298[a]	13.641[a]	8.764[a]	5.627[a]	4.324[a]
3	35.668[b]	29.293[b]	22.677[b]	15.019[b]	10.142[b]	7.005[b]	5.702[b]
4	35.641[a b]	29.265[ab]	22.649[a b]	14.992[ab]	10.115[ab]	6.978[ab]	5.675[ab]
SEM[2]	0.545	0.545	0.545	0.545	0.545	0.545	0.545
P-Value[3]	0.0035	0.0035	0.0035	0.0035	0.0035	0.0035	0.0035

[a-b:] Values that do not share a common superscript in column differ (P > 0.05).
[2]SEM is the pooled standard error (largest) of least square means.
[3]Observed significance levels for treatment effect.
[4]Yield Grades 2-4 were used due to lack of samples within Yield Grade 1 and 5. Yield Grade 1's was incorporated into Yield Grade 2's and Yield Grade 5's were incorporated into Yield Grade 4's for this table.

Table 2.8: Least square means for EUROPE Carcase Classification Confirmation Scores on Temperature (˚C) for time points: Hours 1, 3, 6, 12, 18, 24 and 28

Confirmation Score[4]	Time						
	Hour 1	Hour 3	Hour 6	Hour 12	Hour 18	Hour 24	Hour 28
U	35.653	29.278	22.662	15.004	10.127	6.991	5.687
R	34.953	28.578	21.962	14.304	9.427	6.291	4.987
O	34.416	28.041	21.425	13.767	8.890	5.754	4.450
P	34.301	27.926	21.310	13.652	8.776	5.639	4.336
SEM[2]	0.521	0.521	0.521	0.521	0.521	0.521	0.521
P-Value[3]	0.0175	0.0175	0.0175	0.0175	0.0175	0.0175	0.0175

[2]SEM is the pooled standard error (largest) of least square means.
[3]Observed significance levels for treatment effect.
[4] EUROP Carcase Classification scale 'E' not present due to lack of sample size within the confirmation category.

Table 2.9: Least square means for Ribeye area (in^2) on Temperature (˚C) for time points: Hours 1, 3, 6, 12, 18, 24 and 28

Ribeye Area (in^2)	Time						
	Hour 1	Hour 3	Hour 6	Hour 12	Hour 18	Hour 24	Hour 28
10	32.925	26.550	19.934	12.276	7.399	4.262	2.959
11	34.190	27.815	21.199	13.541	8.664	5.528	4.224
12	33.821	27.446	20.830	13.172	8.295	5.159	3.856
13	34.022	27.647	21.031	13.373	8.497	5.360	4.057
14	34.627	28.252	21.636	13.978	9.101	5.965	4.661
15	35.113	28.738	22.122	14.464	9.587	6.451	5.148
16	34.843	28.468	21.852	14.194	9.318	6.181	4.878
17	34.988	28.613	21.997	14.339	9.462	6.326	5.022
18	36.461	30.085	23.469	15.812	10.935	7.798	6.495
19	35.515	29.139	22.523	14.866	9.989	6.852	5.549
20	35.658	29.283	22.667	15.009	10.132	6.996	5.693
SEM[2]	1.460	1.460	1.460	1.460	1.460	1.460	1.460
P-Value[3]	0.089	0.089	0.089	0.089	0.089	0.089	0.089

[2]SEM is the pooled standard error (largest) of least square means.
[3]Observed significance levels for treatment effect

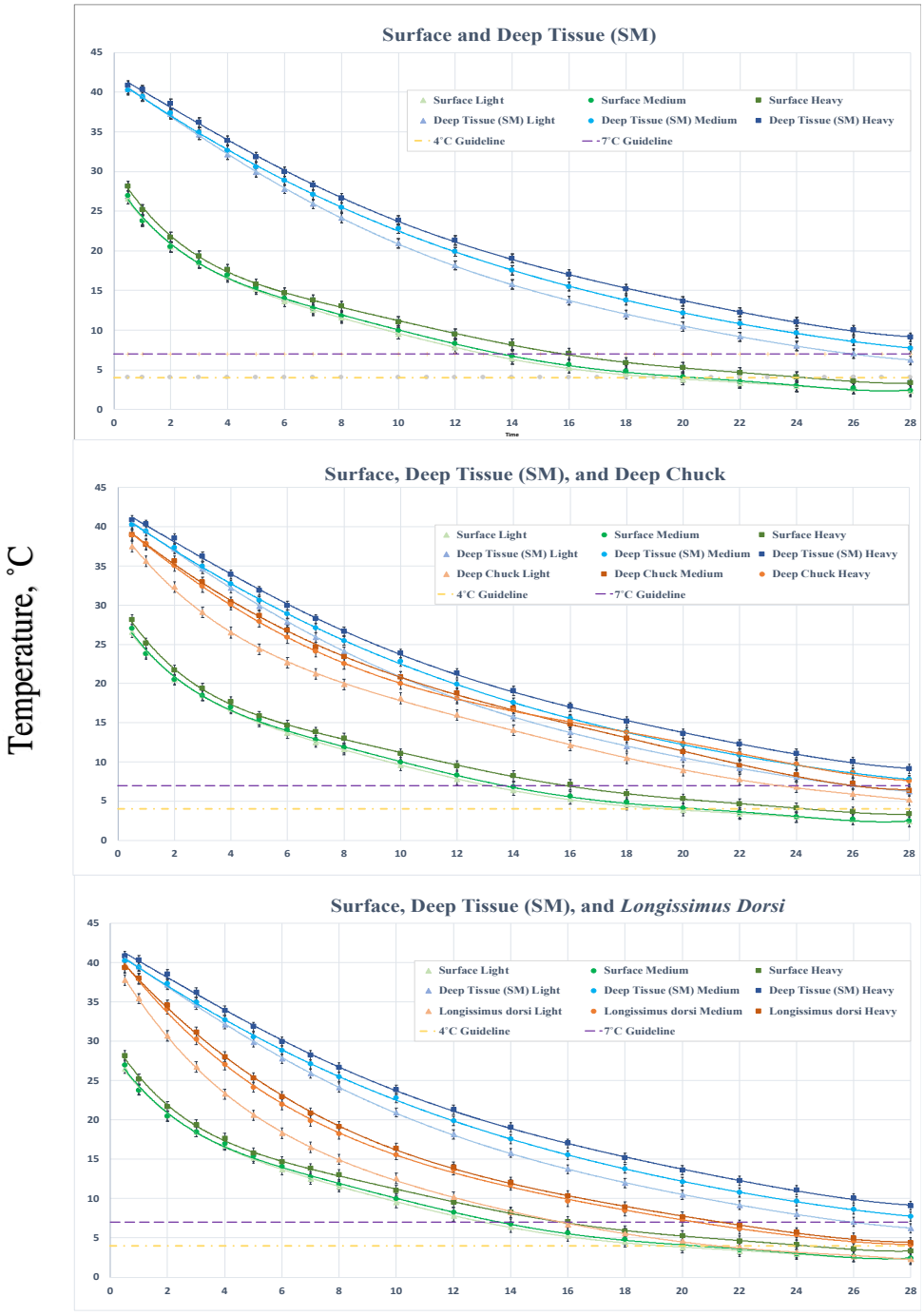

Figure 2.1: Least square means and ±SEM for temperature (˚C) on light (Δ), medium (O), and heavy (□) weight carcasses for the surface, deep tissue (SM), deep chuck, and *Longissimus dorsi* locations at time points ranging from 30 minutes post electrical stimulation to 28 hours post electrical stimulation, and a polynomial line fitted to these points.

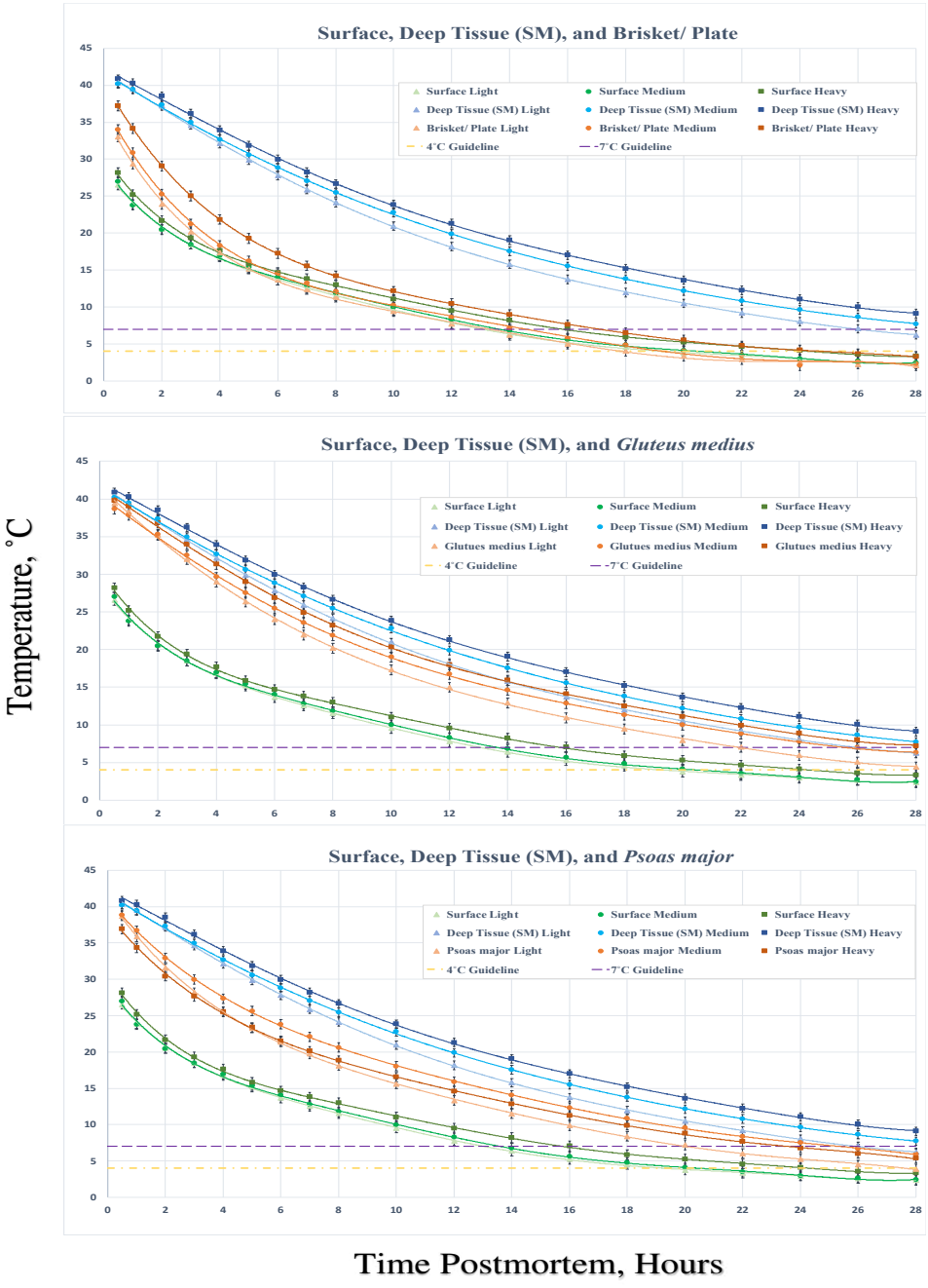

Figure 2.2: Least square means and ±SEM for temperature (˚C) on light (Δ), medium (O), and heavy (□) weight carcasses for the surface, deep tissue (SM), brisket/ plate, and *Gluteusmedius,* and *Psoas major* locations at time points ranging from 30 minutes post electrical stimulation to 28 hours post electrical stimulation, and a polynomial line fitted to these points.

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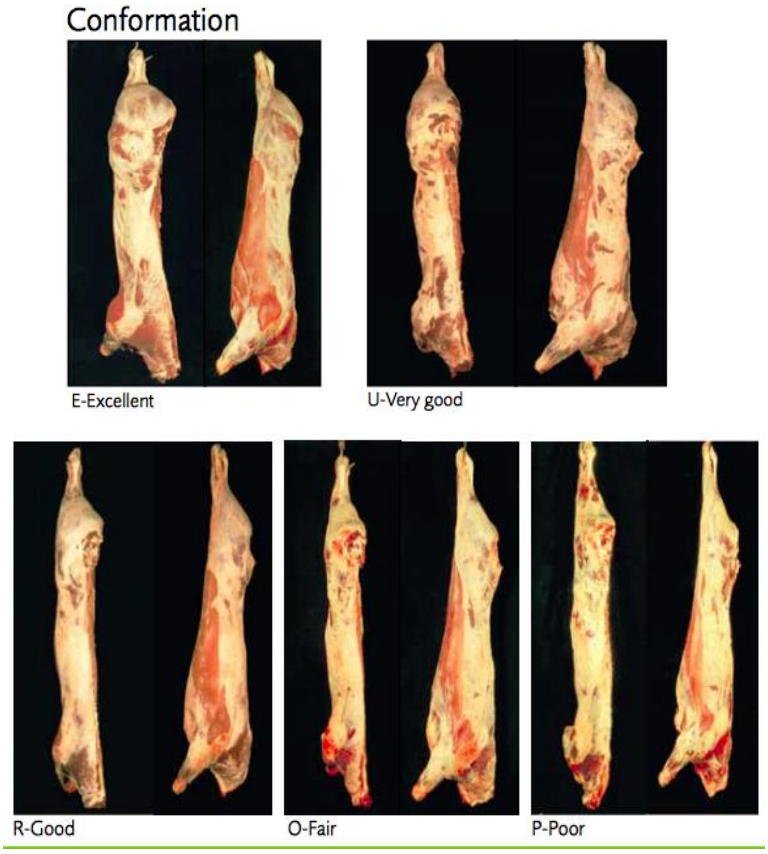
Appendices

Appendix A

EUROP CONFIRMATION SCORE STANDARDS

Conformation class	Description
S: Superior	All profiles extremely convex; exceptional muscle development (double-muscled carcass type)
E: Excellent	All profiles convex to super-convex; exceptional muscle development
U: Very good	Profiles on the whole convex; very good muscle development
R: Good	Profiles on the whole straight; good muscle development
O: Fair	Profiles straight to concave; average muscle development
P: Poor	All profiles concave to very concave; poor muscle development

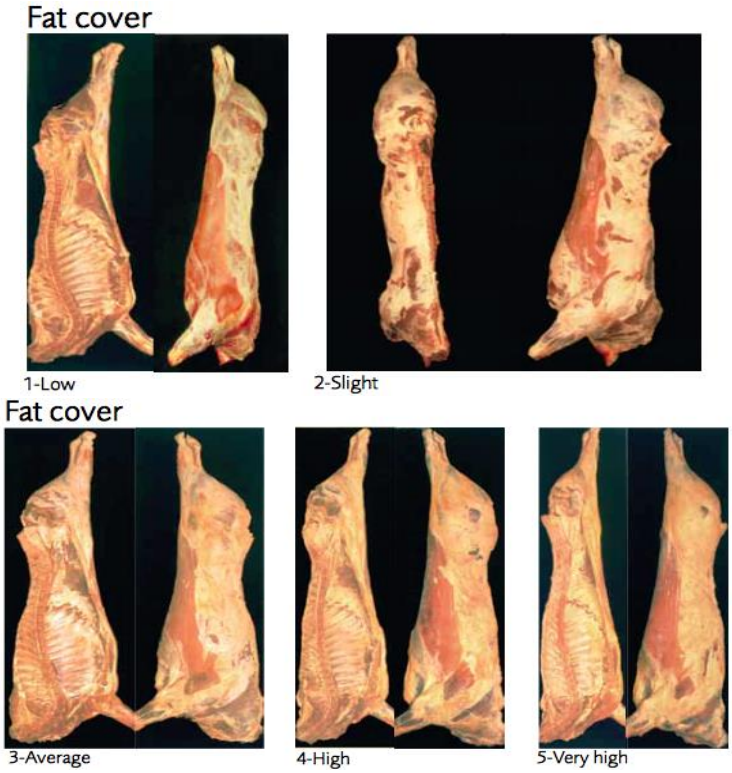


EUROP Confirmation Score

APPENDIX B

EUROP FAT COVER SCORE STANDARDS

Confirmation Score	Description
1: low	None up to low fat cover
2: slight	Slight fat cover, flesh visible almost everywhere
3: average	Flesh, with the exception of the round and shoulder, almost everywhere covered with fat, slight deposits of fat in the thoracic cavity
4: high	Flesh covered with fat, but on the round and shoulder still partly visible, some distinctive fat deposits in the thoracic cavity
5: very high	Entire carcass covered with fat; heavy fat deposits in the thoracic cavity



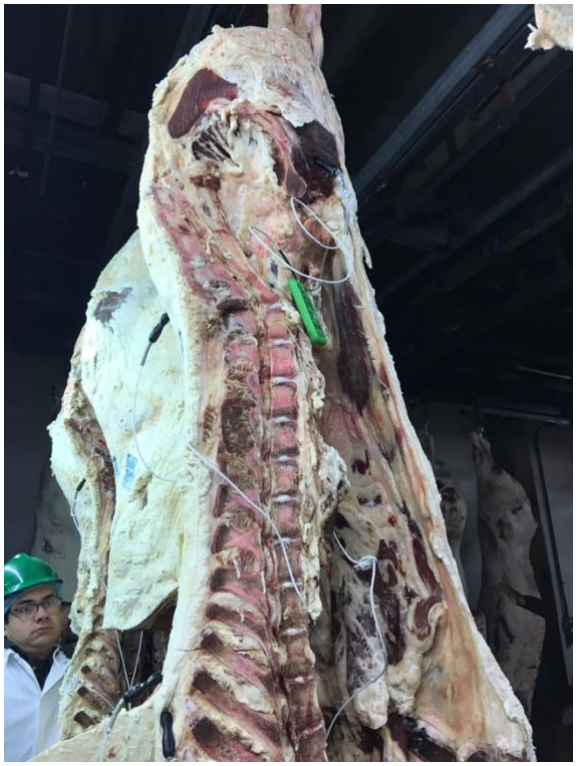
Fat Cover Score

APPENDIX C

Temperature Recorder Carcass Locations

Longissimus dorsi and surface locations

Gluteus medius (Sirloin) Location



Psoas major (tenderloin) location

Brisket/ plate location

Deep Tissue (SM) Location

Deep Chuck Location

Temperature Recorder Locations

APPENDIX D

Correlation Tables

Brisket/ Plate																	
	Electrical Stimulation	Carcass Length	Ribeye Area	Adjusted Preliminary Yield Grade	Kidney, Pelvic, and Heart Fat	USDA Calculated Yield Grade	EUROP Confirmation Score	L*	a*	b*	Hour 1	Hour 3	Hour 6	Hour 12	Hour 18	Hour 24	Hour 28
Electrical Stimulation	1.000																
Carcass Length	0.290	1.000															
Ribeye Area	0.114	0.529	1.000														
Adjusted Preliminary Yield	0.136	0.121	-0.083	1.000													
Kidney, Pelvic, and Heart Fat	-0.152	-0.399	-0.479	-0.106	1.000												
USDA Calculated Yield Grade	0.149	0.228	-0.293	0.892	-0.030	1.000											
Confirmation Score	0.060	-0.026	-0.045	0.836	-0.086	0.704	1.000										
L*	0.040	0.207	0.153	0.180	-0.103	0.213	0.157	1.000									
a*	0.134	0.166	-0.143	0.357	0.125	0.422	0.290	0.212	1.000								
b*	0.126	0.152	-0.151	0.449	0.089	0.484	0.385	0.248	0.814	1.000							
Hour 1	-0.025	0.200	0.123	0.152	-0.121	0.215	0.120	0.065	0.059	0.007	1.000						
Hour 3	0.039	0.243	0.095	0.299	-0.159	0.352	0.211	0.023	0.114	0.107	0.877	1.000					
Hour 6	0.081	0.254	0.046	0.273	-0.150	0.333	0.183	-0.025	0.114	0.137	0.759	0.946	1.000				
Hour 12	0.170	0.315	0.056	0.287	-0.188	0.339	0.190	-0.056	0.129	0.165	0.635	0.853	0.954	1.000			
Hour 18	0.163	0.365	0.008	0.359	-0.238	0.438	0.198	-0.053	0.171	0.182	0.551	0.788	0.869	0.921	1.000		
Hour 24	0.025	0.188	-0.077	0.206	-0.085	0.295	-0.011	-0.057	0.072	0.075	0.284	0.513	0.466	0.449	0.629	1.000	
Hour 28	0.121	0.277	0.012	0.296	-0.224	0.342	0.176	-0.048	0.147	0.162	0.380	0.664	0.734	0.804	0.886	0.696	1.000

Deep Chuck																	
	Electrical Stimulation	Carcass Length	Ribeye Area	Adjusted Preliminary Yield Grade	Kidney, Pelvic, and Heart Fat	USDA Calculated Yield Grade	EUROP Confirmation Score	L*	a*	b*	Hour 1	Hour 3	Hour 6	Hour 12	Hour 18	Hour 24	Hour 28
Electrical Stimulation	1.000																
Carcass Length	0.375	1.000															
Ribeye Area	0.134	0.437	1.000														
Adjusted Preliminary Yield	0.128	0.224	-0.011	1.000													
Kidney, Pelvic, and Heart Fat	-0.191	-0.350	-0.469	-0.149	1.000												
USDA Calculated Yield Grade	0.155	0.339	-0.280	0.874	-0.029	1.000											
Confirmation Score	0.032	0.088	0.006	0.826	-0.125	0.687	1.000										
L*	0.006	0.239	0.177	0.289	-0.161	0.313	0.235	1.000									
a*	0.170	0.366	-0.013	0.361	0.058	0.420	0.273	0.198	1.000								
b*	0.192	0.403	0.019	0.449	0.029	0.468	0.348	0.231	0.839	1.000							
Hour 1	-0.079	0.119	0.026	0.221	-0.011	0.258	0.239	0.067	0.078	0.110	1.000						
Hour 3	0.000	0.138	0.137	0.308	-0.101	0.293	0.301	0.114	0.098	0.156	0.851	1.000					
Hour 6	-0.021	0.157	0.124	0.276	-0.089	0.273	0.287	0.166	0.093	0.158	0.799	0.958	1.000				
Hour 12	-0.036	0.109	0.039	0.217	-0.041	0.253	0.231	0.233	0.128	0.174	0.677	0.803	0.875	1.000			
Hour 18	0.063	0.243	0.103	0.331	-0.111	0.365	0.309	0.309	0.216	0.269	0.597	0.740	0.809	0.946	1.000		
Hour 24	0.016	0.273	0.045	0.329	-0.090	0.394	0.269	0.339	0.225	0.267	0.585	0.666	0.764	0.897	0.952	1.000	
Hour 28	-0.023	0.263	0.047	0.321	-0.077	0.382	0.249	0.351	0.228	0.270	0.573	0.641	0.748	0.868	0.914	0.988	1.000

Deep Tissue (SM)																	
	Electrical Stimulation	Carcass Length	Ribeye Area	Adjusted Preliminary Yield Grade	Kidney, Pelvic, and Heart Fat	USDA Calculated Yield Grade	EUROP Confirmation Score	L*	a*	b*	Hour 1	Hour 3	Hour 6	Hour 12	Hour 18	Hour 24	Hour 28
Electrical Stimulation	1.000																
Carcass Length	0.197	1.000															
Ribeye Area	0.095	0.540	1.000														
Adjusted Preliminary Yield	0.083	0.139	-0.062	1.000													
Kidney, Pelvic, and Heart Fat	-0.190	-0.393	-0.503	-0.067	1.000												
USDA Calculated Yield Grade	0.076	0.215	-0.316	0.883	0.034	1.000											
EUROP Confirmation Score	-0.007	0.034	-0.034	0.829	-0.033	0.704	1.000										
L*	-0.002	0.188	0.167	0.168	-0.101	0.175	0.127	1.000									
a*	0.106	0.226	-0.044	0.397	0.085	0.420	0.312	0.170	1.000								
b*	0.087	0.218	-0.035	0.474	0.060	0.461	0.386	0.194	0.846	1.000							
Hour 1	0.063	0.008	0.173	0.098	-0.160	0.032	0.104	0.135	-0.014	-0.022	1.000						
Hour 3	0.013	0.064	0.253	0.026	-0.219	-0.034	0.039	0.113	-0.009	-0.028	0.922	1.000					
Hour 6	0.013	0.128	0.316	0.003	-0.241	-0.060	0.025	0.097	0.022	-0.005	0.817	0.963	1.000				
Hour 12	0.048	0.252	0.400	0.021	-0.278	-0.037	0.038	0.094	0.068	0.031	0.711	0.877	0.964	1.000			
Hour 18	0.053	0.301	0.426	0.051	-0.315	-0.003	0.061	0.118	0.073	0.035	0.659	0.829	0.927	0.987	1.000		
Hour 24	0.046	0.328	0.436	0.088	-0.347	0.038	0.092	0.141	0.088	0.056	0.629	0.792	0.891	0.957	0.986	1.000	
Hour 28	0.044	0.354	0.444	0.112	-0.355	0.066	0.112	0.155	0.104	0.075	0.600	0.757	0.857	0.931	0.970	0.996	1.000

Gluteus medius (Sirloin)																	
	Electrical Stimulation	Carcass Length	Ribeye Area	Adjusted Preliminary Yield Grade	Kidney, Pelvic, and Heart Fat	USDA Calculated Yield Grade	EUROP Confirmation Score	L*	a*	b*	Hour 1	Hour 3	Hour 6	Hour 12	Hour 18	Hour 24 [1]	Hour 28 [1]
Electrical Stimulation	1.000																
Carcass Length	0.242	1.000															
Ribeye Area	0.030	0.468	1.000														
Adjusted Preliminary Yield	0.144	0.244	0.068	1.000													
Kidney, Pelvic, and Heart Fat	-0.152	-0.379	-0.452	-0.168	1.000												
USDA Calculated Yield Grade	0.187	0.342	-0.187	0.889	-0.100	1.000											
EUROP Confirmation Score	0.054	0.140	0.134	0.842	-0.149	0.705	1.000										
L*	0.003	0.224	0.143	0.229	-0.155	0.262	0.206	1.000									
a*	0.058	0.237	-0.049	0.415	0.066	0.453	0.346	0.237	1.000								
b*	0.050	0.234	-0.027	0.487	0.017	0.488	0.420	0.276	0.831	1.000							
Hour 1	-0.126	0.024	0.073	-0.096	-0.036	-0.081	-0.006	0.057	-0.166	-0.035	1.000						
Hour 3	-0.108	0.116	0.149	-0.027	-0.043	-0.016	0.075	0.105	-0.048	0.045	0.946	1.000					
Hour 6	-0.066	0.193	0.189	0.037	-0.091	0.052	0.116	0.129	0.016	0.099	0.866	0.954	1.000				
Hour 12	-0.035	0.238	0.235	0.193	-0.155	0.175	0.272	0.206	0.101	0.180	0.744	0.875	0.938	1.000			
Hour 18	-0.010	0.301	0.225	0.246	-0.189	0.246	0.306	0.250	0.157	0.226	0.635	0.779	0.872	0.962	1.000		
Hour 24 [1]	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	1.000	
Hour 28 [1]	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	1.000

[1]: depicts "NA" value due to standard deviation being too low to calculate correaltion values against other variables

Longissimus dorsi																	
	Electrical Stimulation	**Carcass Length**	**Ribeye Area**	**Adjusted Preliminary Yield Grade**	**Kidney, Pelvic, and Heart Fat**	**USDA Calculated Yield Grade**	**EUROP Confirmation Score**	**L***	**a***	**b***	**Hour 1**	**Hour 3**	**Hour 6**	**Hour 12**	**Hour 18**	**Hour 24**	**Hour 28 [1]**
Electrical Stimulation	1.000																
Carcass Length	0.348	1.000															
Ribeye Area	0.153	0.513	1.000														
Adjusted Preliminary Yield	0.086	0.162	0.000	1.000													
Kidney, Pelvic, and Heart Fat	-0.177	-0.477	-0.511	-0.232	1.000												
USDA Calculated Yield Grade	0.101	0.258	-0.264	0.875	-0.140	1.000											
Confirmation Score	-0.033	0.022	-0.031	0.830	-0.158	0.710	1.000										
L*	0.029	0.156	0.230	0.182	-0.147	0.140	0.153	1.000									
a*	0.151	0.237	-0.056	0.277	0.008	0.335	0.204	0.141	1.000								
b*	0.148	0.242	-0.062	0.380	-0.028	0.409	0.309	0.167	0.819	1.000							
Hour 1	0.048	0.141	0.079	0.225	-0.052	0.282	0.256	0.258	0.033	0.044	1.000						
Hour 3	0.144	0.307	0.133	0.297	-0.202	0.388	0.268	0.196	0.183	0.208	0.821	1.000					
Hour 6	0.165	0.350	0.163	0.298	-0.256	0.379	0.222	0.154	0.249	0.272	0.659	0.931	1.000				
Hour 12	0.099	0.333	0.086	0.241	-0.198	0.341	0.149	0.068	0.247	0.271	0.503	0.786	0.924	1.000			
Hour 18	0.085	0.283	0.116	0.124	-0.205	0.212	0.058	0.047	0.208	0.197	0.391	0.652	0.841	0.943	1.000		
Hour 24	0.070	0.253	0.118	0.040	-0.199	0.125	-0.006	0.022	0.192	0.155	0.320	0.560	0.766	0.876	0.979	1.000	
Hour 28 [1]	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	1.000

1: depicts "NA" value due to standard deviation being too low to calculate correaltion values against other variables

Surface																	
	Electrical Stimulation	**Carcass Length**	**Ribeye Area**	**Adjusted Preliminary Yield Grade**	**Kidney, Pelvic, and Heart Fat**	**USDA Calculated Yield Grade**	**EUROP Confirmation Score**	**L***	**a***	**b***	**Hour 1**	**Hour 3**	**Hour 6 [1]**	**Hour 12**	**Hour 18**	**Hour 24**	**Hour 28**
Electrical Stimulation	1.000																
Carcass Length	0.258	1.000															
Ribeye Area	0.082	0.487	1.000														
Adjusted Preliminary Yield	0.128	0.123	-0.102	1.000													
Kidney, Pelvic, and Heart Fat	-0.137	-0.358	-0.455	-0.103													
USDA Calculated Yield Grade	0.135	0.237	-0.321	0.892	-0.021	1.000											
Confirmation Score	0.038	0.010	-0.075	0.827	-0.088	0.709	1.000										
L*	-0.010	0.167	0.176	0.115	-0.069	0.137	0.093	1.000									
a*	0.134	0.178	-0.128	0.369	0.123	0.420	0.314	0.159	1.000								
b*	0.143	0.193	-0.123	0.466	0.063	0.496	0.405	0.191	0.815	1.000							
Hour 1	0.028	-0.023	0.139	0.144	-0.052	0.081	0.098	0.119	0.130	0.020	1.000						
Hour 3	0.043	-0.005	0.120	0.153	-0.023	0.087	0.124	0.080	0.186	0.062	0.937	1.000					
Hour 6 [1]	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	1.000				
Hour 12	0.142	0.099	0.137	0.226	-0.068	0.172	0.203	0.068	0.179	0.127	0.720	0.839	*NA*	1.000			
Hour 18	0.080	0.110	0.085	0.220	-0.054	0.194	0.174	0.046	0.209	0.106	0.658	0.779	*NA*	0.918	1.000		
Hour 24	0.048	0.111	0.060	0.205	-0.059	0.196	0.159	0.032	0.208	0.137	0.534	0.653	*NA*	0.858	0.958	1.000	
Hour 28	0.045	0.116	0.052	0.194	-0.062	0.185	0.150	0.043	0.201	0.146	0.462	0.583	*NA*	0.804	0.924	0.985	1.000

[1]: depicts "NA" value due to standard deviation being too low to calculate correaltion values against other variables

Psoas major (Tenderloin)																	
	Electrical Stimulation	**Carcass Length**	**Ribeye Area**	**Adjusted Preliminary Yield Grade**	**Kidney, Pelvic, and Heart Fat**	**Calculated Yield Grade**	**EUROP Confirmation Score**	**L***	**a***	**b***	**Hour 1**	**Hour 3**	**Hour 6**	**Hour 12**	**Hour 18**	**Hour 24**	**Hour 28**
Electrical Stimulation	1.000																
Carcass Length	0.249	1.000															
Ribeye Area	0.119	0.495	1.000														
Adjusted Preliminary Yield	0.125	0.220	0.002	1.000													
Kidney, Pelvic, and Heart Fat	-0.213	-0.431	-0.515	-0.150	1.000												
USDA Calculated Yield Grade	0.118	0.316	-0.238	0.889	-0.054	1.000											
Confirmation Score	0.088	0.074	-0.006	0.820	-0.128	0.709	1.000										
L*	0.047	0.198	0.179	0.200	-0.156	0.246	0.180	1.000									
a*	0.072	0.259	-0.072	0.332	0.025	0.408	0.300	0.186	1.000								
b*	0.061	0.252	-0.080	0.446	0.057	0.483	0.402	0.228	0.869	1.000							
Hour 1	-0.056	-0.286	-0.094	-0.085	0.059	-0.088	-0.086	0.141	0.067	0.090	1.000						
Hour 3	0.005	-0.182	-0.111	0.067	-0.004	0.075	0.012	0.125	0.101	0.119	0.911	1.000					
Hour 6	0.025	-0.152	0.011	0.072	-0.066	0.038	-0.006	0.141	0.077	0.102	0.842	0.864	1.000				
Hour 12	0.092	-0.001	0.090	0.177	-0.140	0.129	0.041	0.169	0.111	0.162	0.700	0.771	0.928	1.000			
Hour 18	0.095	0.012	0.095	0.270	-0.159	0.207	0.115	0.188	0.099	0.164	0.622	0.727	0.869	0.968	1.000		
Hour 24	0.093	0.042	0.110	0.320	-0.173	0.245	0.172	0.212	0.109	0.170	0.538	0.660	0.810	0.913	0.976	1.000	
Hour 28	0.077	0.066	0.120	0.330	-0.175	0.253	0.184	0.220	0.117	0.176	0.495	0.612	0.775	0.888	0.955	0.993	1.000

Correlation Tables