THESIS

# EFFECTS OF EXTENDED POSTMORTEM AGING ON SELECTED BEEF MUSCLES INTENDED FOR RETAIL SALE

Submitted by

Erin D. Karney

Department of Animal Sciences

In partial fulfillment of the requirements

For the Degree of Master of Science

Colorado State University

Fort Collins, CO

Spring 2014

Master's Committee:

Advisor: Dale R. Woerner
Keith E. Belk
J. Daryl Tatum
Dustin L. Pendell

# ABSTRACT

## EFFECTS OF EXTENDED POSTMORTEM AGING ON SELECTED BEEF MUSCLES INTENDED FOR RETAIL SALE

In order to mimic beef commonly found in retail supermarkets, paired strip loins (NAMP #180) and top sirloin butts (NAMP #184) were obtained from USDA Choice carcasses with a marbling score ranging from Small$^{00}$ to Small$^{50}$ (n = 15) and USDA Select carcasses with a marbling score ranging from Slight$^{50}$ to Slight$^{99}$ (n = 15) at a commercial packing plant. Samples were collected from 3 separate groups of carcasses in order to replicate each aging and display period three times. At 48 hours postmortem, paired strip loins and top sirloin butts were portioned into 3-inch sections, vacuum-sealed, and stored 14, 21, 28, 35, 49, or 63 days postmortem. For both strip loin and sirloin sections, once the aging period was designated, the sections were stored in a vacuum-sealed bag at 0°C (± 1°C) and in the dark until their assigned aging period was complete. Two steaks from each aged section for each muscle was placed in a styrofoam tray with a polyvinyl chloride overwrap and placed in a multi-deck retail display case equipped with LED lighting (Hussmann Model No. M3X8GEP) and set at 2°C for 72 hrs. A third steak cut from each aged section was immediately cooked, and Warner-Bratzler shear force (WBSF) analysis was measured to determine the effects of the aging period on tenderness without the display period. During the display period, each steak was evaluated every 8 hours by a minimum of 8 trained panelists for lean color, external fat color, lean percent discoloration, and L* a* b* color values. A trained sensory panel for tenderness and flavor attributes, including off-flavors, also was used to evaluate steaks. As steaks were subjected to longer periods of

postmortem aging, WBSF values decreased and trained sensory panel tenderness ratings improved. A 72 h display time reduced ($P < 0.05$) WBSF values of strip loin and sirloin steaks. A minimum of 28 d of postmortem aging was required to improve the WBSF values of low Choice and Select strip loin steaks compared with the same strip loins steaks aged for 14 d, and a minimum of 35 d of postmortem aging was required to improve sensory tenderness ratings for low Choice and Select strip loin steaks. Strip loin steaks aged up to 28 d before retail display had little impact on display life and the incidence of off-flavors; however, there was no tenderness advantage over 14 d aged steaks from low Choice and Select strip loins. Thirty-five days of postmortem aging were required to achieve an improvement in WBSF compared to that achieved with 14 d aging for low Choice and Select top sirloin steaks, and trained sensory panel scores indicated that at least 49 d of postmortem aging was required to improve the myofibrillar tenderness of low Choice and Select sirloin steaks. Sirloin steaks aged 35 d and beyond produced undesirable lean color scores in as early as the first 24 h of retail display, and top sirloin steaks aged only 14 d and displayed an additional 72 h had relatively intense levels of oxidized and sour/acidic flavors present. Top sirloins cannot be aged for enough time to improve tenderness and maintain a considerable level of display life, and extended aging time is not a viable option for top sirloins intended for retail display and sale.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

# INTRODUCTION

Consumer studies have shown that tenderness is the most important sensory characteristic for determining overall steak acceptance (Huffman et al., 1996; Platter et al., 2003), while the maintenance of fresh beef color is the primary factor in determining retail display life and is a major factor influencing consumer purchase decisions at the retail marketplace. Postmortem muscle aging is an essential and effective management technique to improve tenderness, and for most muscles, extended postmortem aging periods of 14 days or more are required to achieve the majority of the aging response (Gruber et al., 2006). A more definite understanding of the effects of postmortem aging on retail display life of USDA Choice and Select beef that are most likely to appear in retail supermarkets could lead to more extensive implementation of aging, and ultimately, decrease the incidence of unacceptably tough steaks sold at retail.

Gruber et al. (2006) noted that extended aging times were especially needed for loin cuts that were of a lower quality grade (USDA Select); the *longissimus* muscle and *gluteus medius* required 26 and 27 days of aging to optimize tenderness, respectively. The foodservice industry relies heavily on extended aging times to ensure a positive eating experience. This is especially true for beef cuts that have a greater need for tenderness improvement, such as the beef top sirloin butt. The National Beef Tenderness surveys have indicated that substantial variation in the aging time of beef muscle cuts exists (Morgan et al., 1991; NCBA, 1999; Brooks et al., 2000; NCBA, 2006; NCBA, 2011) with the most recent survey reporting a range of 1 day to 358 days of aging time. Nonetheless, the effect of aging period on retail display life has not been well documented. Even though the concept of aging beef has been well received and is heavily

utilized by the wholesale and foodservice segments of the beef industry, postmortem aging practices are not commonly implemented in the retail sector.

Beef retailers are seemingly hesitant to age beef for more than 14 days before placing it in the retail case because product "freshness" is reduced and a shorter display life may result. With this information and the increase in the use of growth promoting agents in the beef industry, retailers need supporting information to justify aging beef cuts to optimize tenderness and reduce the incidence of tough steaks without sacrificing time in retail display. With the ability to confidently utilize extended aging periods to ensure tenderness, companies supplying beef to retailers should experience fewer claims and account for greater customer satisfaction with beef. Therefore, the objective of this study was to identify the impact of extended postmortem aging times on retail shelf-life and eating qualities of beef steaks that are the most likely to appear in retail stores.

CHAPTER II

# REVIEW OF LITERATURE

## *Meat Color*

Color is the primary factor affecting consumer purchasing decisions of fresh meat products at the retail marketplace. Much emphasis has been placed on maintaining and controlling color, since this is the main attribute consumers' use in selecting their meat at retail (Faustman and Cassens, 1990). Consumers routinely use product color and appearance to select or reject products, and suppliers of muscle food products must create and maintain the desired color attributes. The color of muscle foods revolves around myoglobin, the primary pigment in meat. The lignand present at the $6^{th}$ coordination site and the valence state of iron determine meat color via four principle chemical forms of myoglobin: deoxymyoglobin (DMb), oxymyoglobin (OMb), caboxymyoglobin (COMb), and metmyoglobin (MMb). See figure 2.1 for these relationships.

Deoxymyoglobin is the dark purplish-red or purplish-pink color, the typical color of the interior of fresh meat or in vacuum packages that has not been exposed to oxygen. Dmb contains ferrous ($Fe^{2+}$) iron with no ligand attached at the $6^{th}$ coordination site. In order to maintain Dmb state, very low oxygen tension within vacuum packages or the interior is required. Once diatomic oxygen attaches to the $6^{th}$ coordination site of ferrous iron ($Fe^{2+}$), oxygenation of Dmb occurs and a bright-red color will form. Myoglobin oxygenation (i.e. blooming) depends on a number of factors including: time, temperature, pH, and competition for oxygen by mitochondria. The competition for oxygen between myoglobin and mitochondria determines oxygen penetration beneath the meat's surface, which affects the intensity of the meat's surface

color. Deoxymyoglobin can form MMb by oxidation of oxygen radicals and reactive oxygen species. Carboxymyoglobin is formed when a carbon monoxide attached to the vacant $6^{th}$ position of DMb, producing a stable bright red color when the environment is devoid of oxygen. When oxygen is present, COMb will take either OMb or MMb forms. Metmyoglobin is the oxidized tan to brown colored form of myoglobin and it contains ferric iron ($Fe^{3+}$). Water is present at the $6^{th}$ position of the iron in MMb. Metmyoglobin is typically formed at low concentrations of oxygen. Conditions that can delay MMb formation include: low temperature, high pH, antioxidant capacity and greater reducing activity.

Ultimate muscle pH is important for color stability as it influences many factors and usually ranges from 5.4 to 5.8 for beef. It has been found that as oxygen consumption rate increased, pH increased from 5.6 to 7.2 (Bendall, 1972; Bendall and Taylor, 1972**).** Oxygen consumption rate is related to residual mitochondrial activity in muscle. It is thought that high oxygen consumption rates deter the development of oxymyoglobin (Ashmore et al., 1972**).** However, many studies have produced results in which the muscles with the lowest color stability had the highest oxygen consumption rate (O' Keefe and Hood, 1982; Renerre and Labas, 1987). Futhermore, color stability has been found to be muscle dependent with the *longissimus dorsi* having greater color stability compared to the *gluteus medius.* Faustman and Cassens (1991) results found that *longissimus dorsi* muscles accumulated 9.2 percent less metmyoglobin than *gluteus medius* muscles. Slow-twitch oxidative muscle fibers contain a greater amount of myoglobin and possess higher enzymatic reducing activity compared to fast-twitch glycolytic or fast-twitch oxidative glycolytic muscle fibers, resulting in greater color stability and red color (Renerre, 1990).

Ledward (1972**)** determined that the reduction of metmyoglobin in meat was the primary determinant in color stability. Metmyoglobin reduction activity is unique to each muscle (Leward et al., 1977). The enzymatic pathway for metmyoglobin reduction activity results in the reduction of the iron molecule in the presence of coenzyme nicotinimide dinucleotide (NADH) (Renerre, 1990). However, there has been much debate on the role of metmyoglobin reductase as a determinant of color stability. Reddy and Carpenter (1991) determined that muscles that have traditionally been characterized as the most color stable had a high metmyoglobin reductase activity. Madhavi and Carpenter (1993) reported that the *M. longissimus lumborum* was more color stable than *M. psoas major*, and the metmyoglobin reductase activity was the main color-determining characteristic that differed between the two muscles. Even though these conclusions have been made, others have found little evidence to support that reducing ability is related to meat discoloration or color stability. O'Keefe and Hood (1982) reported high metmyoglobin reductase activity was associated with more color stable muscles, but that there was no correlation between metmyoglobin reductase activity and discoloration. They concluded that metmyoglobin reductase activity had little effect on metmyoglobin activity. Other studies have shown that the ability to reduce iron in metmyoglobin has been reported to be more dependent on the availability of NADH then metmyoglobin reducing activity (Bekhit et al., 2003). Lactase dehydrogenase replenishes the supply of NADH in lactate enhanced beef by converting lactate to pyruvate and NADH (Mancini et al., 2004). This supply of NADH restores MRA and increases color stability.

Lipid oxidation is believed to be a promoter of myoglobin oxidation. Numerous research studies have linked the relationship between meat discoloration and lipid oxidation. Lipid oxidation is positively correlated with pigment oxidation (Liu et al., 1995). Rancidity in meat is

primarily attributed to the oxidation of unsaturated fatty acids of phospholipids that play an integral role in mitochondrial membranes (Lauridsen et al., 2000). More than 50% of the fatty acids found in the mitochondria are unsaturated and susceptible to lipid oxidation (Gutierrez et al., 2002; Lass and Sohal, 1998). Lipid oxidation and myoglobin oxidation appear to be interrelated (Arnold et al., 1993; Faustman et al., 1998; Strohecker et al., 1997; Tang et al., 2005). Faustman and Cassens (1990) reported a strong correlation between lipid and myoglobin oxidation, but it is not understood if myoglobin oxidation catalyzes lipid oxidation or vice versa. Tang et al. (2005) reported that mitochondria containing a greater amount of α-tocopherol had less lipid oxidation than those possessing lower levels. Faustman et al. (1989) found muscles from cattle fed Vitamin E had greater color stability. Tang et al. (2005) later concluded that postmortem mitochondrial lipid oxidation and myoglobin oxidation were interrelated and they were both inhibited by increased α-tocopherol concentrations. Also, oxygen consumption rate was elevated with increased α-tocopherol concentrations. Hutchins et al. (1967) found that metmyoglobin accumulation and malonaldehyde were positively correlated ($r = 0.73$). In order to measure lipid oxidation in meats, there are a variety of methods used but the most widely used is the TBA test (2-thiobarbituric acid test). The method is based on the spectrophotometric determination of the extracted malonaldehyde from the food product (Tarladgis et al., 1960).

*Objective Color Measurement*

Two devices have historically been used to obtain objective color measurements: a colorimeter or a spectrophotometer. A colorimeter only measures tistimulus values (CIE L*a*b*) and have a combination of illuminant and observer. A colorimeter is used for detecting and measuring small color differences between samples that are nearly alike in color. Spectrophotometers are more complex instruments that offer several illuminant/observer

combinations for the calculation of stimulus values and supply spectral analysis in intervals of 1 to 10 nm. The reflectance color measurement used by a spectrophotometer is a more rapid approach that can be used repeatedly on meat samples.

McKenna et al. (2005) reported that L* (lightness) appeared to play a minimal role in color stability. Evaluating his correlation coefficients between muscles, there were low to not significant. McKenna et al. (2005) reported a* values (redness) to have the most correlation throughout the display period. Brewer et al. (2000) reported a 92% correlation between a* values and visual color panelists ratings on pork *longissimus lumborum.* The relationship between b*-values (yellowness) and color stability is not clear. There was no significant trend seen and few differences were noted.

***Postmortem Tenderness***

Increased time of postmortem aging increases meat tenderness (Goll et al., 1964; Gruber et al., 2006; Calkins and Seidman, 1988; Savell et al., 1981)**.** Numerous studies have reported that tenderness is improved during 1 to 14 d of postmortem aging (Savell et al., 1981; Calkins and Seidman, 1988; Koohmaraie et al., 1991). Throughout these studies, it was found that the biggest increase in tenderness occurred during the first 6 to 8 d postmortem and with most of the tenderization happening within the first 3 to 4 days after death (Goll et al., 1964; Davey and Gilbert, 1969; Minks and Stringer, 1972; Gruber et al., 2006). It is noted that tenderness continues to decrease but at a much slower rate.

Numerous studies have tried to capture muscle tenderness within the first 24 h (*pre-rigor)* postmortem but have found it to be difficult due to varying levels of adenosine triphosphate (ATP) concentrations (Klose et al., 1970; Dransfield and Rhodes, 1975; Cia and Marsh, 1976). Goll et al. (1997) found that contraction of pre-rigor muscle during cooking increases toughness

and ultimately leads to extremely high shear force values. Wheeler and Koohmaraie (1994) developed a novel approach to measure of prerigor ovine muscle. They found that Warner-Bratzler shear force values (WBSF) increased during the first 24 h postmortem, decreased rapidly from 24 to 72 hours, and then continued to decrease until 336 h but at a much slower rate. Even though differences exist between species (bovine, ovine, porcine), it is generally assumed that meat toughness increases during the early postmortem period (the first 24 h), decreases rapidly from 24 to 72 h, and continues to decrease until 336 h but at a much slower rate (Figure 2.2).

*Disruption of Muscle Structure*

The first observable change in ultrastructure of postmortem muscle occurs in myofibrils, where degradation of the Z disks begins. Proteolytic degradation of proteins associated with the Z disk cause a complete loss of structure, especially to desmin and nebulin. The degradation of the Z-disks and myofibrillar proteins (desmin and nebulin) are responsible for increased fragmentation of myofibrils during postmortem aging. This is measured by the Myofibril Fragmentation Index (MFI) and has been determined to be highly related to meat tenderness (Davey and Gilbert, 1969; Olson et al., 1976). Several other proteins of the myofibril are degraded during postmortem storage, which are thought to contribute to postmortem tenderization (Robson and Huiatt, 1983; Taylor et al., 1995; Robson et al., 1997). Cytoskeleton proteins, including titin and nebulin, are integral to the structural integrity of muscle cells (Robson and Huiatt, 1983; Robson et al., 1997). The N-terminal of the titin molecule is attached to the Z-line and the C-terminal is located near the M-line. Where the titin molecule is bound to the A-band is thought to be inelastic, and where the titin molecule is bound to the Z-line is thought to be elastic. Titin function is to maintain the structural integrity of the sarcomere and

provide an elastic element that connects the thick filament to the Z-line (Robson et al., 1995). Nebulin is believed to offer stability to the thin filament and help anchor them to the Z-line. Nebulin is anchored at the C-terminal of the Z-disk and extends to the length of the I-band (Robson et al., 1995).

Degradation of nebulin and titin increase tenderness between 24 to 72 h postmortem. Taylor et al. (1995) found that titin was almost entirely degraded between 24 and 72 h postmortem and 25% of the nebulin present in the skeletal muscle was degraded within the first 24 hours. This degradation resulted in weakening of the I-band and the Z-disk (Taylor et al., 1995). It has been reported that steaks characterized as "tender" had more extensive and rapid degradation than those classified as "tough" (Huff-Lonergan et al., 1995; Anderson and Parrish, 1989). However, Fritz et al. (1993) concluded that there was no relationship between tenderness, determined by WBSF and titin content, which was measured 48 to 384 h postmortem.

Troponin-t degrades during postmortem aging, but does not play an important role in maintaining the structure of the myofibril. Therefore, it is unclear whether troponin-t degradation impacts postmortem tenderization or just serves as an indicator of myofibrillar proteolysis (Ho et al., 1994; Huff-Lonergan et al., 1995**)**. Degradation of costamere proteins contributes to aging as shown by the rate of degradation within the 72 h postmortem time period (Taylor et al., 1995). Also, desmin has been linked to the rate at which aging occurs and the detachment of adjacent myofibrils.

Even though not fully understood, it is thought that cathespsins, calpains and calcium ions could be possible contributors to myofibril degradation. Cathespins are enzymes located within the lysosome. They are known to work in acidic conditions and their concentrations are increased during aging. They are known to be ineffective during early stages of aging since

there is little to no myofibrillar degradation early on. The biggest debate against the involvement of cathespins is that all catheptic proteases degrade myofibrillar proteins including major contractile proteins (actin and myosin) (Koohmaraie et al., 1988). Many studies have reported that these major contractile proteins are not degraded in muscle that is stored at 0 to 4 °C. It is believed that if this tenderization takes place at all, it is from 7 to 10 d postmortem (Koohmaraie et al., 1988). Calpains are endogenous proteases that are activated by calcium. Calpains are responsible for 90% or more of the tenderization that occurs during postmortem storage at 2 to 4°C (Goll et al., 1991) and is largely responsible for postmortem degradation of myofibrillar proteins (Koohmaraie, 1992; Koohmaraie, 1996; Hopkins and Thompson, 2002). Calpains are known to not degrade actin, α-actinin, myosin, or troponin-C (Goll et al., 1983).

Since the $Ca^{2+}$ concentration in postmortem muscle is too low for any significant m-calpain activity to occur, μ-calpain is thought to be responsible for postmortem proteolysis (Boehm et al., 1998). Calpastatin is known to inhibit calpain activity, and muscle contains an excess of calpastatin relative to μ-calpain. Koohmaraie (1996) suggest that the ratio of calpastatin to μ-calpain was 2:1 in beef. The difference in this ratio has been used to explain tenderness difference among *longissimus* muscle samples (Wheeler et al., 1990; Koohmaraie et al., 1991). Some studies have shown that $Ca^{2+}$ ions could contribute to postmortem weakening of the myofibril structure, but it proves to be difficult to separate the role of the $Ca^{2+}$ and calpains.

Besides myofibril changes contributing to postmortem tenderization, some researchers have suggested other mechanisms. Goll et al. (1995) attributed the large increase in toughness that occurs during the first 24 to 36 hours postmortem and the decrease in toughness thereafter to the weakening of the actin/myosin cross-bridge. Also, changes to the extracellular matrix may

contribute to postmortem tenderization (Greaser, 1997; Nishimura et al., 1998; Takahashi, 1996). The mechanism responsible for the degradation of the endomysium and permysium is unknown.

The majority of research regarding the mechanisms of postmortem tenderization has focused on myofibrillar proteolysis. As time has gone by, thoughts and theories have changed about the mechanisms causing the increase in tenderness postmortem. This is no doubt a complex topic, which will continue to evolve as the mechanisms are more heavily researched. All of these mechanisms will continue to be affected as we are manipulating our preharvest and postharvest management.

*Aging techniques*

There are two methods of aging commonly used in the beef industry, wet aging and dry aging. Wet aging involves storing a meat product in a vacuum-sealed, non-permeable package at refrigerated temperatures (Campbell et al., 2001; Sitz et al., 2006; Warren and Kastner, 1992). This is the most commonly used method of the two used in the United States (Laster et al., 2008; Smith et al., 2008). Wet aging commonly results in significantly higher yields compared to dry aging (Laster et al., 2008; Smith et al., 2008; Warren and Kastner, 1992). Dry aging refers to storing product unpackaged in a controlled environment and can be utilized for whole carcasses or sub-primal cuts (Campbell et al., 2001, Smith et al., 2008; Warren and Kastner, 1992; Sitz et al., 2006). Between the two aging techniques, when aging time is held constant, there is no difference inWBSF (Smith et al., 2008). It is believed that aging to a certain point increases positive flavor attributes, but after a certain point undesirable flavors will be noted. The point at which undesirable flavors appear has yet to be found. Smith et al. (2008) thought this was at 21 day of aging; however, steaks aged for 21 d resulted in the highest flavor level and beyond 21 d resulted in decreased beef flavor.

*Aging at retail level*

Numerous studies have reported the aging period applied to cuts in the United States marketplace. The first National Beef Tenderness Survey (Morgan et al., 1991) reported post fabrication aging times (PFT) (days for subprimal cut to arrive at retail outlet from fabrication plant) for all cuts were a minimum of 3 d, a maximum of 30 d and an average of 17 d. Results of the National Beef Tenderness Survey- 1998 (Brooks et al., 2000) showed a minimum PFT of 2 d, a maximum PFT of 61 d and an average PFT at 19 d. Additionally 34.1% of subprimals had a PFT less than 14 days. The National Beef Tenderness Survey- 2005/2006 (NCBA, 2006) stated that minimum PFT was 3 d, maximum PFT was 83 d and average PFT was 22.6 d. The National Beef Tenderness Survey- 2010/2011 determined the minimum PFT was 1 d, maximum PFT was 358 d and average PFT was 20.5 d (NCBA, 2011).

Many studies have tried to identify the ideal postmortem aging period for a beef subprimal (Smith et al., 1978; Eilers et al., 1996). Texas A&M University researchers (Lorenzen et al., 1998) developed an "aging index" to assist retailers in managing postmortem aging times in order to maximize palatability and consistency. They recommended that ribeyes and shortloins be aged for 13 days. Colorado State University (Mies et al., 1999) developed a review of literature to identify the appropriate postmortem time to recommend to retailers and they concluded that the strip loin should be aged 14 days and top sirloin cuts be aged for 21 days. Additionally, Gruber et al. (2006) noted that extended aging times were especially needed for loin cuts that were lower quality grade (USDA Select) with the *longissimus* muscle and the *gluteus medius* requiring 26 and 27 d of aging to optimize tenderness. It was also reported that tenderness in strip loin steaks could be improved a minimum of 14% and top sirloins could be improved up to 22% with more extensive aging. Gruber et al. (2006) used these results to

classify muscles into aging response categories based on the length of postmortem aging needed for a majority of the change in shear force to occur. They classified the *gluteus medius* to have a moderate aging response and the *longissimus dorsi* to have a high aging response time. These classifications were based on high, moderately high, moderate, moderately low and low categories.

*Beef Sensory Attributes*

Beef flavor is very complex with a variety of influences as well as descriptive terms. Lawrie (1966) described the sensations of odor, taste, texture, temperature and pH all combine to create flavor. Diet plays a large role in flavor development as it can undergo direct changes based on the feed type. Flavors are different and all have an additive effect to the complexity of beef flavor. One of the more standard beef lexicons used today, developed by Adhikari and Miller (2010), focuses on major beef flavor notes and aroma such as brown/roasted, bloody/serumy, fat-like, metallic, livery, hay-like. It assists in creating a standard for referencing back to a taste sensory panel for each flavor note. Juiciness has contributed to differences in pH, water-holding capacity, fatness and firmness of the cooked meat product (Lawrie, 1966). When evaluating juiciness, it is the combined effects of initial fluid release as well as the sustained juiciness (Weir, 1960). Tenderness is considered the single most important attribute in determining beef palatability and acceptability (Bratzler, 1971). Weir (1960) described it as the initial ease of penetration of the sample by the teeth, how easily the meat is fragmented and the amount of particle left after chewing. Tenderness and juiciness are highly associated. Carpenter (1962) concluded that the lubricating properties of fat confound the sensation of tenderness.

*Objective Tenderness Evaluation*

Warner-Bratzler shear force (WBSF) and slice shear force (SSF) are two forms of shear force analysis most commonly used in the measurement of tenderness. With WBSF, steaks must equilibrate to room or refrigerated temperature for 2 to 24 hours (Crouse and Koohmaraie, 1990; Wheeler, 1994). A WBSF machine testing machine or a machine equipped with a WBSF attachment must be used. A 60-degree angle, vee shaped slides through a 1.245 mm thick space on the apparatus for the actual measurement. Cores (1.27cm) are obtained from the steak, and each core is sheared once perpendicular to the fibers with a crosshead speed of 200 mm/min (Shackelford et al., 1997).

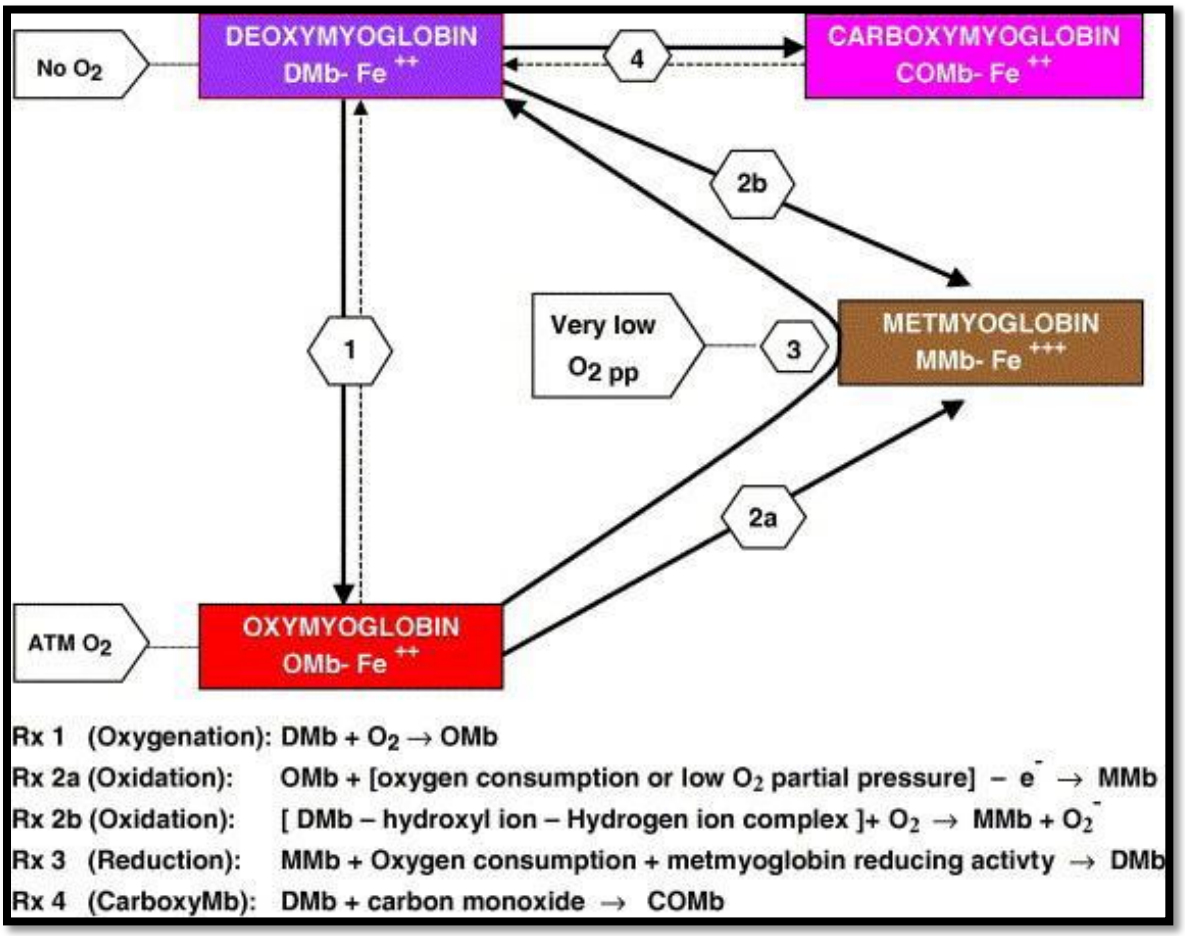
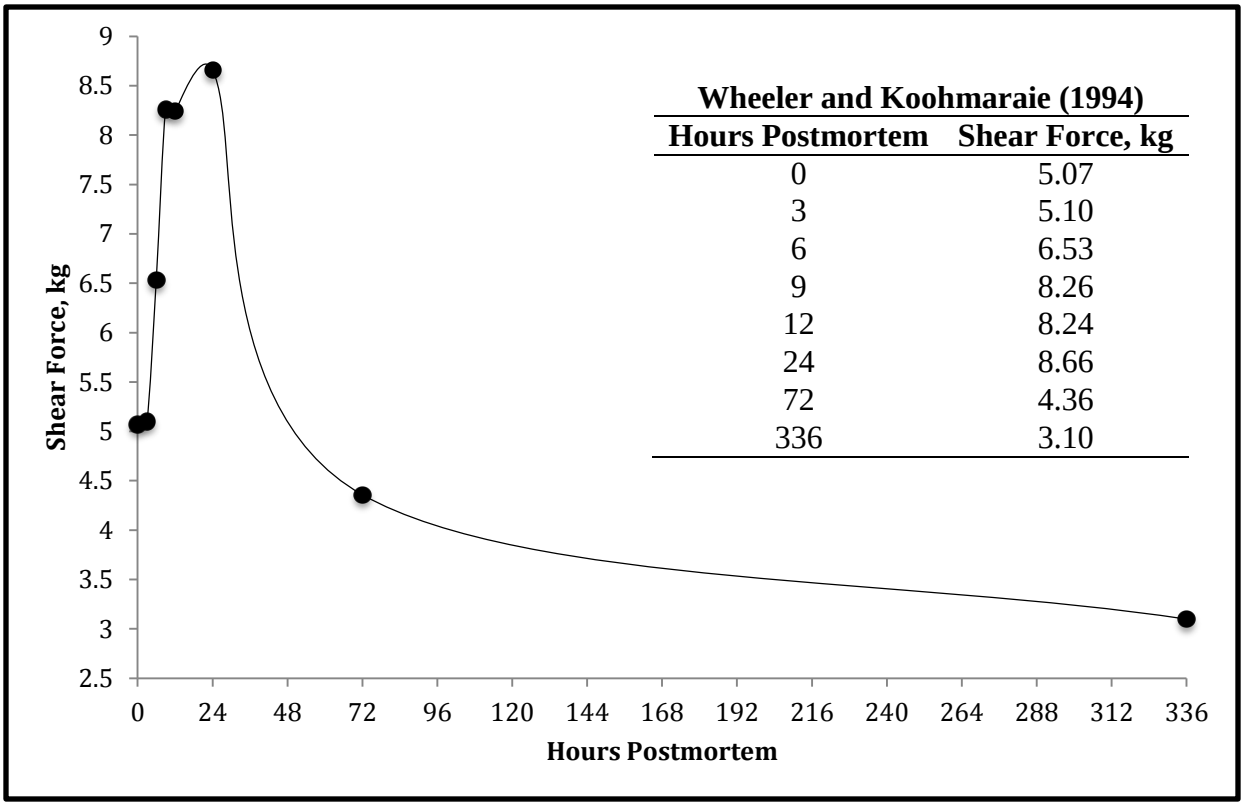



**Figure 2.1** Chemistry of Fresh Meat Color Triangle. Schematic of the interconversions of myoglobin redox forms in fresh meat color (Mancini and Hunt, 2005).




**Wheeler and Koohmaraie (1994)**

| Hours Postmortem | Shear Force, kg |
|---|---|
| 0 | 5.07 |
| 3 | 5.10 |
| 6 | 6.53 |
| 9 | 8.26 |
| 12 | 8.24 |
| 24 | 8.66 |
| 72 | 4.36 |
| 336 | 3.10 |

**Figure 2.2.** Postmortem changes in ovine longissimus shear force (Wheeler and Koohmaraie, 1994).

CHAPTER III

# MATERIALS AND METHODS

*Product Selection*

Paired strip loins (NAMP #180) and top sirloin butts (NAMP #184) were obtained from a commercial packing plant. Strip loins and top sirloin butts were collected at approximately 48 h postmortem from USDA Choice carcasses with a marbling scores ranging from Small$^{00}$ to Small$^{50}$ (n = 15) or USDA Select carcasses with a marbling scores ranging from Slight $^{50}$ to Slight$^{99}$ (n = 15) (Table 3.1). Samples were collected from 3 separate groups of carcasses (2 separate trips to the packing plant) in order to replicate aging and display period three times. These collection groups served as a block to control variance among different groups of carcasses. Samples were then transported under refrigeration (0 – 2°C) to Colorado State University Meat Laboratory for further processing.

*Muscle Fabrication and Steak Allocation*

Strip loins from the left and right sides of an individual animal were fabricated into six portions (excluding portions containing the *gluteus medius*). Each portion was randomly assigned to one of 6 postmortem aging periods: 14, 21, 28, 35, 45 or 63 days. Each top sirloin butt was fabricated by removing the *biceps femoris, gluteus accessorius,* and *gluteus profundus* in order to isolate the *gluteus medius* muscle. Once isolated, each *gluteus medius* portion was sectioned into 3 equal portions from posterior to anterior, yielding 6 uniform sections per animal. Then, each portion was randomly assigned to one of 6 postmortem aging periods: 14, 21, 28, 35, 49 or 63 days. The sections for both strip loin and top sirloin butts were vacuum-sealed in a non-

oxygen permeable package and stored fresh, not frozen at 0°C (±1°C) in the absence of light for their designated aging period. Once the aging period was complete, each section was removed from storage, faced and hand-cut into 3 strip loin steaks (2.54 cm thick) and 6 top sirloin steaks (2.54 cm thick) with a maximum of 0.32 cm of external fat remaining.

*Retail Display*

Two steaks from the aged section for each muscle were placed in Styrofoam trays containing soaker pads and overwrapped with polyvinylchloride film. Each package was placed in a multi-deck retail display case (Hussman Model No. M3X8GEP) set at 2°C (±1°C) for 72 hour period or until the steak was 33% discolored. Retail display cases were equipped with Light Emitting Diodes (LED) lighting that illuminated at an average light intensity of 900 Lux (±184 Lux). Samples were exposed to light the entire 72 h period they were in the display case. Every 8 hours, samples were rotated to account for any variation in light intensity or temperature.

*Color Evaluation*

Every 8 h during the 72-hour display period, each steak was evaluated by a minimum of 8 trained panelists for lean color, fat color, and percent lean discoloration. Trained panelists quantified the predominant lean and fat color of each steak using a 15 cm unstructured line scales anchored at both ends with descriptive terms. For predominant lean color, 0 cm denoted very dark red or brown/green, and 15 cm denoted bright cherry-red to very dark red. For predominant external fat color, 0 cm denoted dark tan or brown/green, and 15 cm indicated bright, creamy white. Once the display period was complete, steaks were removed from retail display. After each scoring session, individual panelist ratings were averaged to obtain a single panel rating for each visual attribute of each sample. From each package, one steak was randomly designated for

sensory panel evaluation while the second steak was designated for shear force testing and oxidation analysis (2-thiobarbituric acid reactive substance).

*Objective Color Measurement*

Objective lean color measurements were recorded every 8 hours for the 72 hour period. Measurements were obtained using a portable spectrophotometer equipped with a 6 mm measurement port (Miniscan Model 4500S, Hunter Laboratories, Reston, VA) that was standardized before each use. A total of nine readings of CIE L*- (lightness), a*-(redness), b*-values (yellowness) for each steak were collected through the overwrap film and averaged for each package.

*Warner-Bratzler Shear Force Determination*

Upon completion of designated aging periods, Warner- Bratzler Shear Force (WBSF) was conducted on each steak (fresh; never frozen) at 0 and 72 h of retail display. For 0 h shear force determination, after the section was removed from storage, the third steak cut from each aged section was immediately cooked, and WBSF was conducted to determine the effects of the aging period on tenderness without the display period. Once the 72 h display period was completed, steaks were removed from the package, and were immediately cooked. Steaks were cooked on electric grills (model GGR64, Salton, Inc., Lake Forest, IL) that heated steaks from both sides simultaneously to a peak internal temperature of 71°C, measured in the geometric center of the steak, using a Type K thermocouple thermometer (AccuTuff 340, model 34040, Cooper-Atkins Corporation, Middlefield, CT). After cooking, the steaks were allowed to equilibrate to room temperature (22°C) and 6 to 10 cores (1.27 cm in diameter) were removed from each steak parallel to the muscle fiber orientation. Each core was sheared once, perpendicular to the muscle fiber orientation, using a universal testing machine (model 4443,

Instron Corp., Canton, MA) fitted with a Warner-Bratzler shear head (cross head speed: 200 mm/min). Peak shear force measurements were recorded for individual cores and averaged to obtain a single WBSF value for each steak.

*Lipid Oxidation Analysis*

Immediately following removal from the package, a 35 g portion was removed from the medial portion of each steak designated for WBSF. The 35 g portion was frozen at -80°C and then shipped with dry ice to Food Safety Net Services (San Antonio, TX) for further evaluation. Steaks were evaluated for lipid oxidation by measurement of 2-thiobarbituric acid reactive substances (TBARS) using methods described by Tarladgis et al. (1960) and modified by (Rhee et al., 1978).

*Descriptive Sensory Analysis*

Descriptive sensory analysis was conducted at Colorado State University. Panelists were trained to characterize sensory attributes for both strip loin and sirloin steaks using the standards outlined in the lexicon of descriptive attributes, developed using guidelines provided by AMSA (1995) and Adhikari and Miller (2011).The attributes that they were trained to identify included tenderness (myofibrillar, connective tissue tenderness, and overall), juiciness, and the following beef flavor descriptors: beef flavor intensity, buttery/beef fat flavor, oxidized, sour/acidic, livery/organy, and bloody/metallic.

Following removal from the display case, both strip loins and sirloin steaks designated for sensory analysis were immediately placed in a vacuum sealed bag and kept frozen (-20°C) until all aging and display periods were complete. Samples (both strip loin and sirloin) were strategically and randomly assigned to a sensory session to ensure that all aging periods for each cut were represented in a single sensory panel session. A maximum of 12 samples were served

during a single panel session, and a maximum of 24 samples were served to each trained panelist each day. Also, sensory panel sessions were scheduled a minimum of 2 h apart.

Frozen strip loin and sirloin steaks used for each panel session were tempered for 24 to 36 h at 2°C to ensure that raw internal steak temperatures were between 1 and 5°C and then cooked on electric grills (model GGR64, Salton, Inc., Mt. Prospect, Il) to a peak internal temperature of 71°C. A Type K thermocouple thermometer (AccuTuff 340, model 34040, Cooper-Atkins Corporation, Middlefield, CT) was placed in the geometric center of each steak and the internal temperature was monitored during cooking. After cooking, steaks were cut into sections (1.3 cm x 1.3 cm x cooked steak thickness) and sections were placed in a ceramic bowl, covered with aluminum foil, and held in a warming cabinet (60°C) for a maximum of 30 minutes before being served to a minimum of 8 trained panelists. Each panelist received 2 sections from each steak. Panelists were seated in individual cubicles equipped with red incandescent light to mask color differences among samples. Panelists were supplied with distilled water, apple juice, and unsalted saltine crackers, which were used for palate cleansing between samples. Panelists evaluated each sample and rated it on a 15 cm unstructured line scale anchored at both ends with descriptive terms. For juiciness and all tenderness attributes (myofibrillar, connective, overall), 0 cm indicated extremely dry and extremely tough, respectively, and 15 cm indicated extremely juicy and extremely tender, respectively. For tenderness, the mid-point of the line (7.5 cm) was considered a neutral response (i.e., neither tough nor tender). For beef flavor descriptors, 0 cm signified “no presence”, and 15 cm signified “very strong presence”. After each panel session, individual panelists’ ratings were averaged to obtain a single panel rating for each sensory attribute of each sample.

*Statistical Methods*

Analysis of variance (ANOVA) was conducted using the restricted maximum likelihood method (REML) in the mixed procedure of SAS (Statistical Analysis Software, Version 9.3, Cary, NC). Data for strip loins and sirloins were analyzed separately. Sample collection group (retail display groups) were included as a block effect in each model to control for variance in product and storage conditions. The ANOVA model included fixed effects of quality grade (grade) and postmortem aging treatment (age) and the two-way interaction as fixed effects. Random effects included carcass and the interaction between age and carcass. Random effects included in the model designated age and retail display period (hour; 0 h through 72 h) as a repeated measure. When the dependent variable was measured multiple times during the retail display period, hour was also included in the model as a fixed effect. The Kenward- Roger approximation was used to calculate denominator degrees of freedom, and peak internal steak temperature served as a covariate when analyzing WBSF and sensory data. A test for the most appropriate covariance structure (compound symmetry or autoregressive) was performed to determine the most appropriate analyses for each dependent variable. The most appropriate covariance structure was selected using the lowest AICC value. The AICC value is the second order criterion to the Akaike Information Criterion (AIC), which is a way of selecting a model from a set of models. The AICC value takes into account sample size by, essentially, increasing the relative penalty for model complexity with small data sets. In each model, main effects and interactions were analyzed for each fixed effect ($\alpha = 0.05$).

Non-linear regression (PROC NLIN: SAS Inst. Inc., Cary, NC) was used to characterize change in WBSF during postmortem storage. There was not a significant difference between grades, so they were fitted to a single curve. Within each cut (strip loins and sirloins) least

squares means (cut x age) were fitted to the following exponential decay model: $WBSF = b_2 + b_1 exp(-b_0 t)$ where $b_2$ is the distance from the asymptote, $b_1$ is the distance from the asymptote to the y-intercept, $b_0$ is a constant rate of change, and $t$ is the time (d) postmortem (Figure A1.2 and Figure A1.3). Coefficients of determination ($R^2$) were calculated as the ratio of the residual sums of squares to the corrected total sums of squares.

## RESULTS AND DISCUSSION

The beef utilized in this study was intended to represent the majority of beef destined for retail sale in the United States marketplace. Least squares means for carcass traits for the carcasses from which the strip loins and sirloins were collected are presented in Table 3.1. Mean marbling score for both USDA low Choice and USDA Select product was near the median value of the selection range (Slight 50-99 and Small 00-50), and all of the other carcass traits were reasonably similar and did not differ ($P > 0.05$) by quality grade. Data for strip loin steaks and top sirloin steaks were analyzed independently in this study and results will be discussed separately.

### *Strip Loin Steaks*

*Color Evaluation*

USDA quality grade did not affect the results of retail display, and all results are reported averaging over USDA Choice and USDA Select strip loin steaks ($P > 0.05$). There was an age x hour interaction ($P < 0.05$) for lean discoloration scores for strip loin steaks and the values are reported in Table 3.2. Surface discoloration was minimal during retail display, only 2 steaks discolored. This observation was consistent for all steaks resulting from all levels of postmortem aging time. Previous research has characterized the *longissimus dorsi* as having very high color stability (McKenna, 2005; Renerre and Labas, 1990; Renerre and Labas, 1987; O'Keefe and Hood, 1982; Bendall and Taylor, 1972). The results of the present study support the findings of the previously mentioned studies in that strip loin steaks resulting from all postmortem aging treatments had extremely low levels of discoloration following 72 h of retail display. As steaks were aged for longer periods postmortem, the level of lean discoloration increased, but only to

negligible levels with the highest discoloration scores occurring among 49 and 63 d aged steaks (Table 3.2). It is possible that the strip loin steaks utilized in this study resulted from beef animals that had been supplemented with Vitamin E during the finishing period; however, this information is not known for the product utilized. Sanders et al. (1997) noted that supplementing Vitamin E to cattle resulted in increased color stability and extended shelf life of beef. Zerby et al. (1999) suggested that strip loin steaks could last approximately 2.5 d for Non-Vitamin E supplemented cattle and approximately 3 d for Vitamin E supplemented cattle in a simulated retail display case before they reached an unacceptable level, where the product would be discounted. However, the level of discoloration that was observed in the current study indicates that strip loins could be aged for extended aging periods and still be purchased within 3 d of being placed in the retail case with extremely low levels of browning and discoloration. An unpublished study from Kansas State University that compared LED and fluorescent lighting, suggested that LED lighting extended color life based on visual color scores (Steele, 2011). These visual color evaluation scores resulted in an extended display life of 0.5 to 1 d for beef *longissimus dorsi* and the superficial portion of the beef *semimembranosus* steaks under LED lighting compared to fluorescent lighting.

Even though metmyoglobin formation on the surface was minimal, color panel ratings for lean color and fat color suggested that lengthy postmortem aging before retail display influences the overall appearance of steaks. Ratings for lean color of strip steaks are presented in Table 3.3 and ratings for fat color are presented in Table 3.4. A significant age x hour interaction existed for lean color scores ($P < 0.05$). For all aging treatments, throughout the 72 h display period, lean color scores decreased, indicating a darkening of the red color and transitioning away from bright, cherry-red colored lean. Fat color scores also decreased throughout the display period but

at a much less noticeable level. Fat color data for strip loin steaks are in Table 3.4 and an age x hour interaction ($P<0.05$) existed. Similar to lean color scores, the external fat color scores of strip loin steaks were affected by age. Aging alone (0 h of retail display) reduced fat color scores, indicating that the color of the fat was less white with longer periods of postmortem aging. Fat color scores decreased for all aging treatments over the 72 h of display, but were still indicative of a white colored fat. Nonetheless, considerable reductions in fat color scores were observed in steaks that had been aged 28 d and 35 d postmortem after 40 h of retail display, and clear changes in fat color were observed in strip steaks aged 49 d and 63 d postmortem as early as 24 h of retail display Objective color measurements (L*a*b*) for strip loin steaks are presented in Table 3.5, Table 3.6, and Table 3.7 respectively. Lean a* scores support the results of the trained color panel showing that redness decreased during retail display for strip loin steaks in all aging treatments. With the exception of one aging treatment (49 d), redness, as indicated by a high a* value, increased in the first 8 h of display. This data indicates that following extended periods of gaining in vacuum-sealed bags, beef strip loin steaks require longer than usual time to fully bloom. In this study, steaks were allowed to bloom for approximately 2 hours before objective color measurements were taken. A similar increase in a* was also reported by McKenna et al. (2005); their values showed that a* values increased from day 0 to day 1. Steaks aged 14 d before being placed in retail display maintained the most cherry-red colored lean throughout 72 h of retail display, whereas 63 d aged steaks showed the greatest decline in lean color scores over the 72 h display period. Despite the fact that lean color scores declined for all postmortem aging treatments, all age levels maintained an acceptable, red colored lean throughout the 72 h display period. However, lean a* showed significant reductions

following 32 h of display in 63 d aged steaks and after 64 h of display in 49 d aged strip loins steaks (Table 3.6).

Color panel findings indicated that extended periods of postmortem aging contribute to a reduction in bright cherry-red lean beef color, but did not necessarily shorten the display life of strip loin steaks in a 72 h period. Objective measurements of L* and b* were not attributed to any meaningful differences in visual appearance of the lean in strip loin steaks. Similarly McKenna et al. (2005) reported that lean L* and b* values were of minimal significance in predicting color stability.

*Effects on Postmortem Tenderness*

The effects of age, quality grade, and age x grade on WBSF and trained sensory panel ratings for strip loin steaks were tested, and the effects of grade and the age x grade interaction were not significant ($P > 0.05$). Therefore, all reported and discussed differences for WBSF and trained sensory panel ratings for strip loin steaks are based on the main effect of age averaging over quality grade.

Warner-Bratzler shear force values of strip loin steaks are reported in Table 3.8 and trained sensory panel ratings for strip loin steaks are presented in Table 3.9. As expected, when steaks were subjected to longer periods of postmortem aging, WBSF values decreased and trained sensory panel tenderness ratings improved. The WBSF values of steaks decreased ($P < 0.05$) following 72 h of retail display (Table 3.10). Even though the reduction in WBSF during the 3 days of display was minimal, these results demonstrate that tenderness is improving during the display period.

Least squares means for WBSF of strip loins steaks at the different postmortem aging periods are presented in Table 3.8. As postmortem aging time was increased, WBSF values

decreased for all strip loin steaks. It was most notable that 49 d and 63 d aged strip loin steaks had the lowest WBSF value, while 14 d had the highest WBSF value. There was no statistical difference between 21 d, 28 d and 35 d aged steaks. The least squares means for all steaks represented in all 6 aging periods, were under the ASTM tough vs. tender threshold, (WBSF < 4.4kg) based on ASTM (2011) guidelines.

Several studies have recommended aging times based on improvements in shear force (Smith et al., 1978; Weatherly et al., 1998; Gruber et al., 2006). Smith et al. (1978) found no improvement in shear force past 11 d postmortem for the *longissimus dorsi* (USDA Choice) and Weatherly et al. (1998) suggested aging strip loins for only 13 d. Gruber et al. (2006) reported that USDA Select *longissimus dorsi* tenderness improved up to 28 d postmortem, and USDA Choice *longissimus dorsi* showed no improvement in shear force past 21 d postmortem. In order to fully identify correct strategies for postmortem aging management, similarly to Gruber et al. (2006), in the present study, non-linear regression models that were fitted to the least squares means were developed (Figure 4.1). Since the effect of USDA quality grade was not significant ($P > 0.05$), a single curve was constructed to represent both USDA Choice and Select strip loin steaks. Gruber et al. (2006) classified the *longissimus dorsi* (USDA Select) as having a high aging response. In the present study, during aging from 14 to 63 d, shear force values decline by approximately 1 kg. Approximately half of the total decline in WBSF value was achieved from 14 to 28 days, while the remaining aging response occurred from 28 to 63 days; however, WBSF did not significantly decline from 49 d to 63 d postmortem. This data indicated that considerable tenderness improvement ceases following 49 d postmortem in USDA Choice and Select strip loin steaks.

In agreement with WBSF data, trained sensory panel ratings indicated that an advantage in myofibrillar tenderness (MT), connective tissue tenderness (CT), and overall tenderness (OT) compared with 14 d aged strip loin steaks is not distinguishable until strip loins have been aged for 35 d, further suggesting that there is a minimal advantage in aging strip loins for an extended period to gain recognizable tenderness advantages (Table 3.9). It should be noted that 63 d aged steaks had the highest rating for all three tenderness attributes. Trained sensory panel ratings were used to quantify the levels of off-flavors associated with oxidation of the strip loin steaks following 72 h of display. Sour/acidic, oxidized, and livery/organy flavors were affected by age and least squares means are presented in Table 3.9. Sensory panel ratings for oxidized flavors indicated that aging steaks up to 35 d did not significantly increase the level of detectable oxidized flavor in strip loins steaks when compared to 14 d aged steaks. Similarly, sour acidic flavors in strip loin steaks are not significantly different ($P > 0.05$) from 14 d aged steaks, unless they were aged for greater than 35 days postmortem. Oxidized and sour/acidic flavors increased ($P < 0.05$) over the levels of flavors found in 14 d aged product when strip loins are aged greater than 35 days. This was most evident when 63 d aged steaks are most tender but have the greatest amount of off flavors associated with them.

An age effect was observed on TBAR values of strip loin steaks ($P < 0.05$; Table 3.11); however, there were no meaningful trends or associations with TBAR values and postmortem aging and the development of discoloration and off flavors. This was potentially due to the fact that strip loins were vacuum sealed in high barrier bags and at a very low temperature in the absence of light during the entire aging period, and all steaks, regardless of age, were displayed for the same period of time in a traditional, oxygen permeable package. These samples were also shipped to a separate location to be analyzed. Even though they were froze in an -80°C freezer

before shipping, this could contribute to the inconsistency and low TBAR values that were recorded.

***Sirloin Steaks***

*Color Evaluation*

A age x hour interaction existed for lean discoloration scores of sirloin steaks displayed for 72 h ($P < 0.05$; Table 3.12). Discoloration scores for sirloin steaks that had been aged 49 d postmortem indicated extremely low levels of browning throughout the retail display period. Sirloin steaks that had been aged for 49 d and 63 d, had very low levels of lean discoloration following 48 h of retail display. . Even though extensive surface browning was not observed for the majority of aging treatments and display periods, color panel ratings for lean color and fat color indicated that postmortem aging before retail display effects the appearance and shelf stability of sirloin steaks. Ratings for lean color of sirloin steaks are presented in Table 3.13 and ratings for fat color are presented in Table 3.14. Objective lean color measurements, L* a* b*, for the same steaks, are presented in Table 3.15, Table 3.16, and Table 3.17, respectively.

An age x hour interaction existed for lean color scores ($P < 0.05$; Table 3.13). Lean color scores decreased during 72 h of retail display for all aging treatments, indicating a darkening of red color and transitioning away from a bright, cherry-red colored lean,. Lean a* scores agreed with the results of the trained color panel showing that redness decreased for all age strip loin steaks over the retail period. Steaks aged only 14 d before being placed in retail display maintained the most cherry-red colored lean throughout 72 h of retail display. Lean redness scores indicated that sirloin steaks aged 14 d, 21 d, and 28 d before retail display maintained an acceptably colored lean throughout all 72 h of display, while steaks aged 35 d, 49 d, and 63 d had lean color scores reaching a darker, undesirable level of red after 32 h, 24 h, and 16 h of display,

respectively. A number of studies have shown that the *gluteus medius* muscle has color stability issues compared to other muscles such as the *longissimus dorsi* (Hood, 1980; O'Keefe & Hood,1982). Based on a simulated 5 d retail display, McKenna et al. (2005) classified it as an "intermediate" color-stable muscle when compared to other muscles. The results of the current study agree that the color stability is lesser than that of the *longissimus dorsi* muscle; especially following extended periods of postmortem aging. Sirloin steaks aged 28 d or less maintained an acceptable external fat color throughout 72 h of retail display. After that, external fat color fell to unacceptable levels at 64 h, 48 h and 32 h for 35 d, 49 d and 63 postmortem, respectively.

Objective color values agreed with the lean color ratings of panelists as a* values decreased significantly during the 72 h display time for all aging periods. Most notable color deterioration occurred in steaks that had been aged for more than 21 d. For all aging periods, an increase in a*value was seen from 0 h to 8 h., the 0 h measurement was taken after allowing steaks to oxygenate for approximately 2 h. As discussed previously in reference to strip loin steaks, this increase in a* values was also observed in strip loin steaks in this study. It is not fully understood why this took place. There was no meaningful trend in L* values. McKenna et al. (2005) reported that L* values played a minimal role in color stability. In this study, b* values gradually decreased for all aging periods during the 72 h display period. This suggests that b* values were moving from a more yellow color to a more neutral color range (gray).

*Effects on Postmortem Tenderness*

The effects of age, quality grade, and age x grade on WBSF, trained sensory panel ratings and TBARS for strip loin steaks were tested, and the effects of grade and the age x grade interaction were not significant ($P > 0.05$). Therefore, all reported and discussed differences for WBSF, trained sensory panel ratings and TBARS for strip loin steaks are based on the main

effect of age averaging over quality grade. Steaks represented in this study were USDA Choice (Sm $^{00\text{-}49}$) and USDA Select ($^{50\text{-}100}$).

Gruber et al. (2006) reported that the tenderness of USDA Select *gluteus medius* steaks improved up to 28 d postmortem, and USDA Choice *gluteus medius* showed no significant improvement in shear force past 21 d postmortem. In order to fully identify correct strategies for postmortem aging management, Gruber et al. (2006) ran non-linear regression models that were fitted to the least square means of WBSF. In this study, we also fit non-linear regression models to the least square means of WBSF (Figure A1.3). Since there was not a significant quality grade effect, WBSF values by aging treatment were averaged over grade to yield one curve. Gruber et al. (2006) reported an aging response value that was determined by the length of postmortem aging needed for the majority of the change in shear force values to occur from 2 to 28 d postmortem. *Gluteus Medius* (USDA Select) was reported to have a moderate aging response from the categories: high, moderately high, moderate, moderately low and low. In this data, aging 14 d to 63 d postmortem there was approximately a 1kg improvement in WBSF, and over half of the overall decline happened after 35 d. These data suggest that tenderness improvement continues beyond 28 d of postmortem aging for USDA Choice and Select *gluteus medius* steaks. In accordance with the aging curves developed in this study, the *gluteus medius* will continue to improve in tenderness beyond 63 d of age.

Warner-Bratzler shear force values of sirloin steaks by age are reported in Table 3.8 and trained sensory panel ratings for sirloin steaks are presented in Table 3.18. Aging treatment affected WBSF values ($P < 0.05$) and trained sensory panel assessments of tenderness including myofibrillar tenderness ($P < 0.05$) and connective tissue tenderness ($P < 0.05$), but only tended to affect sensory panel ratings for overall tenderness ($P > 0.05$) Even though WBSF was

improved by aging sirloin steaks, a significant ($P < 0.05$) improvement in WBSF over 14 d aged steaks was not observed until sirloins were aged at least 35 d. It should be noted that for all aging treatments taken for sirloin steaks, the least squares means would fall below a WBSF value for the tough vs. tender threshold (4.4 kg) based on the ASTM (2011) guidelines.

Trained sensory panel scores for myofibrillar tenderness indicate that tenderness was not improved over 14 d aged steaks until 49 d of age was accomplished. However, improvements in connective tissue tenderness over 14 d aged sirloin steaks were observed in steaks aged only 21 d. In comparison to other middle-meat muscle cuts containing the *longissimus dorsi* (strip loins and ribeyes), the top sirloin has been shown to contain higher levels of connective tissue, which could contribute to the differences in connective tissue tenderness but not in myofibrillar and overall tenderness. When comparing top sirloin steaks and strip loin steaks, the difference in tenderness appeared to be due to higher amounts of collagen in top sirloin steaks and a tendency toward lower collagen solubility, shorter sarcomere length and higher (less tender) fragmentation index (Harris et al., 2006). The findings of the present study indicate that in order to reasonably improve the tenderness of low Choice and Select sirloin steaks via postmortem aging prior to retail display, top sirloin buts would have to be aged between 35 and 45 d postmortem. Hour, as a main effect, was shown to significantly reduce ($P < 0.05$) WBSF values over a 3 d display period (Table 3.10). Even though the reduction in WBSF during the 3 days of display was minimal, this data demonstrates that tenderness is improving during the display period.

Trained sensory panel ratings were used to quantify the levels of off-flavors associated with oxidation of the sirloin steaks following 72 h of display (Table 3.18). In comparison to the results for strip loin steaks (Table 3.9), sirloin steaks aged for 14 d and displayed for 72 h had detectable levels oxidized and sour/acidic flavors. Nonetheless, the intensity of oxidized flavor

was not significantly ($P < 0.05$) increased beyond that of the 14 d aged steaks until sirloins had been aged for 49 d or more. Sirloin steaks that had been aged for 49 d and 63 d postmortem had significantly higher ($P < 0.05$) sensory panel ratings for the intensity of oxidized flavor. Sour/acid flavors did not significantly ($P < 0.05$) increase over 14 d aged sirloin steaks until 35 d of postmortem aging had been implemented. Sirloin steaks that had only been aged for 14 d prior to retail display had the lowest intensity of livery/organy off-flavors. These results suggest that with as little as 14 d of postmortem aging, followed by 72 h of retail display, presents challenges to the acceptability of flavor and freshness of sirloin steaks.

Even though relatively high levels of oxidized flavor were detected, an age effect was observed on TBAR values of strip loin steaks ($P < 0.051$; Table 11). However, there were no meaningful trends or associations of lipid oxidation (TBAR) and postmortem aging and/or off flavors. This is potentially due to the fact that strip loins were vacuum sealed in high barrier bags and at a very low temperature in the absence of light during the entire aging period, and all steaks, regardless of AGE, were displayed for the same period of time in a traditional, oxygen permeable package. These samples were also shipped to a separate location to be analyzed. Even though they were froze in an -80°C freezer before shipping, this could contribute to the inconsistency and low TBAR values that were observed.

***Conclusions***

Results of this study indicate that a minimum of 28 d of postmortem aging is required to improve the WBSF values of low Choice and Select strip loin steaks over the same strip loins steaks that have been aged for only 14 d, and a minimum of 35 d of postmortem aging is required to significantly improve sensory tenderness ratings for low Choice and Select strip loin steaks. Sensory panel ratings of off-flavors also supported that aging strip loin steaks for 35 d or more

postmortem for retail display and sale is undesirable as the intensity of oxidized and sour/acidic off-flavors significantly increased. These data suggest that strip loin steaks can be aged for 28 d prior to retail display with little effect on display life and the incidence of off-flavors, however, there was no significant tenderness advantage over 14 d aged steaks from low Choice and Select strip loins.

The findings of the present study indicate that 35 d of postmortem aging are required to achieve an improvement in WBSF over 14 d aged low Choice and Select top sirloin steaks, and trained sensory panel scores indicated that at least 49 d of postmortem aging is required to improve the myofibrillar tenderness of low Choice and Select sirloin steaks. Lean color scores indicated a drastically reduced display life for sirloin steaks aged 35 d or more prior to retail display. Sirloin steaks aged 35 d and more produced undesirable lean color scores in as early as the first 24 h of retail display, which would suggest the need to discount the price of these steaks or even remove them from retail display. Additionally, low Choice and Select top sirloin steaks aged only 14 d and displayed an additional 72 h had relatively intense levels of oxidized and sour/acidic flavors present. With all factors considered for low Choice and Select top sirloins, it is not realistic to conclude that top sirloins can be aged for a long enough period to improve tenderness and maintain a considerable level of display life. Extended postmortem aging treatments for top sirloins is most well suited for foodservice where display life is a non-issue.

Table 3.1. Simple means for carcass traits of the experimental sample stratified by quality grade.

| Quality Grade[1] | Carcass Traits | | | | | | |
|---|---|---|---|---|---|---|---|
| | aFat (cm) | HCW (kg) | REA($cm^2$) | KPH (%) | Yield Grade | Lean Maturity[2] | Marbling[3] |
| USDA Choice | 0.89±0.05 | 374.85±29.29 | 87.74±7.1 | 2.5±0.20 | 2.72±0.50 | 173±16.98 | 428±16.98 |
| USDA Select | 1.02±0.04 | 365.23±36.47 | 89.10±6.00 | 2.5±0.25 | 2.76±0.50 | 169±9.15 | 374±12.98 |

[1]USDA Choice carcasses were selected to have marbling scores ranging from Small 00 to 50; USDA Select carcasses were selected to have marbling scores ranging from Slight 50 to 99
[2]A maturity = 100 to 200
[3]300 to 399 = Slight, 400 to 499 = Small

Table 3.2. Least squares means ± SEM for trained color panel lean discoloration scores[1] for strip loin steaks displayed for 72 h ($P_{\text{AGE x HOUR}} < 0.0001$).

| | Age (d) | | | | | |
|---|---|---|---|---|---|---|
| Display (h) | 14d | 21d | 28d | 35d | 49d | 63d |
| 0 | 0.01± 0.58 | 0.06± 0.58 | 0.09± 0.58 | 0.01± 0.58 | 0.01± 0.58 | $0.00^{d}$± 0.58 |
| 8 | 0.07 ± 0.58 | 0.03± 0.58 | 0.15± 0.58 | 0.07 ± 0.58 | 0.05 ± 0.58 | $0.76^{c}$± 0.58 |
| 16 | 0.00 ± 0.58 | 0.05 ± 0.58 | 0.11 ± 0.58 | 0.08 ± 0.58 | 0.06 ± 0.58 | $0.84^{c}$± 0.58 |
| 24 | 0.12 ± 0.58 | 0.13 ± 0.58 | 0.16 ± 0.58 | 0.00± 0.58 | 0.13 ± 0.58 | $0.75^{c}$± 0.58 |
| 32 | $0.18^{yz}$±0.58 | $0.07^{z}$± 0.58 | $0.10^{z}$± 0.58 | $0.09^{z}$± 0.58 | $0.04^{z}$± 0.58 | $1.11^{bcy}$± 0.58 |
| 40 | $0.14^{z}$± 0.58 | $0.06^{z}$± 0.58 | $0.16^{z}$± 0.58 | $0.06^{z}$± 0.58 | $0.02^{z}$± 0.58 | $1.21^{bcy}$± 0.58 |
| 48 | $0.08^{z}$± 0.58 | $0.18^{z}$± 0.58 | $0.12^{z}$± 0.58 | $0.10^{z}$± 0.58 | $0.11^{z}$± 0.58 | $1.31^{by}$± 0.58 |
| 56 | $0.15^{z}$± 0.58 | $0.12^{z}$± 0.58 | $0.07^{z}$± 0.58 | $0.07^{z}$± 0.58 | $0.21^{z}$± 0.58 | $1.25^{bcy}$± 0.58 |
| 64 | $0.06^{z}$± 0.58 | $0.18^{z}$± 0.58 | $0.34^{z}$± 0.58 | $0.02^{z}$± 0.58 | $0.34^{z}$± 0.58 | $1.84^{ay}$± 0.58 |
| 72 | $0.14^{z}$± 0.58 | $0.12^{z}$± 0.58 | $0.27^{z}$± 0.58 | $0.03^{z}$± 0.58 | $0.27^{z}$± 0.58 | $2.22^{ay}$± 0.58 |

[1]Panelists marked a fixed 15 cm line scale to indicate their response. 15 cm = 100 % discoloration; 0 cm = 0 % discoloration.
[a-d] Within column, means without a common superscript letter differ ($P < 0.05$).
[y-z] Within rows, means without a common superscript letter differ ($P < 0.05$).

Table 3.3. Least squares means ± SEM for trained color panel lean color scores[1] for strip loin steaks displayed for 72 h ($P_{\text{AGE x HOUR}} < 0.0001$).

| Display (h) | Age (d) | | | | | |
|---|---|---|---|---|---|---|
| | 14d | 21d | 28d | 35d | 49d | 63d |
| 0 | $11.05^{av}$±1.59 | $9.54^{bcw}$±1.59 | $8.94^{bcx}$±1.59 | $8.42^{dey}$±1.59 | $8.46^{dy}$±1.59 | $9.51^{aw}$±1.59 |
| 8 | $10.76^{abv}$±1.59 | $9.80^{bcw}$±1.59 | $9.43^{awx}$±1.59 | $9.54^{bwx}$±1.59 | $8.66^{awx}$±1.59 | $9.39^{ax}$±1.59 |
| 16 | $10.99^{av}$±1.59 | $10.22^{aw}$±1.59 | $9.25^{abx}$±1.59 | $9.90^{aw}$±1.59 | $9.36^{bx}$±1.59 | $9.03^{bx}$±1.59 |
| 24 | $10.36^{cv}$±1.59 | $10.04^{abv}$±1.59 | $9.28^{abw}$±1.59 | $8.71^{dx}$±1.59 | $8.88^{cx}$±1.59 | $8.69^{cx}$±1.59 |
| 32 | $10.66^{bv}$±1.59 | $9.73^{bcw}$±1.59 | $9.09^{bx}$±1.59 | $9.12^{cx}$±1.59 | $8.41^{dy}$±1.59 | $8.93^{bcx}$±1.59 |
| 40 | $9.90^{dv}$±1.59 | $9.65^{bcv}$±1.59 | $8.14^{dy}$±1.59 | $8.64^{dx}$±1.59 | $9.24^{bw}$±1.59 | $8.94^{bcwx}$±1.59 |
| 48 | $10.20^{cv}$±1.59 | $9.49^{cw}$±1.59 | $8.69^{cxy}$±1.59 | $8.29^{ey}$±1.59 | $7.86^{ez}$±1.59 | $8.92^{bcx}$±1.59 |
| 56 | $10.65^{bcv}$±1.59 | $9.69^{bcw}$±1.59 | $8.51^{cxy}$±1.59 | $8.83^{cdy}$±1.59 | $8.40^{dz}$±1.59 | $8.77^{bcx}$±1.59 |
| 64 | $10.50^{bcv}$±1.59 | $9.84^{bw}$±1.59 | $8.07^{dz}$±1.59 | $8.63^{dey}$±1.59 | $9.39^{abx}$±1.59 | $8.10^{dxz}$±1.59 |
| 72 | $10.07^{cdv}$±1.59 | $9.65^{bcw}$±1.59 | $8.49^{cx}$±1.59 | $8.73^{dx}$±1.59 | $8.60^{cdx}$±1.59 | $8.05^{dy}$±1.59 |

[1]Panelists marked a fixed 15 cm line scale to indicate their response. Higher values indicate a more bright, cherry-red color while low values indicate a more dark, purplish-red lean color.

[a-e] Within column, means without a common superscript letter differ ($P < 0.05$).

[v-z] Within rows, means without a common superscript letter differ ($P < 0.05$).

Table 3.4. Least squares means ± SEM for trained color panel externalfat color scores[1] for strip loin steaks displayed for 72 h ($P_{\text{AGE x HOUR}} < 0.0001$).

| Display (h) | Age (d) | | | | | |
|---|---|---|---|---|---|---|
| | 14d | 21d | 28d | 35d | 49d | 63d |
| 0 | $12.70^{av}$±0.93 | $11.31^{abw}$±0.93 | $10.64^{axy}$±0.93 | $10.90^{bx}$±0.93 | $10.30^{cy}$±0.94 | $10.44^{ay}$±0.93 |
| 8 | $12.00^{cv}$±0.93 | $10.81^{cwx}$±0.93 | $10.51^{abx}$±0.93 | $10.55^{cx}$±0.93 | $11.08^{aw}$±0.94 | $10.10^{by}$±0.93 |
| 16 | $12.43^{bv}$±0.93 | $11.30^{abw}$±0.93 | $10.29^{by}$±0.93 | $11.55^{aw}$±0.93 | $10.84^{bx}$±0.94 | $10.22^{aby}$±0.93 |
| 24 | $11.21^{ev}$±0.93 | $11.22^{bv}$±0.93 | $10.36^{bw}$±0.93 | $10.41^{cw}$±0.93 | $10.52^{cw}$±0.94 | $9.84^{cx}$±0.93 |
| 32 | $11.61^{dv}$±0.93 | $11.50^{av}$±0.93 | $10.72^{aw}$±0.93 | $10.95^{bw}$±0.93 | $10.34^{cx}$±0.94 | $9.86^{cy}$±0.93 |
| 40 | $11.21^{ev}$±0.93 | $11.33^{av}$±0.93 | $9.64^{cx}$±0.93 | $10.05^{dw}$±0.93 | $10.01^{dwx}$±0.94 | $9.73^{cx}$±0.93 |
| 48 | $11.48^{dev}$±0.93 | $10.65^{cw}$±0.93 | $9.45^{cdx}$±0.93 | $10.31^{cw}$±0.93 | $9.71^{ex}$±0.94 | $9.48^{dx}$±0.93 |
| 56 | $11.71^{dv}$±0.93 | $11.03^{bcw}$±0.93 | $9.61^{cdx}$±0.93 | $9.87^{dx}$±0.93 | $9.20^{fy}$±0.94 | $8.88^{ey}$±0.93 |
| 64 | $11.46^{dev}$±0.93 | $10.91^{cw}$±0.93 | $9.16^{dy}$±0.93 | $9.30^{exy}$±0.93 | $9.64^{ex}$±0.94 | $8.69^{ez}$±0.93 |
| 72 | $11.30^{ev}$±0.93 | $10.73^{cw}$±0.93 | $9.31^{dx}$±0.93 | $9.18^{exy}$±0.93 | $8.80^{gy}$±0.94 | $8.91^{ey}$±0.93 |

[1]Panelists marked a fixed 15 cm line scale to indicate their response. Higher values indicate a brighter, creamy white color while low values indicate a more dark tan or brown/green fat color.

[a-g] Within column, means without a common superscript letter differ ($P < 0.05$).

[v-z] Within rows, means without a common superscript letter differ ($P < 0.05$).

Table 3.5. Least squares means ± SEM for lean L* values for strip loin steaks displayed for 72 h ($P_{\text{AGE x HOUR}} < 0.0001$).

| Display (h) | Age (d) | | | | | |
|---|---|---|---|---|---|---|
| | 14d | 21d | 28d | 35d | 49d | 63d |
| 0 | $34.56^{cy}$±0.43 | $37.62^{ax}$±0.43 | $35.99^{by}$±0.43 | $34.51^{aby}$±0.43 | $40.70^{aw}$±0.43 | $34.80^{ay}$±0.43 |
| 8 | $35.31^{bcw}$±0.43 | $34.90^{bwx}$±0.43 | $35.62^{bw}$±0.43 | $34.25^{bwx}$±0.43 | $33.62^{bcx}$±0.43 | $34.68^{awx}$±0.43 |
| 16 | $35.69^{bw}$±0.43 | $34.52^{bwx}$±0.43 | $35.79^{bw}$±0.43 | $34.39^{abwx}$±0.43 | $33.41^{bcx}$±0.43 | $34.79^{awx}$±0.43 |
| 24 | $34.39^{aw}$±0.43 | $34.71^{bx}$±0.43 | $37.69^{aw}$±0.43 | $31.76^{cy}$±0.43 | $33.20^{cxy}$±0.43 | $34.74^{ax}$±0.43 |
| 32 | $34.07^{cw}$±0.43 | $34.98^{bw}$±0.43 | $34.86^{bw}$±0.43 | $32.26^{cx}$±0.43 | $33.82^{bcwx}$±0.43 | $34.04^{aw}$±0.43 |
| 40 | $38.54^{aw}$±0.43 | $35.01^{bxy}$±0.43 | $35.69^{bx}$±0.43 | $33.63^{by}$±0.43 | $34.37^{bcxy}$±0.43 | $34.44^{axy}$±0.43 |
| 48 | $34.18^{cxy}$±0.43 | $38.15^{aw}$±0.43 | $35.36^{bx}$±0.43 | $33.19^{bcy}$±0.43 | $34.04^{bcxy}$±0.43 | $34.47^{axy}$±0.43 |
| 56 | $35.00^{bcw}$±0.43 | $34.32^{bw}$±0.43 | $35.54^{bw}$±0.43 | $35.60^{aw}$±0.43 | $34.50^{bw}$±0.43 | $34.78^{aw}$±0.43 |
| 64 | $34.31^{cw}$±0.43 | $33.96^{bw}$±0.43 | $35.37^{bw}$±0.43 | $31.24^{cx}$±0.43 | $33.93^{bcw}$±0.43 | $34.17^{aw}$±0.43 |
| 72 | $37.51^{aw}$±0.43 | $34.66^{bx}$±0.43 | $35.47^{bx}$±0.43 | $32.01^{cy}$±0.43 | $33.81^{bcx}$±0.43 | $34.19^{ax}$±0.43 |

$^{a-c}$ Within column, means without a common superscript letter differ ($P < 0.05$).
$^{w-z}$ Within rows, means without a common superscript letter differ ($P < 0.05$).

Table 3.6. Least squares means ± SEM for lean a* values for strip loin steaks displayed for 72 h ($P_{\text{AGE x HOUR}} < 0.0001$).

| Display (h) | Age (d) | | | | | |
|---|---|---|---|---|---|---|
| | 14d | 21d | 28d | 35d | 49d | 63d |
| 0 | $11.96^{cw}$±0.22 | $12.09^{aw}$±0.22 | $12.65^{bcvw}$±0.22 | $11.48^{bcwx}$±0.22 | $13.26^{av}$±0.22 | $10.98^{abx}$±0.22 |
| 8 | $13.59^{av}$±0.22 | $12.50^{aw}$±0.22 | $13.59^{av}$±0.22 | $12.59^{aw}$±0.22 | $12.26^{bw}$±0.22 | $11.41^{aw}$±0.22 |
| 16 | $12.80^{bvw}$±0.22 | $12.15^{aw}$±0.22 | $13.07^{bv}$±0.22 | $11.84^{bwx}$±0.22 | $11.41^{cdx}$±0.22 | $10.99^{ax}$±0.22 |
| 24 | $12.87^{bv}$±0.22 | $11.94^{aw}$±0.22 | $13.14^{abv}$±0.22 | $11.44^{bcw}$±0.22 | $11.68^{cw}$±0.22 | $10.46^{bx}$±0.22 |
| 32 | $11.93^{cvw}$±0.22 | $11.92^{avw}$±0.22 | $12.16^{cv}$±0.22 | $11.35^{cw}$±0.22 | $11.03^{dw}$±0.22 | $9.80^{cx}$±0.22 |
| 40 | $12.73^{bv}$±0.22 | $11.36^{bwx}$±0.22 | $12.02^{cw}$±0.22 | $10.99^{cdx}$±0.22 | $10.57^{ex}$±0.22 | $9.44^{cdy}$±0.22 |
| 48 | $11.46^{dvx}$±0.22 | $11.98^{av}$±0.22 | $11.77^{cv}$±0.22 | $10.91^{dw}$±0.22 | $10.53^{ew}$±0.22 | $9.35^{dx}$±0.22 |
| 56 | $11.05^{ew}$±0.22 | $11.11^{bcw}$±0.22 | $11.27^{dw}$±0.22 | $12.24^{abv}$±0.22 | $10.24^{ex}$±0.22 | $8.87^{ey}$±0.22 |
| 64 | $11.20^{dev}$±0.22 | $11.01^{bcv}$±0.22 | $11.30^{dv}$±0.22 | $10.24^{ew}$±0.22 | $9.54^{fw}$±0.22 | $8.63^{ex}$±0.22 |
| 72 | $12.05^{cv}$±0.22 | $10.96^{cw}$±0.22 | $10.94^{dw}$±0.22 | $10.05^{ex}$±0.22 | $9.36^{fy}$±0.22 | $8.41^{ez}$±0.22 |

[a-f] Within column, means without a common superscript letter differ ($P < 0.05$).
[v-z] Within rows, means without a common superscript letter differ ($P < 0.05$).

Table 3.7. Least squares means ± SEM for lean b* values for strip loin steaks displayed for 72 h ($P_{\text{AGE x HOUR}} < 0.0001$).

| Display (h) | Age (d) | | | | | |
|---|---|---|---|---|---|---|
| | 14d | 21d | 28d | 35d | 49d | 63d |
| 0 | $13.66^{cdxy}$±0.15 | $14.03^{abx}$±0.15 | $14.64^{abwx}$±0.15 | $13.63^{bxy}$±0.15 | $15.14^{aw}$±0.15 | $13.19^{ay}$±0.15 |
| 8 | $15.42^{aw}$±0.15 | $14.13^{ax}$±0.15 | $15.03^{aw}$±0.15 | $14.19^{ax}$±0.15 | $13.92^{bxy}$±0.15 | $13.34^{ay}$±0.15 |
| 16 | $13.91^{cwx}$±0.15 | $13.55^{bcx}$±0.15 | $14.42^{bw}$±0.15 | $13.56^{bx}$±0.15 | $13.11^{cx}$±0.15 | $13.08^{abx}$±0.15 |
| 24 | $14.54^{bwx}$±0.15 | $13.47^{bcx}$±0.15 | $14.69^{abw}$±0.15 | $12.83^{cxy}$±0.15 | $13.47^{bcx}$±0.15 | $12.61^{by}$±0.15 |
| 32 | $13.34^{dwx}$±0.15 | $13.58^{bcwx}$±0.15 | $13.77^{cw}$±0.15 | $12.68^{cdx}$±0.15 | $13.14^{cx}$±0.15 | $11.90^{cy}$±0.15 |
| 40 | $14.33^{bw}$±0.15 | $13.24^{cx}$±0.15 | $13.94^{cw}$±0.15 | $12.94^{cx}$±0.15 | $12.91^{cx}$±0.15 | $11.73^{cdy}$±0.15 |
| 48 | $13.16^{dex}$±0.15 | $13.69^{bw}$±0.15 | $13.72^{cw}$±0.15 | $12.76^{cx}$±0.15 | $12.78^{cx}$±0.15 | $11.74^{cy}$±0.15 |
| 56 | $12.78^{ex}$±0.15 | $12.94^{cdx}$±0.15 | $13.26^{dx}$±0.15 | $13.82^{abw}$±0.15 | $12.86^{cx}$±0.15 | $11.49^{cdy}$±0.15 |
| 64 | $13.01^{dew}$±0.15 | $12.93^{cdw}$±0.15 | $13.28^{dw}$±0.15 | $12.30^{dx}$±0.15 | $11.92^{ex}$±0.15 | $11.31^{dy}$±0.15 |
| 72 | $13.75^{cdw}$±0.15 | $12.83^{dx}$±0.15 | $13.12^{dx}$±0.15 | $12.25^{dy}$±0.15 | $11.96^{dy}$±0.15 | $11.23^{ez}$±0.15 |

$^{a-e}$ Within column, means without a common superscript letter differ ($P < 0.05$).
$^{w-z}$ Within rows, means without a common superscript letter differ ($P < 0.05$).

Table 3.8. Least squares means ± SEM of Warner-Bratzler shear force (WBSF) values (kg) by postmortem aging treatment and muscle.

| | Age (d) | | | | | | |
|---|---|---|---|---|---|---|---|
| Muscle | 14 | 21 | 28 | 35 | 49 | 63 | $P_{age}$ |
| Strip loin | $3.86^{a} \pm 0.15$ | $3.49^{b} \pm 0.15$ | $3.44^{b} \pm 0.15$ | $3.27^{b} \pm 0.15$ | $2.99^{c} \pm 0.15$ | $2.93^{c} \pm 0.15$ | < 0.0001 |
| Sirloin | $4.08^{a} \pm 0.13$ | $4.21^{ab} \pm 0.13$ | $4.02^{ab} \pm 0.13$ | $3.78^{b} \pm 0.13$ | $3.48^{bc} \pm 0.13$ | $3.20^{c} \pm 0.13$ | < 0.0001 |

[a-c] Within muscle, means without a common superscript letter differ ($P < 0.05$).

Table 3.9. Least squares means ± SEM for trained sensory panel ratings[1] for strip loin steaks that were displayed for 72 h.

| | Sensory Attribute | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Age (d) | Myofibrillar Tenderness | Con. Tissue Tenderness | Overall Tenderness | Juiciness | Beef Flavor | Buttery/ Beef Fat Flavor | Sour /Acidic | Oxidized | Metallic /Bloody | Livery /Organy |
| 14d | 8.88$^{c}$ ±0.18 | 9.61$^{c}$±0.20 | 8.98$^{c}$±0.17 | 8.00$^{a}$ ±0.19 | 8.31±0.54 | 5.81$^{ab}$±0.15 | 0.84$^{b}$ ±0.23 | 1.54$^{c}$ ±0.24 | 0.41$^{a}$±0.07 | 0.18$^{ab}$±0.06 |
| 21d | 8.63$^{c}$ ±0.18 | 9.88$^{c}$ ±0.20 | 8.98$^{c}$±0.17 | 7.58$^{b}$±0.19 | 8.40 ±0.54 | 6.06$^{a}$±0.15 | 0.78$^{b}$ ±0.23 | 1.72$^{bc}$ ±0.24 | 0.21$^{ab}$±0.07 | 0.07$^{b}$±0.06 |
| 28d | 8.76$^{c}$±0.18 | 9.75$^{c}$±0.20 | 8.97$^{c}$ ±0.17 | 7.33$^{b}$±0.19 | 8.45 ±0.54 | 5.74$^{ab}$ ±0.15 | 0.84$^{b}$ ±0.23 | 1.78$^{bc}$ ±0.24 | 0.20$^{ab}$±0.07 | 0.12$^{b}$±0.06 |
| 35d | 9.38$^{b}$ ±0.18 | 10.23$^{bc}$ ±0.20 | 9.59$^{b}$ ±0.17 | 7.74$^{ab}$±0.19 | 8.21 ±0.54 | 5.96$^{ab}$ ±0.15 | 1.11$^{b}$ ±0.23 | 2.17$^{bc}$ ±0.24 | 0.31$^{ab}$±0.07 | 0.15$^{b}$±0.06 |
| 49d | 9.68$^{ab}$ ±0.18 | 10.50$^{b}$ ±0.20 | 9.8$^{b}$ ±0.17 | 7.88$^{ab}$±0.19 | 8.42 ±0.54 | 5.96$^{ab}$ ±0.15 | 1.70$^{a}$ ±0.23 | 2.25$^{b}$ ±0.24 | 0.39$^{a}$±0.07 | 0.21$^{ab}$±0.06 |
| 63d | 9.88$^{a}$ ±0.18 | 10.88$^{a}$ ±0.20 | 10.15$^{a}$ ±0.17 | 7.77$^{ab}$±0.19 | 8.21 ±0.54 | 5.67$^{b}$ ±0.15 | 2.19$^{a}$ ±0.23 | 3.11$^{a}$±0.24 | 0.17$^{b}$±0.07 | 0.37$^{a}$±0.06 |
| $P_{age}$ | <.0001 | <.0001 | <.0001 | 0.0093 | 0.5495 | 0.1458 | <.0001 | <.0001 | 0.0357 | 0.0105 |

[1]panelists marked a fixed 15 cm line scale to indicate their response. 150 cm = highest level of each attribute; 0 cm = absence of each attribute.
[a-c] Within column, means without a common superscript letter differ ($P < 0.05$).

Table 3.10 Least squares means ± SEM for Warner-Bratzler shear force (WBSF) values (kg) by display time.

| | Display time | | |
|---|---|---|---|
| Muscle | 0 h | 72 h | $P_{\text{display time}}$ |
| Strip loin | 3.33 ± 0.05 | 3.11 ± 0.05 | < 0.0001 |
| Sirloin | 3.79 ± 0.07 | 3.51 ± 0.07 | < 0.0001 |

Table 3.11. Least squares means ± SEM for TBAR values by muscle and postmortem aging period following 72 h of retail display.

| | Age (d) | | | | | | |
|---|---|---|---|---|---|---|---|
| Muscle | 14d | 21d | 28d | 35d | 49d | 63d | $P_{age}$ |
| Strip loin | $0.46^{ab}$±0.04 | $0.82^{a}$±0.04 | $0.76^{a}$±0.04 | $0.48^{ab}$±0.04 | $0.47^{ab}$±0.04 | $0.37^{b}$±0.04 | 0.0009 |
| Sirloin | $0.44^{bc}$±0.04 | $0.37^{c}$±0.04 | $0.82^{a}$±0.04 | $0.59^{b}$±0.04 | $0.48^{b}$±0.04 | $0.28^{c}$±0.04 | <0.0001 |

[a-c] Within muscle, means without a common superscript letter differ ($P < 0.05$).

Table 3.12. Least squares means ± SEM for trained color panel percent lean discoloration scores[1] for sirloin steaks displayed for 72 h. ($P_{\text{AGE x HOUR}} < 0.0001$).

| | Age (d) | | | | | |
|---|---|---|---|---|---|---|
| Display (h) | 14d | 21d | 28d | 35d | 49d | 63d |
| 0 | $0.01^{c}$±1.32 | $0.02^{b}$±1.32 | $0.02^{b}$±1.32 | $0.00^{a}$±1.32 | $0.00^{c}$±1.32 | $0.07^{cd}$±1.32 |
| 8 | $0.03^{c}$±1.32 | $0.04^{b}$±1.32 | $0.10^{b}$±1.32 | $0.08^{a}$±1.32 | $0.01^{c}$±1.32 | $0.21^{cd}$±1.32 |
| 16 | $0.12^{c}$±1.32 | $0.15^{ab}$±1.32 | $0.09^{b}$±1.32 | $0.00^{a}$±1.32 | $0.01^{c}$±1.32 | $0.12^{cd}$±1.32 |
| 24 | $0.09^{c}$±1.32 | $0.19^{ab}$±1.32 | $0.19^{ab}$±1.32 | $0.06^{a}$±1.32 | $0.00^{c}$±1.32 | $0.06^{d}$±1.32 |
| 32 | $0.15^{c}$±1.32 | $0.30^{ab}$±1.32 | $0.31^{ab}$±1.32 | $0.05^{a}$±1.32 | $0.18^{c}$±1.32 | $0.11^{cd}$±1.32 |
| 40 | $0.19^{c}$±1.32 | $0.11^{bz}$±1.32 | $0.19^{de}$±1.32 | $0.06^{a}$±1.32 | $0.09^{c}$±1.32 | $0.11^{cd}$±1.32 |
| 48 | $0.11^{c}$±1.32 | $0.38^{ab}$±1.32 | $0.11^{b}$±1.32 | $0.08^{a}$±1.32 | $0.19^{c}$±1.32 | $0.49^{c}$±1.32 |
| 56 | $1.26^{awx}$±1.32 | $0.30^{aby}$±1.32 | $0.12^{by}$±1.32 | $0.04^{axy}$±1.32 | $0.98^{bx}$±1.32 | $1.61^{bw}$±1.32 |
| 64 | $1.57^{ax}$±1.32 | $0.11^{bz}$±1.32 | $0.59^{ay}$±1.32 | $0.04^{ayz}$±1.32 | $1.53^{ax}$±1.32 | $2.15^{aw}$±1.32 |
| 72 | $0.80^{bx}$±1.32 | $0.57^{ax}$±1.32 | $0.39^{abx}$±1.32 | $0.40^{ax}$±1.32 | $1.83^{aw}$±1.32 | $2.10^{aw}$±1.32 |

[1]Panelists marked a fixed 15 cm line scale to indicate their response. Higher values indicate a more bright, cherry-red color while low values indicate a more dark, purplish red lean color.

[a-e] Within column, means without a common superscript letter differ ($P < 0.05$).

[w-z] Within rows, means without a common superscript letter differ ($P < 0.05$).

Table 3.13. Least squares means ± SEM for trained color panel lean color scores[1] for sirloin steaks displayed for 72 h ($P_{\text{AGE x HOUR}} < 0.0001$).

| | Age (d) | | | | | |
|---|---|---|---|---|---|---|
| Display (h) | 14d | 21d | 28d | 35d | 49d | 63d |
| 0 | $10.99^{aw}$±0.13 | $9.40^{ax}$±0.13 | $8.72^{aby}$±0.13 | $8.04^{bz}$±0.13 | $8.43^{bcyz}$±0.13 | $9.22^{ax}$±0.13 |
| 8 | $10.37^{bw}$±0.13 | $9.41^{ax}$±0.13 | $9.16^{ax}$±0.13 | $8.68^{axy}$±0.13 | $9.07^{axy}$±0.13 | $8.49^{by}$±0.13 |
| 16 | $10.60^{abw}$±0.13 | $9.27^{abx}$±0.13 | $9.08^{abxy}$±0.13 | $8.60^{ay}$±0.13 | $8.48^{by}$±0.13 | $7.98^{czv}$±0.13 |
| 24 | $9.37^{cdw}$±0.13 | $8.82^{bx}$±0.13 | $9.02^{abwx}$±0.13 | $7.72^{bcy}$±0.13 | $8.00^{cy}$±0.13 | $7.57^{cdy}$±0.13 |
| 32 | $9.59^{cw}$±0.13 | $8.10^{cdy}$±0.13 | $8.70^{bx}$±0.13 | $7.83^{bcy}$±0.13 | $7.23^{dz}$±0.13 | $7.67^{cdyz}$±0.13 |
| 40 | $8.75^{dw}$±0.13 | $8.28^{cx}$±0.13 | $7.56^{dy}$±0.13 | $7.46^{cy}$±0.13 | $8.12^{bcx}$±0.13 | $7.35^{dy}$±0.13 |
| 48 | $8.97^{dw}$±0.13 | $7.71^{dxy}$±0.13 | $8.09^{cx}$±0.13 | $6.69^{dz}$±0.13 | $6.46^{ez}$±0.13 | $7.10^{dy}$±0.13 |
| 56 | $8.84^{dw}$±0.13 | $7.82^{dx}$±0.13 | $7.93^{cdx}$±0.13 | $6.90^{dyz}$±0.13 | $6.54^{ez}$±0.13 | $6.27^{dy}$±0.13 |
| 64 | $8.82^{dw}$±0.13 | $7.94^{cdx}$±0.13 | $7.60^{dx}$±0.13 | $7.39^{cdy}$±0.13 | $7.58^{cdxy}$±0.13 | $6.05^{ez}$±0.13 |
| 72 | $8.82^{dw}$±0.13 | $7.76^{dx}$±0.13 | $7.73^{cdx}$±0.13 | $6.96^{dy}$±0.13 | $6.77^{ey}$±0.13 | $6.02^{ez}$±0.13 |

[1]Panelists marked a fixed 150 mm line scale to indicate their response. 15 cm = 100 % discoloration; 0 cm = 0 % discoloration.
[a-e] Within column, means without a common superscript letter differ ($P < 0.05$).
[v-z] Within rows, means without a common superscript letter differ ($P < 0.05$).

Table 3.14. Least squares means ± SEM for least square means for trained color panel external fat color scores[1] for sirloin steaks displayed for 72 h ($P_{\text{AGE x HOUR}} < 0.0001$).

| Display (h) | Age (d) | | | | | |
|---|---|---|---|---|---|---|
| | 14d | 21d | 28d | 35d | 49d | 63d |
| 0 | $11.74^{av}$±1.16 | $10.33^{aw}$±1.15 | $10.03^{ax}$±1.15 | $9.48^{by}$±1.15 | $9.33^{ay}$±1.12 | $9.36^{ay}$±1.12 |
| 8 | $11.31^{bv}$±1.16 | $10.05^{abw}$±1.15 | $10.08^{aw}$±1.15 | $9.40^{bw}$±1.15 | $9.62^{ax}$±1.12 | $8.70^{by}$±1.12 |
| 16 | $11.67^{av}$±1.16 | $10.14^{abw}$±1.15 | $10.03^{av}$±1.15 | $9.84^{ax}$±1.15 | $9.49^{ax}$±1.12 | $8.43^{by}$±1.12 |
| 24 | $10.37^{dv}$±1.16 | $9.76^{bx}$±1.15 | $10.16^{aw}$±1.15 | $8.88^{cx}$±1.15 | $9.01^{by}$±1.12 | $7.98^{cz}$±1.12 |
| 32 | $10.83^{cv}$±1.16 | $9.59^{bcw}$±1.15 | $10.10^{ax}$±1.15 | $9.28^{bx}$±1.15 | $8.50^{cx}$±1.12 | $7.83^{cy}$±1.12 |
| 40 | $10.49^{cdv}$±1.16 | $9.88^{bw}$±1.15 | $8.89^{bcw}$±1.15 | $8.71^{cx}$±1.15 | $8.88^{bcx}$±1.12 | $7.37^{dy}$±1.12 |
| 48 | $10.56^{cdv}$±1.16 | $9.19^{cw}$±1.15 | $9.00^{bcw}$±1.15 | $8.17^{dx}$±1.15 | $7.77^{dy}$±1.12 | $7.09^{dey}$±1.12 |
| 56 | $10.24^{dv}$±1.16 | $9.28^{cw}$±1.15 | $9.08^{bw}$±1.15 | $7.78^{dx}$±1.15 | $6.87^{ey}$±1.12 | $6.66^{ey}$±1.12 |
| 64 | $9.98^{dv}$±1.16 | $9.63^{cv}$±1.15 | $8.57^{cw}$±1.15 | $8.17^{dw}$±1.15 | $7.53^{dx}$±1.12 | $6.11^{fy}$±1.12 |
| 72 | $10.12^{dv}$±1.16 | $9.18^{dw}$±1.15 | $8.50^{cx}$±1.15 | $7.16^{ey}$±1.15 | $6.77^{ey}$±1.12 | $6.59^{ey}$±1.12 |

[1]Panelists marked a fixed 15 cm line scale to indicate their response. Higher values indicate a more bright, creamy white color while low values indicate a more dark tan or brown/green fat color.

[a-f] Within column, means without a common superscript letter differ ($P < 0.05$).

[v-z] Within rows, means without a common superscript letter differ ($P < 0.05$).

Table 3.15. Least squares means ± SEM for lean L* values for sirloin steaks displayed for 72 h ($P_{\text{AGE x HOUR}} < 0.0001$).

| Display (h) | Age (d) | | | | | |
|---|---|---|---|---|---|---|
| | 14d | 21d | 28d | 35d | 49d | 63d |
| 0 | $37.41^{dy}$±0.49 | $39.65^{ax}$±0.49 | $36.65^{byz}$±0.49 | $35.45^{bz}$±0.49 | $43.19^{aw}$±0.48 | $36.54^{ayz}$±0.48 |
| 8 | $37.46^{dw}$±0.49 | $36.30^{bcwx}$±0.49 | $36.63^{bwx}$±0.49 | $36.03^{b}$±0.49 | $36.37^{b}$±0.48 | $36.73^{a}$±0.48 |
| 16 | $38.57^{cw}$±0.49 | $36.90^{bwy}$±0.49 | $36.37^{by}$±0.49 | $35.41^{bx}$±0.49 | $35.01^{cwx}$±0.48 | $36.76^{awx}$±0.48 |
| 24 | $40.05^{bw}$±0.49 | $36.47^{bcy}$±0.49 | $38.30^{ax}$±0.49 | $33.97^{cz}$±0.49 | $35.30^{cy}$±0.48 | $36.30^{ay}$±0.48 |
| 32 | $37.05^{dw}$±0.49 | $36.21^{bcwx}$±0.49 | $35.87^{bcwx}$±0.49 | $35.33^{bcx}$±0.49 | $35.87^{bcwx}$±0.48 | $36.48^{awx}$±0.48 |
| 40 | $41.53^{aw}$±0.49 | $36.30^{bcx}$±0.49 | $35.06^{cx}$±0.49 | $35.06^{bcx}$±0.49 | $35.20^{bcx}$±0.48 | $35.95^{ax}$±0.48 |
| 48 | $36.85^{dy}$±0.49 | $40.49^{aw}$±0.49 | $35.70^{bcy}$±0.49 | $34.19^{cz}$±0.49 | $36.54^{by}$±0.48 | $37.05^{ax}$±0.48 |
| 56 | $36.61^{dwx}$±0.49 | $36.27^{bcwx}$±0.49 | $35.89^{bcx}$±0.49 | $37.45^{aw}$±0.49 | $35.99^{bcwx}$±0.48 | $36.10^{awx}$±0.48 |
| 64 | $36.43^{dw}$±0.49 | $35.60^{cw}$±0.49 | $35.70^{bcw}$±0.49 | $31.65^{dx}$±0.49 | $36.03^{bcw}$±0.48 | $36.46^{aw}$±0.48 |
| 72 | $39.61^{bw}$±0.49 | $36.47^{bcx}$±0.49 | $35.58^{bcx}$±0.49 | $33.24^{cy}$±0.49 | $36.09^{bcw}$±0.48 | $36.93^{aw}$±0.48 |

[a-d] Within column, means without a common superscript letter differ ($P < 0.05$).
[w-z] Within rows, means without a common superscript letter differ ($P < 0.05$).

Table 3.16. Least squares means ± SEM for lean a* values for sirloin steaks that were displayed for 72 h ($P_{\text{AGE x HOUR}} < 0.0001$).

| Display (h) | Age (d) | | | | | |
|---|---|---|---|---|---|---|
| | 14d | 21d | 28d | 35d | 49d | 63d |
| 0 | $16.23^{bcvw}$±0.24 | $15.74^{abw}$±0.24 | $13.92^{bx}$±0.24 | $14.77^{bx}$±0.24 | $16.87^{av}$±0.24 | $14.20^{ax}$±0.24 |
| 8 | $17.79^{av}$±0.24 | $16.12^{aw}$±0.24 | $14.59^{ax}$±0.24 | $15.66^{awx}$±0.24 | $14.97^{bx}$±0.24 | $14.38^{ax}$±0.24 |
| 16 | $16.06^{cv}$±0.24 | $15.29^{w}$±0.24 | $13.73^{bxy}$±0.24 | $14.39^{bx}$±0.24 | $14.00^{cx}$±0.24 | $13.08^{by}$±0.24 |
| 24 | $16.57^{bv}$±0.24 | $14.84^{bw}$±0.24 | $13.65^{bx}$±0.24 | $13.71^{cx}$±0.24 | $13.36^{dx}$±0.24 | $12.34^{cy}$±0.24 |
| 32 | $14.47^{ev}$±0.24 | $14.35^{cv}$±0.24 | $12.66^{cw}$±0.24 | $12.85^{dw}$±0.24 | $12.51^{ew}$±0.24 | $11.41^{dx}$±0.24 |
| 40 | $15.23^{dv}$±0.24 | $13.53^{dw}$±0.24 | $12.26^{dx}$±0.24 | $12.57^{dx}$±0.24 | $11.56^{y}$±0.24 | $10.96^{ez}$±0.24 |
| 48 | $13.41^{fv}$±0.24 | $13.78^{dv}$±0.24 | $12.08^{ew}$±0.24 | $12.09^{ew}$±0.24 | $11.46^{fx}$±0.24 | $10.28^{fy}$±0.24 |
| 56 | $12.80^{gv}$±0.24 | $12.46^{ev}$±0.24 | $11.57^{fw}$±0.24 | $12.74^{dv}$±0.24 | $10.85^{gx}$±0.24 | $9.80^{gy}$±0.24 |
| 64 | $12.61^{gv}$±0.24 | $12.31^{ev}$±0.24 | $11.14^{fgw}$±0.24 | $11.02^{fw}$±0.24 | $10.59^{hx}$±0.24 | $9.40^{gy}$±0.24 |
| 72 | $13.29^{fv}$±0.24 | $12.07^{ew}$±0.24 | $10.99^{gx}$±0.24 | $10.38^{gy}$±0.24 | $9.85^{iy}$±0.24 | $8.87^{hz}$±0.24 |

[a-g] Within column, means without a common superscript letter differ ($P < 0.05$).
[v-z] Within rows, means without a common superscript letter differ ($P < 0.05$).

Table 3.17. Least squares means ± SEM for lean b* values for sirloin steaks that were displayed for 72 h ($P_{\text{AGE x HOUR}} < 0.0001$).

| | Age (d) | | | | | |
|---|---|---|---|---|---|---|
| Display (h) | 14d | 21d | 28d | 35d | 49d | 63d |
| 0 | $17.50^{cx}$±0.30 | $17.34^{ax}$±0.30 | $15.58^{aby}$±0.30 | $16.25^{aby}$±0.30 | $18.32^{aw}$±0.30 | $16.02^{ay}$±0.30 |
| 8 | $19.04^{aw}$±0.30 | $17.33^{ax}$±0.30 | $15.93^{ay}$±0.30 | $16.77^{axy}$±0.30 | $16.43^{by}$±0.30 | $16.23^{ay}$±0.30 |
| 16 | $17.41^{cw}$±0.30 | $16.60^{bx}$±0.30 | $15.28^{by}$±0.30 | $15.90^{by}$±0.30 | $15.77^{cy}$±0.30 | $15.29^{by}$±0.30 |
| 24 | $18.20^{bw}$±0.30 | $16.40^{bcx}$±0.30 | $15.34^{bxy}$±0.30 | $15.30^{cxy}$±0.30 | $15.46^{cdy}$±0.30 | $14.92^{by}$±0.30 |
| 32 | $16.23^{dw}$±0.30 | $16.07^{cw}$±0.30 | $14.51^{cxy}$±0.30 | $14.66^{dxy}$±0.30 | $15.10^{dx}$±0.30 | $14.23^{cxy}$±0.30 |
| 40 | $17.48^{cw}$±0.30 | $15.70^{cx}$±0.30 | $14.18^{cdyz}$±0.30 | $14.65^{dy}$±0.30 | $14.45^{eyz}$±0.30 | $13.92^{cdz}$±0.30 |
| 48 | $15.76^{dew}$±0.30 | $16.23^{bcw}$±0.30 | $14.21^{cdxy}$±0.30 | $14.48^{dx}$±0.30 | $14.53^{ex}$±0.30 | $13.61^{dy}$±0.30 |
| 56 | $15.35^{ew}$±0.30 | $15.13^{dw}$±0.30 | $13.94^{dxy}$±0.30 | $15.40^{cw}$±0.30 | $14.19^{ex}$±0.30 | $13.32^{dey}$±0.30 |
| 64 | $15.32^{ew}$±0.30 | $15.09^{dw}$±0.30 | $13.62^{dx}$±0.30 | $13.62^{ex}$±0.30 | $13.69^{fx}$±0.30 | $13.07^{ex}$±0.30 |
| 72 | $16.07^{dw}$±0.30 | $14.84^{dx}$±0.30 | $13.60^{dy}$±0.30 | $13.49^{ey}$±0.30 | $13.44^{fy}$±0.30 | $12.45^{fz}$±0.30 |

[a-e] Within column, means without a common superscript letter differ ($P < 0.05$).
[w-z] Within rows, means without a common superscript letter differ ($P < 0.05$).

Table 3.18. Least squares means ± SEM for trained sensory panel ratings[1] for sirloin steaks that were displayed for 72 h.

| | Sensory Attribute | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Age (d) | Myofibrillar Tenderness | Con. Tissue Tenderness | Overall Tenderness | Juiciness | Beef Flavor | Buttery/Beef Fat Flavor | Sour /Acidic | Oxidized | Metallic /Bloody | Livery /Organy |
| 14d | $8.17^{b}$±0.25 | $8.35^{c}$±0.28 | $8.49^{b}$±0.39 | $7.57^{ab}$±0.34 | $8.04^{a}$±0.15 | 4.92±0.15 | $1.53^{c}$±0.25 | $3.07^{b}$±0.33 | $0.86^{b}$±0.13 | $0.23^{c}$±0.17 |
| 21d | $8.57^{b}$±0.25 | $9.18^{ab}$±0.28 | $8.80^{b}$±0.39 | $8.36^{a}$±0.34 | $7.98^{a}$±0.15 | 4.91±0.15 | $1.63^{c}$±0.25 | $3.36^{b}$±0.33 | $0.95^{ab}$±0.13 | $0.58^{b}$±0.17 |
| 28d | $8.54^{b}$±0.25 | $9.33^{ab}$±0.28 | $8.83^{b}$±0.39 | $7.34^{ab}$±0.34 | $7.93^{a}$±0.15 | 4.83±0.15 | $1.74^{c}$±0.25 | $3.65^{ab}$±0.33 | $0.92^{ab}$±0.13 | $0.44^{b}$±0.17 |
| 35d | $8.54^{b}$±0.25 | $9.04^{b}$±0.28 | $9.13^{ab}$±0.39 | $7.41^{ab}$±0.34 | $7.95^{a}$±0.15 | 4.92±0.15 | $1.83^{c}$±0.25 | $3.75^{ab}$±0.33 | $0.96^{ab}$±0.13 | $0.77^{ab}$±0.17 |
| 49d | $8.64^{b}$±0.25 | $9.15^{b}$±0.28 | $8.83^{b}$±0.39 | $7.22^{b}$±0.34 | $7.84^{ab}$±0.15 | 4.78±0.15 | $2.37^{b}$±0.25 | $4.00^{ab}$±0.33 | $0.96^{ab}$±0.13 | $0.70^{ab}$±0.17 |
| 63d | $9.16^{a}$±0.25 | $9.72^{a}$±0.28 | $9.35^{a}$±0.39 | $7.16^{b}$±0.34 | $7.59^{b}$±0.15 | 4.72±0.15 | $3.30^{a}$±0.25 | $4.14^{a}$±0.33 | $1.15^{a}$±0.13 | $0.99^{a}$±0.17 |
| $P_{age}$ | 0.0075 | 0.0002 | 0.0910 | 0.0419 | 0.0379 | 0.0251 | < 0.0001 | 0.0143 | 0.3696 | < .0001 |

[1]Panelists marked a fixed 15 cm line scale to indicate their response. 15 cm = highest level of each attribute; 0 cm = absence of each attribute..

[a-c] Within column, means without a common superscript letter differ ($P < 0.05$).

## LITERATURE CITED


Adhikari, K., E. Chambers Iv, R. Miller, L. Vazquez-Araujo, N. Bhumiratana and C. Philip. 2011. Development of a lexicon for beef flavor in intact muscle. J. Sens. Stud. 26: 413-420.

AMSA. 2003. Meat Color Evaluation Guidelines. Savoy, IL: American Meat Science Association.

Anderson, T., and F. Parrish. 1989. Postmortem degradation of titin and nebulin of beef steaks varying in tenderness. J. Food Sci. 54: 748-749.

Arnold, R., S. Arp, K. Scheller, S. Williams, and D. Schaefer. 1993. Tissue equilibration and subcellular distribution of vitamin E relative to myoglobin and lipid oxidation in displayed beef. J. Anim. Sci. 71: 105-118.

ASTM, 2011. ASTM F2925011 Standard specification for tenderness marketing claims association with meat cuts derived from beef. Accessed February 20, 2014. http://www.astm.org/Standards/F2925.htm.

Bekhi, A.E.D., Geesink, G.H., Ilian, M.A., Morton, J.D., and Bickerstaffe, R. 2003. The effects of natural antioxidants on oxidative processes and metmyoglobin reducing activity in beef patties. Food Chemistry. 81:175-187.

Bendall, J. 1972. Consumption of oxygen by the muscles of beef animals and related species, and its effect on the colour of meat. I. Oxygen consumption in pre- rigor muscle. J. Sci. Food Agric. 23: 61-72.

Bendall, J., and A. Taylor. 1972. Consumption of oxygen by the muscles of beef animals and related species. II. Consumption of oxygen by post- rigor muscle. J. Sci. Food Agric. 23: 707-719.

Boehm, M. L., T. L. Kendall, V. F. Thompson, and D. E. Goll. 1998. Changes in the calpains and calpastatin during postmortem storage of bovine muscle. J. Anim. Sci. 76: 2415-2434.

Bratzler, L. 1971. Palatability factors and evaluations. The Science of Meat and Meat Products. WH Freeman and Company. San Francisco, Calif.

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

Calkins, C. R., and S. C. Seideman. 1988. Relationships among calcium-dependent protease, cathepsins B and H, meat tenderness and the response of muscle to aging. J. Anim. Sci. 66: 1186-1193.

Campbell, R., M. Hunt, P. Levis, and E. Chambers. 2001. Dry- Aging Effects on Palatability of Beef Longissimus Muscle. J. Food Sci. 66: 196-199.

Carpenter, Z. L. 1962. Histological and physical characteristics of pork muscle and their relationship to pork quality. University of Wisconsin--Madison.

Cia, G., and B. Marsh. 1976. Properties of beef cooked before rigor onset. J. Food Sci. 41: 1259-1262.

Crouse, J.D. and M. Koohmaraie. 1990. Effect of post-cooking storage conditions on shear-force values of beef steaks. J. Food Sci. 55:858,860.

Davey, C., and K. Gilbert. 1969. The effect of sample dimensions on the cleaving of meat in the objective assessment of tenderness. International Journal of Food Science & Technology 4: 7-15.

Dean, R., and C. Ball. 1960. Analysis of the myoglobin fractions on the surfaces of beef cuts. Food Tech. 14: 271-286.

Dransfield, E., and D. N. Rhodes. 1975. Texture of beef M. semitendinosus heated before, during and after development of rigor mortis. J. Sci. Food Agric. 26: 483-491.

Eilers, J.D., J.D. Tatum, J.B. Morgan, and G.C. Smith. 1996. Modification of early postmortem muscle pH and use of postmortem aging to improve beef tenderness. J. Anim. Sci. 74:790-798.

Faustman, C., and R. Cassens. 1991. The effect of cattle breed and muscle type on discoloration and various biochemical parameters in fresh beef. J. Anim. Sci. 69: 184-193.

Faustman, C., and R. G. Cassens. 1990. The biochemical basis for discoloration in fresh meat: A review. J. Mus. Foods 1: 217-243.

Faustman, C., R. Cassens, D. Schaefer, D. Buege, S. Williams and K. Scheller. 1989. Improvement of pigment and lipid stability in Holstein steer beef by dietary supplementation with vitamin E. J. Food Sci. 54: 858-862.

Faustman, C., W. Chan, D. Schaefer, and A. Havens. 1998. Beef color update: the role for vitamin E. J. Anim. Sci. 76: 1019-1026.

Fritz, J., M. Mitchell, B. Marsh, and M. Greaser. 1993. Titin content of beef in relation to tenderness. Meat Sci. 33: 41-50.

Goll, D. E., D. W. Henderson, and E. Kline. 1964. Post- Mortem Changes in Physical and Chemical Properties of Bovine Musclea. J. Food Sci. 29: 590-596.

Goll, D., G. Geesink, R. Taylor, and V. Thompson. 1995. Does proteolysis cause all postmortem tenderization, or are changes in the actin/myosin interaction involved? In: Annual International Congress of Meat Science and Technology. p 537-544.

Goll, D., M. Boehm, G. Geesink, and V. Thompson. 1997. What causes postmortem tenderization. In: Proceedings of the 50 th Annual Reciprocal Meat Conference. p 60-67.

Goll, D., W. Dayton, I. Singh, and R. Robson. 1991. Studies of the alpha-actinin/actin interaction in the Z-disk by using calpain. J. Biol. Chem. 266: 8501-8510.

Goll., D.E., Y. Otsuka. P.A. Nagainis, J.D. Shannon, S.K. Sathe and M. Muguruma. 1983. Role of muscle proteinases in maintenance of muscle integrity and mass. Journal of Food Biochemistry 7: 137-177.

Gotoh, T., and K. Shikama. 1974. Autoxidation of native oxymyoglobin from bovine heart muscle. Arch. Biochem. Biophys. 163: 476-481.

Greaser, M. 1997. Postmortem changes in muscle extracellular matrix proteins. In: Proceedings of the Reciprocal Meat Conference. p 53-59.

Gruber, S. L., J. D. Tatum, J. A. Scanga, P. L. Chapman, G. C. Smith and K. E. Belk. 2006. Effects of postmortem aging and USDA quality grade on Warner-Bratzler shear force values of seventeen individual beef muscles. J. Anim. Sci. 84: 3387-3396.

Gutiérrez, A. M., G. R. Reboredo, and A. Catalá. 2002. Fatty acid profiles and lipid peroxidation of microsomes and mitochondria from liver, heart and brain of Cairina moschata. The international journal of biochemistry & cell biology 34: 605-612.

Harris, J., R. Miller, J. Savell, H. Cross, and L. Ringer. 1992. Evaluation of the tenderness of beef top sirloin steaks. J. Food Sci. 57: 6-9.

Ho, C., M. Stromer, and R. Robson. 1994. Identification of the 30 kDa polypeptide in post mortem skeletal muscle as a degradation product of troponin-T. Biochimie 76: 369-375.

Hopkins, D., and J. Thompson. 2002. Factors contributing to proteolysis and disruption of myofibrillar proteins and the impact on tenderisation in beef and sheep meat. Crop and Pasture Science 53: 149-166.

Huff-Lonergan, E., F. Parrish, and R. M. Robson. 1995. Effects of postmortem aging time, animal age, and sex on degradation of titin and nebulin in bovine longissimus muscle. J. Anim. Sci. 73: 1064-1073. Huff-Lonergan, E., F. Parrish, and R. M. Robson. 1995. Effects of postmortem aging time, animal age, and sex on degradation of titin and nebulin in bovine longissimus muscle. J. Anim. Sci. 73: 1064-1073.

Huffman, K., M. Miller, L. Hoover, C. Wu, H. Brittin and C. Ramsey. 1996. Effect of beef tenderness on consumer satisfaction with steaks consumed in the home and restaurant. J. Anim. Sci. 74: 91-97.

Hutchins, B.K., T.H. Liu, and B.M. Watts. 1967. Effect of additives and refrigeration on reducing activity, metmyoglobin and malonaldehyde of raw ground beef. J. Food Sci. 32: 214-217.

Kellermeier, J. D., A. W. Tittor, J. C. Brooks, M. L. Galyean, D. A. Yates, J. P. Hutcheson, W. T. Nichols, M. N. Streeter, B. J. Johnson, and M. F. Miller. 2009. Effects of zilpaterol hydrochloride with or without and estrogen-trenbolone acetate terminal implant on carcass traits, retail cutout, tenderness, and muscle fiber diameter in finishing steers. J. Anim. Sci. 87:3702-3711.

Klose, A., B. Luyet, and L. Menz. 1970. Effect of contraction on tenderness of poultry muscle cooked in the prerigor state. J. Food Sci. 35: 577-581.

Koohmaraie, M. 1992. The role of Ca 2-dependent proteases (calpains) in post mortem proteolysis and meat tenderness. Biochimie 74: 239-245.

Koohmaraie, M. 1996. Biochemical factors regulating the toughening and tenderization processes of meat. Meat Sci. 43: 193-201.

Koohmaraie, M., G. Whipple, D. Kretchmar, J. Crouse, and H. Mersmann. 1991. Postmortem proteolysis in longissimus muscle from beef, lamb and pork carcasses. J. Anim. Sci. 69: 617-624.

Koohmaraie, M., S. C. Seideman, J. E. Schollmeyer, T. R. Dutson, and A. S. Babiker. 1988. Factors associated with the tenderness of three bovine muscles. J. Food Sci. 53: 407-410.

Lass, A., and R. S. Sohal. 1998. Electron transport-linked ubiquinone-dependent recycling of α-tocopherol inhibits autooxidation of mitochondrial membranes. Arch. Biochem. Biophys. 352: 229-236.

Laster, M. A., R. D. Smith, K. L. Nicholson, J. D. W. Nicholson, R. K. Miller, D. B. Griffin, K. B. Harris and J. W. Savell. 2008. Dry versus wet aging of beef: Retail cutting yields and consumer sensory attribute evaluations of steaks from ribeyes, strip loins, and top sirloins from two quality grade groups. Meat Sci. 80: 795-804.

Lauridsen, C., H. Engel, A. M. Craig, and M. Traber. 2002. Relative bioactivity of dietary RRR- and all-rac-alpha-tocopheryl acetates in swine assessed with deuterium-labeled vitamin E. J. Anim. Sci. 80: 702-707.

Lawrie, R.A. 1966. The eating quality of meat. Meat Sci. Pergamon Press, London, England.

Ledward, D. 1972. Metmyoglobing reduction and formation in beef during aerobic storage at l° C. J. Food Sci. 37: 634-635.

Liu, Q., M. Lanari, and D. Schaefer. 1995. A review of dietary vitamin E supplementation for improvement of beef quality. J. Anim. Sci. 73: 3131-3140.

Lorenzen, C.L., B.H. Weatherly, and J.W. Savell. 1998. Determination of an aging index. Final Report to the Texas Beef Council. Department of Animal Science, Texas Agricultural Experiment Station, Texas A&M University, College Station, TX.

Madhavi, D., and C. E. Carpenter. 1993. Aging and processing affect color, metmyoglobin reductase and oxygen consumption of beef muscles. J. Food Sci. 58: 939-942.

Mancini, R. A., and M. C. Hunt. 2005. Current research in meat color. Meat Sci. 71: 100-121.

McKenna, D., P. Mies, B. Baird, K. Pfeiffer, J. Ellebracht and J. Savell. 2005. Biochemical and physical factors affecting discoloration characteristics of 19 bovine muscles. Meat Sci. 70: 665-682.

Mies, P.D., K.E. Belk, J.D. Tatum, and G.C. Smith. 1999. Effects of postmortem aging on beef tenderness, and aging guidelines to maximize tenderness of different beef subprimal cuts. Beef Program Report, Program in Meat Sciences, Colorado State University, Fort Collins, CO: 127-133.

Minks, D., and W. C. Stringer. 1972. The influence of aging beef in vacuum. J. Food Sci. 37: 736-738.

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

NCBA. 1999. Executive summary – 1999 National beef tenderness survey. National Cattlemen's Beef Association, Centennial, CO 80112. www.beefresearch.org.

NCBA. 2006. Executive summary – 2005 National beef tenderness survey. National Cattlemen's Beef Association, Centennial, CO 80112. www.beefresearch.org.

NCBA. 2011. Executive Summary – 2010/2011 National beef tenderness survey. National Cattlemen's Beef Association, Centennial, CO 80112. www.beefresearch.org.

Nishimura, T., A. Liu, A. Hattori, and K. Takahashi. 1998. Changes in mechanical strength of intramuscular connective tissue during postmortem aging of beef. J. Anim. Sci. 76: 528-532.

O'keefe, M., and D. Hood. 1982. Biochemical factors influencing metmyoglobin formation on beef from muscles of differing colour stability. Meat Sci. 7: 209-228.

Olson, D. G., and M. Stromer. 1976. Myofibril fragmentation and shear resistance of three bovine muscles during postmortem storage. J. Food Sci. 41: 1036-1041.

Platter, W. J., J. D. Tatum, K. E. Belk, J. A. Scanga, and G. C. Smith. 2003. Effects of repetitive use of hormonal implants on beef carcass quality, tenderness, and consumer ratings of beef palatability. J. Anim. Sci. 81: 984-996.

Platter, W. J., J. D. Tatum. K. E. Belk, P. L. Chapman, J. A. Scanga, and G. C. Smith. 2003. Relationships of consumber sensory ratings, marbling score, and shear force value to consumer acceptance of beef strip loin steaks. J. Anim. Sci. 81:2741-2750.

Reddy, L. M., and C. E. Carpenter. 1991. Determination of metmyoglobin reductase activity in bovine skeletal muscles. J. Food Sci. 56: 1161-1164.

Renerre, M. 1990. Review: Factors involved in the discoloration of beef meat. International Journal of Food Science and Technology. 25:613-630.

Renerre, M., and R. Labas. 1987. Biochemical factors influencing metmyoglobin formation in beef muscles. Meat Sci. 19: 151-165.

Rhee, K. S. 1978. Minimization of further lipid peroxidation in the distillation 2-thiobarbituric acid test of fish and meat. J. Food Sci. 43:1776.

Robson, R. 1995. Myofibrillar and cytoskeletal structures and proteins in mature skeletal muscle cells. Expression of tissue proteinases and regulation of protein degradation as related to meat quality: 267-288.

Robson, R., and T. Huiatt. 1983. Roles of the cytoskeletal proteins desmin, titin and nebulin in muscle [Meat quality]. In: Proceedings Annual Reciprocal Meat Conference.

Robson, R.M., E. Huff-Lonergan, F.C. Parrish, Jr., C-Y, Ho, M.H. Stomer, T.W. Huiatt, R.M. Bellin, and S.W. Serrett. 1997. Proc. 50th Annu. Recip. Meat Conf. Natl. Livest. and Meat Board, Chicago, IL:43-52.

Savell, J., F. McKeith, and G. Smith. 1981. Reducing postmortem aging time of beef with electrical stimulation. J. Food Sci. 46: 1777-1781.

Shackelford, S., T. Wheeler, and M. Koohmaraie. 1997. Tenderness classification of beef: I. Evaluation of beef longissimus shear force at 1 or 2 days postmortem as a predictor of aged beef tenderness. J. Anim. Sci. 75: 2417-2422.

Sitz, B. M., C. R. Calkins, D. M. Feuz, W. J. Umberger, and K. M. Eskridge. 2006. Consumer sensory acceptance and value of wet-aged and dry-aged beef steaks. J. Anim. Sci. 84: 1221-1226.

Smith, G., G. Culp, and Z. Carpenter. 1978. Postmortem aging of beef carcasses. J. Food Sci. 43: 823-826.

Smith, R., K. Nicholson, J. Nicholson, K. Harris, R. Miller, D. Griffin and J. Savell. 2008. Dry versus wet aging of beef: Retail cutting yields and consumer palatability evaluations of steaks from US Choice and US Select short loins. Meat Sci. 79: 631-639.

Steele, K. S. 2011. Shelf life of five meat products displayed under light emitting diode or fluorescent lighting, Kansas State University.

Strohecker, M., C. Faustman, H. Furr, T. Hoagland, and S. Williams. 1997. Vitamin E supplementation effects on color and lipid stability of whole and ground lamb. J. Mus. Foods 8: 413-426.

Takahashi, K. 1996. Structural weakening of skeletal muscle tissue during post-mortem ageing of meat: the non-enzymatic mechanism of meat tenderization. Meat Sci. 43: 67-80.

Tang, J., C. Faustman, T. A. Hoagland, R. A. Mancini, M. Seyfert and M. C. Hunt. 2005. Postmortem oxygen consumption by mitochondria and its effects on myoglobin form and stability. J. Agric. Food Chem. 53: 1223-1230.

Tarladgis, B. G., B. M. Watts, M. T. Younathan, and L. Dugan Jr. 1960. A distillation method for the quantitative determination of malonaldehyde in rancid foods. J. Am. Oil Chem. Soc. 37: 44-48.

Taylor, R. G., G. Geesink, V. Thompson, M. Koohmaraie, and D. Goll. 1995. Is Z-disk degradation responsible for postmortem tenderization? J. Anim. Sci. 73: 1351-1367.

Warren, K. E., and C. L. Kastner. 1992. A comparison of dry-aged and vacuum-aged beef strip loins. J. Mus. Foods 3: 151-157.

Weatherly, B., C. Lorenzen, and J. Savell. 1998. Determining optimal aging times for beef subprimals. J. Anim. Sci 76: 598.

Weir, C. 1960. Palatability characteristics of meat. The science of meat and meat products: 212.

Wheeler, T. L., J. W. Savell, H. R. Cross, D. K. Lunt, and S. B. Smith. 1990. Effect of postmortem treatments on the tenderness of meat from Hereford, Brahman and Brahman-cross beef cattle. J. Anim. Sci. 68: 3677-3686.

Wheeler, T., and M. Koohmaraie. 1994. Prerigor and postrigor changes in tenderness of ovine longissimus muscle. J. Anim. Sci. 72: 1232-1238.

Wheeler, T., M. Koohmaraie, L. Cundiff, and M. Dikeman. 1994. Effects of cooking and shearing methodology on variation in Warner-Bratzler shear force values in beef. J. Anim. Sci. 72: 2325-2330.

Zerby, H., K. Belk, J. Sofos, L. McDowell, and G. Smith. 1999. Case life of seven retail products from beef cattle supplemented with alpha-tocopheryl acetate. J. Anim. Sci. 77: 2458-2463.

# APPENDIX A

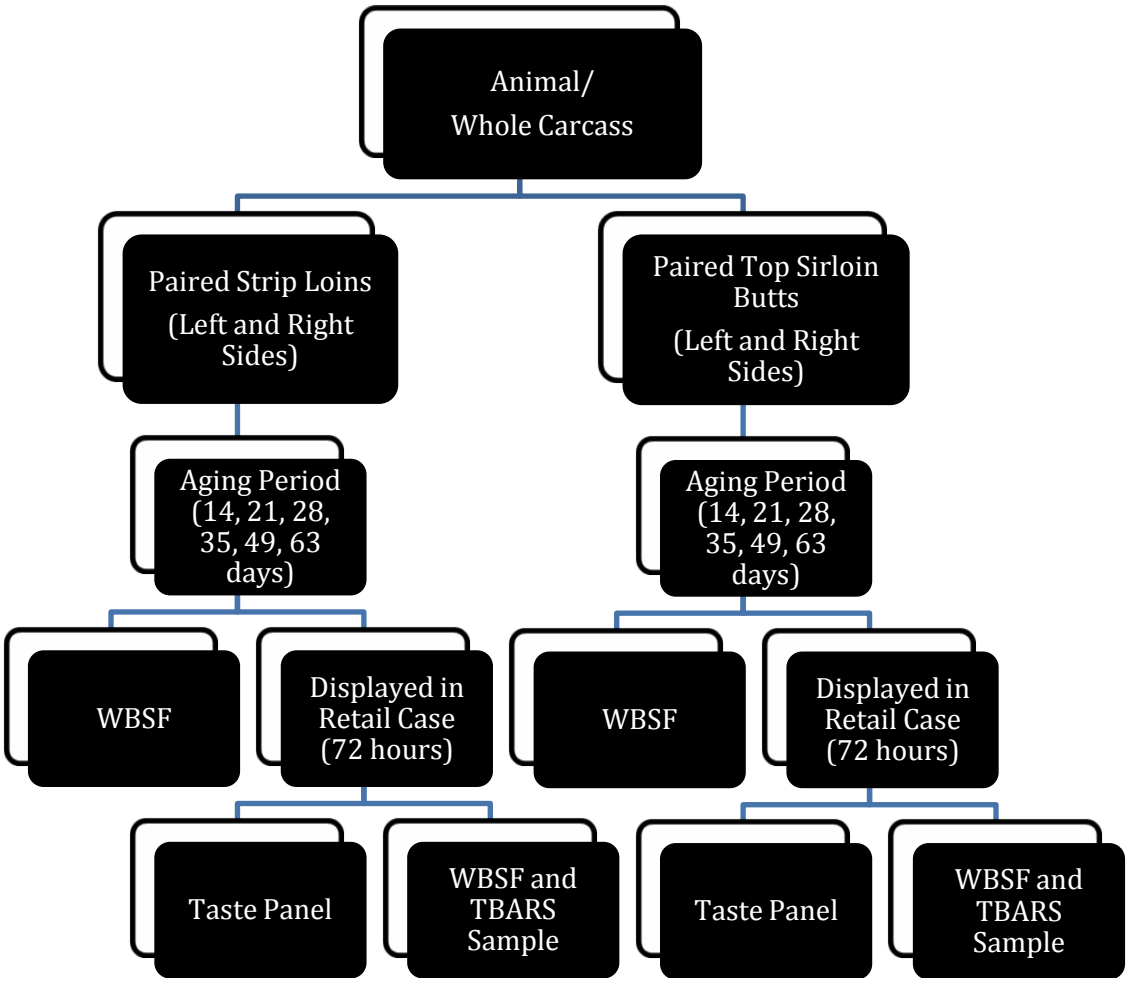



Figure A1.1. Experimental design of the study.

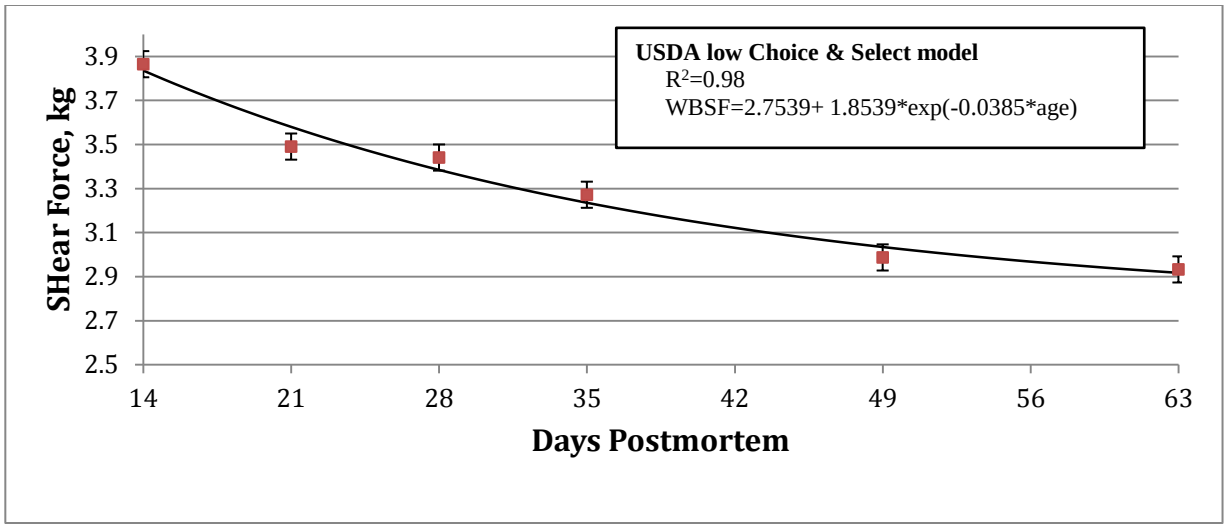



Figure A1.2**.** Least squares means ± SEM for Warner-Bratzler shear force (WBSF) for both USDA Select and low Choice *longissimus dorsi* steaks at 6 different aging periods, and the non-linear regression models fitted to these points. There variable "age" is the number of days postmortem. The $R^2$ is the maximum proportion of total variability explained by the model. The constant "exp" equals the base of the natural logarithm (2.718282).

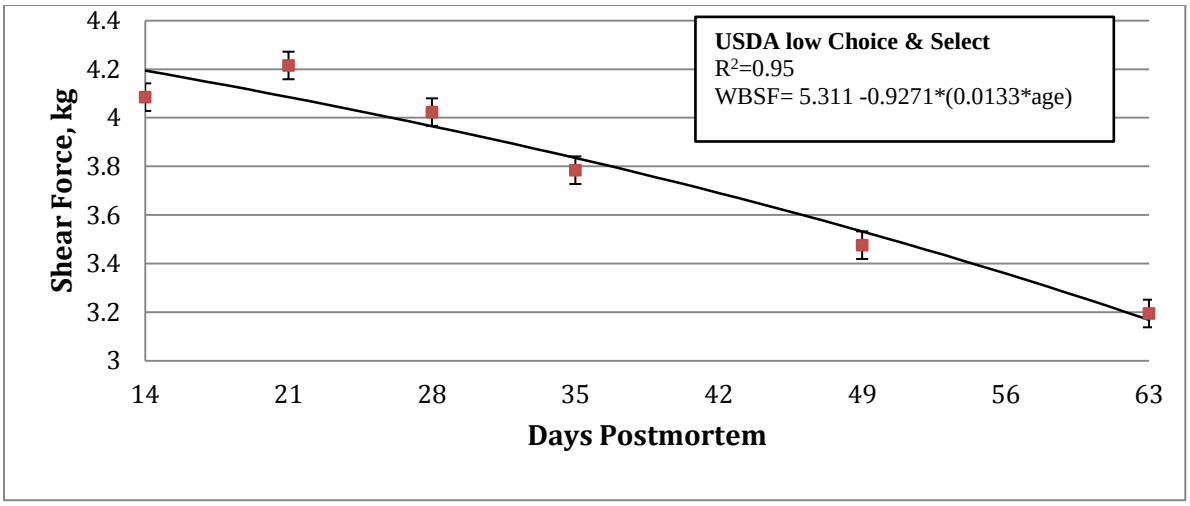



Figure A1.3. Least squares means ± SEM for Warner-Bratzler shear force (WBSF) for both USDA Select and low Choice *gluteus medius* steaks at 6 different aging periods, and the non-linear regression models fitted to these points. There variable "age" is the number of days postmortem. The $R^2$ is the maximum proportion of total variability explained by the model. The constant "exp" equals the base of the natural logarithm (2.718282).

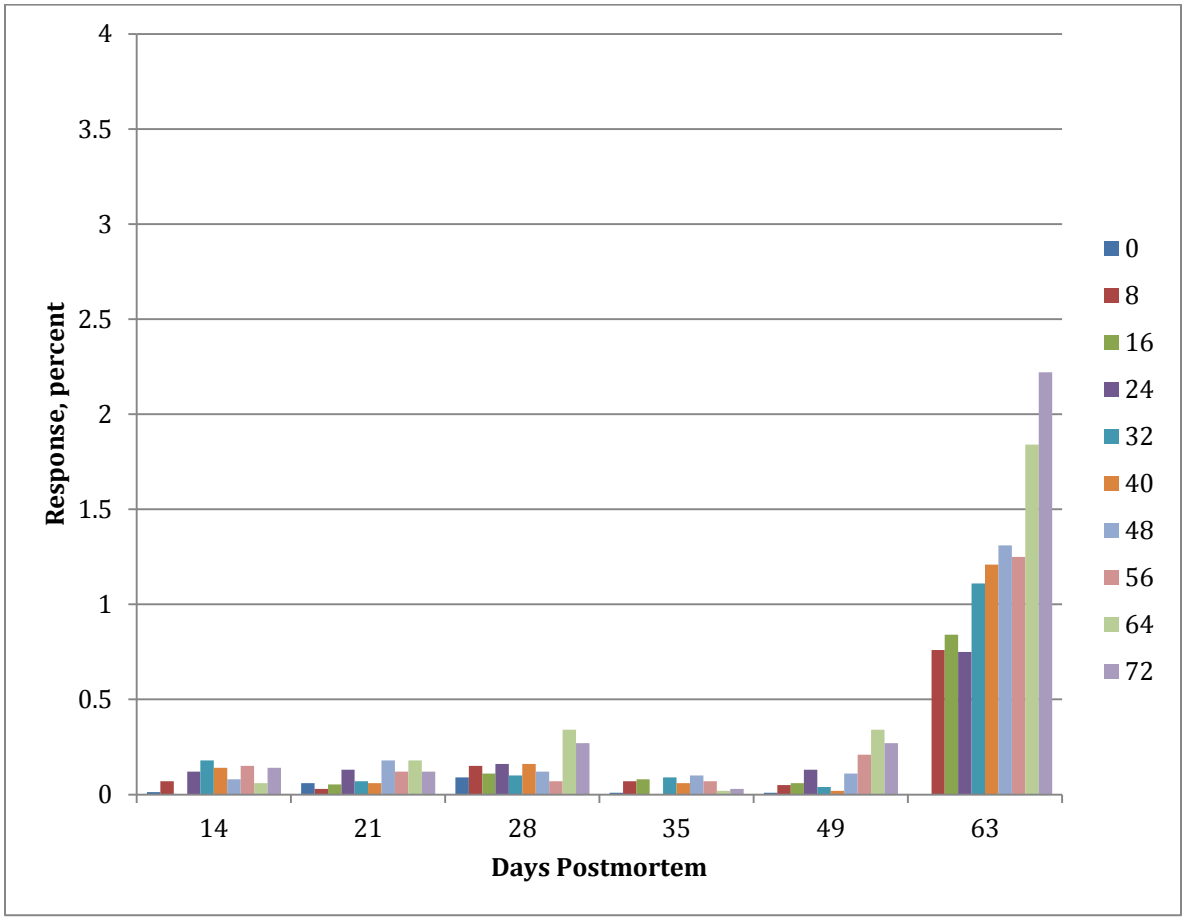


Figure A1.4. Trained color panel lean discoloration scores for strip loin steaks displayed for 72 hours.

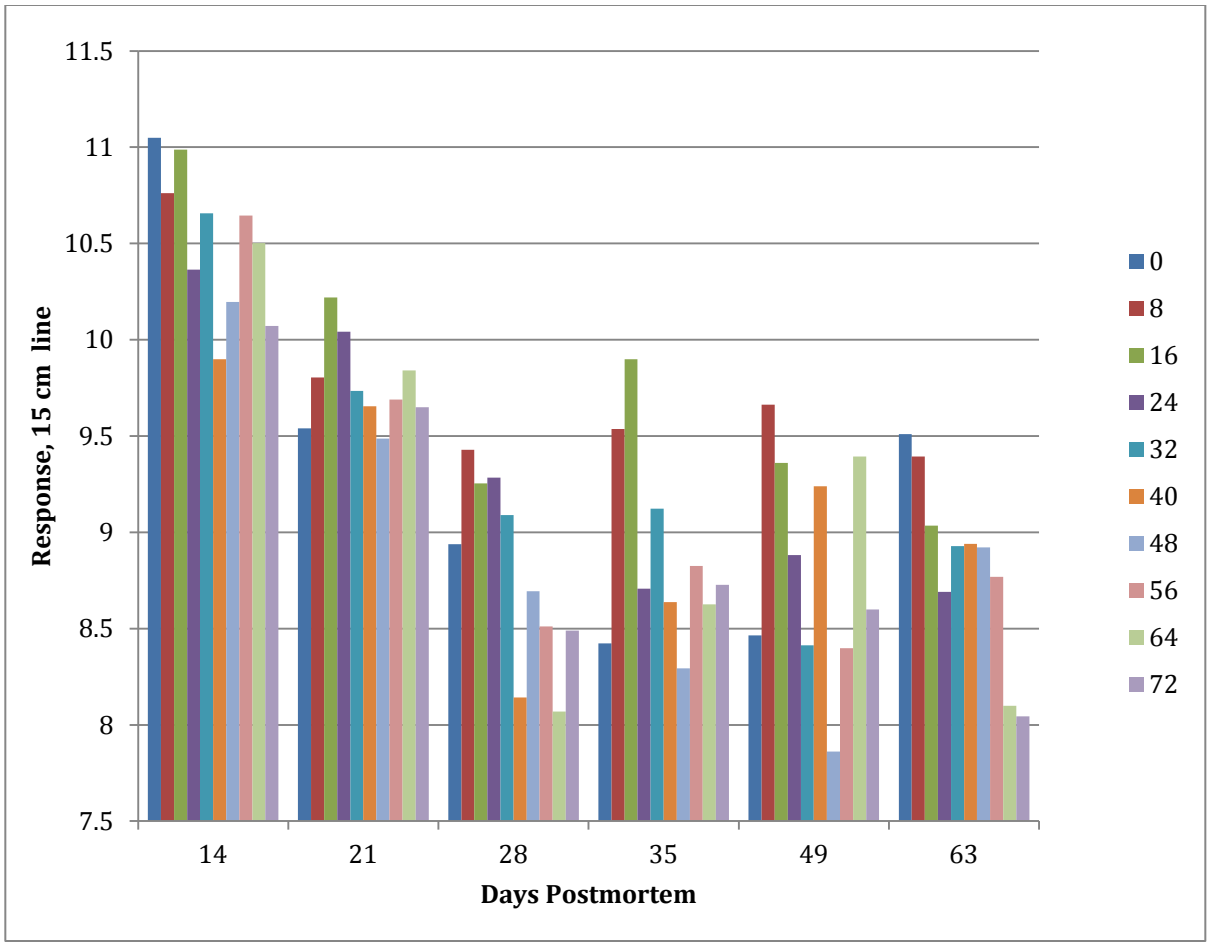



Figure A1.5. Trained color panel lean color scores for strip loin steaks displayed for 72 hours.

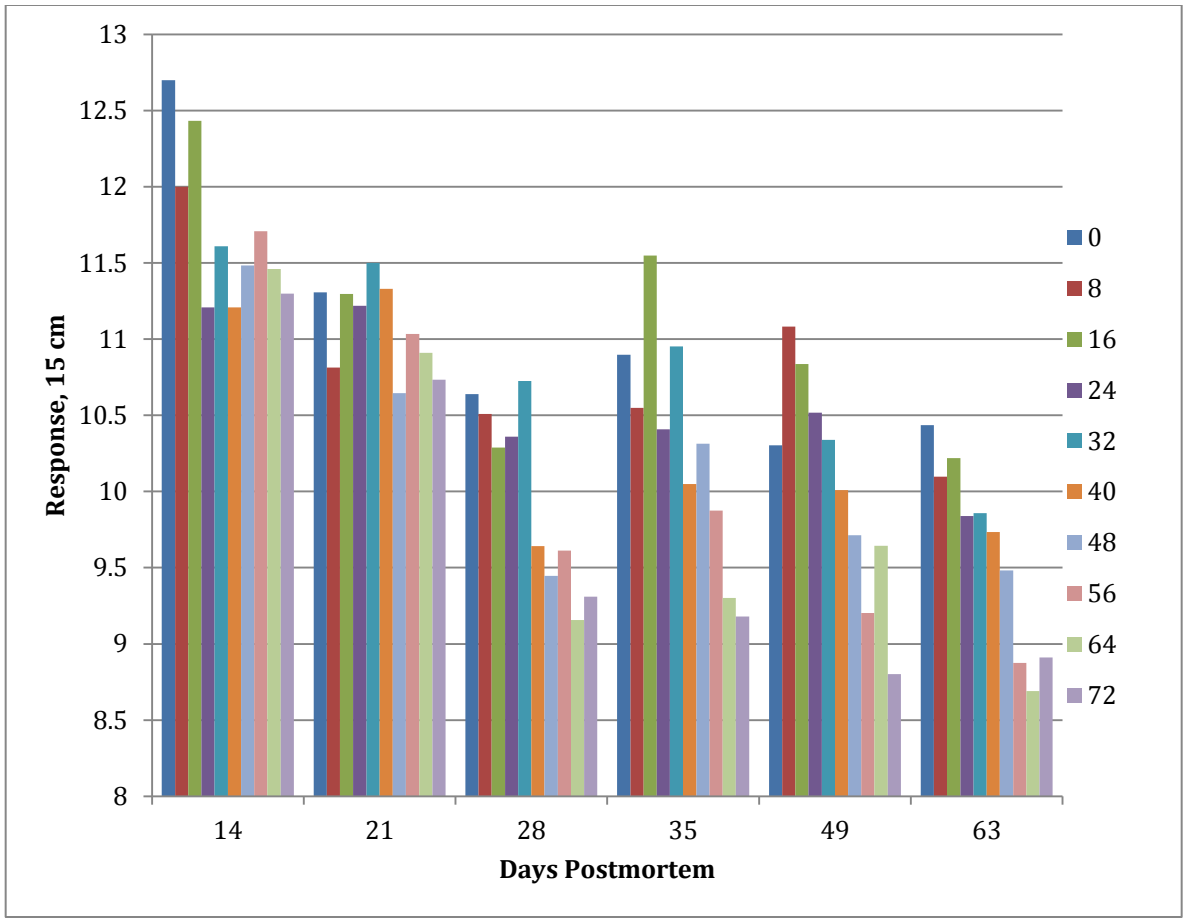



Figure A1.6. Trained color panel external fat color scores for strip loin steaks displayed for 72 hours.

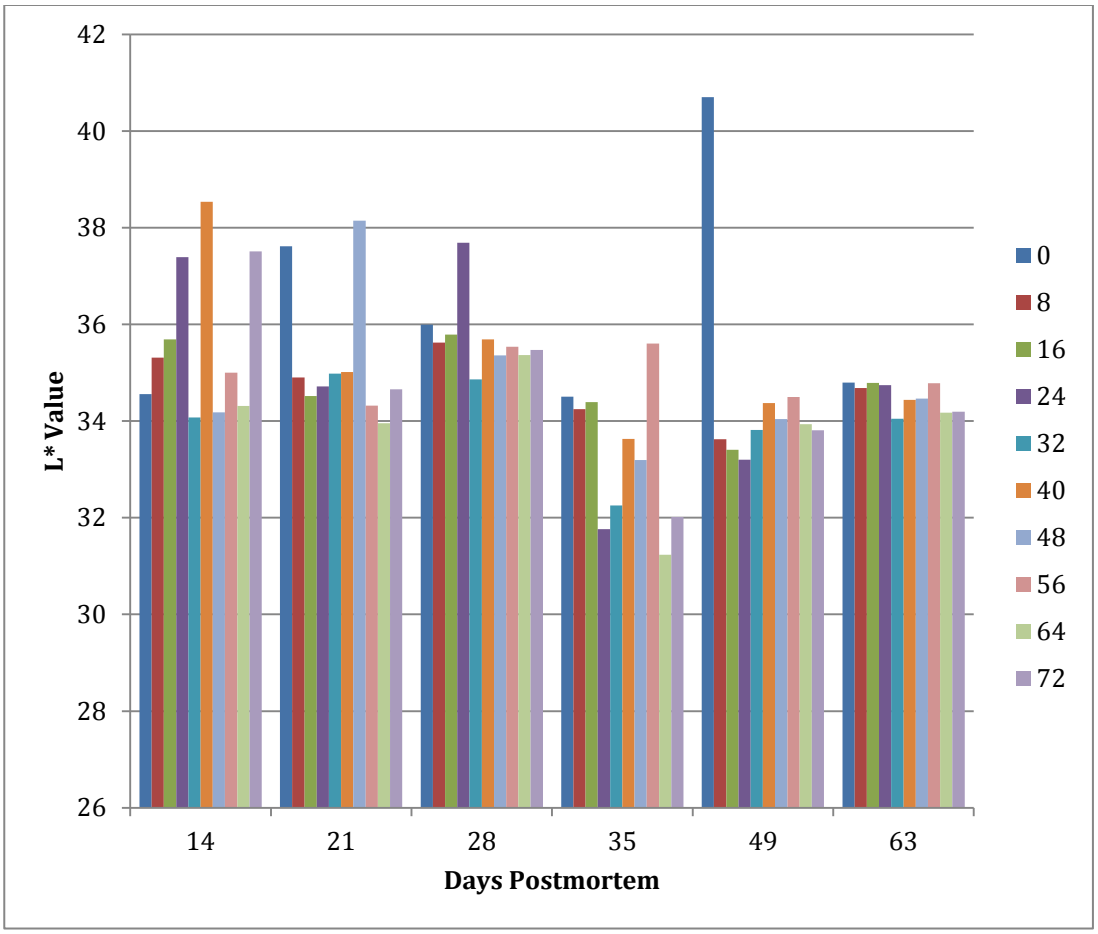



Figure A1.7. Lean L* values for strip loin steaks displayed for 72 hours.

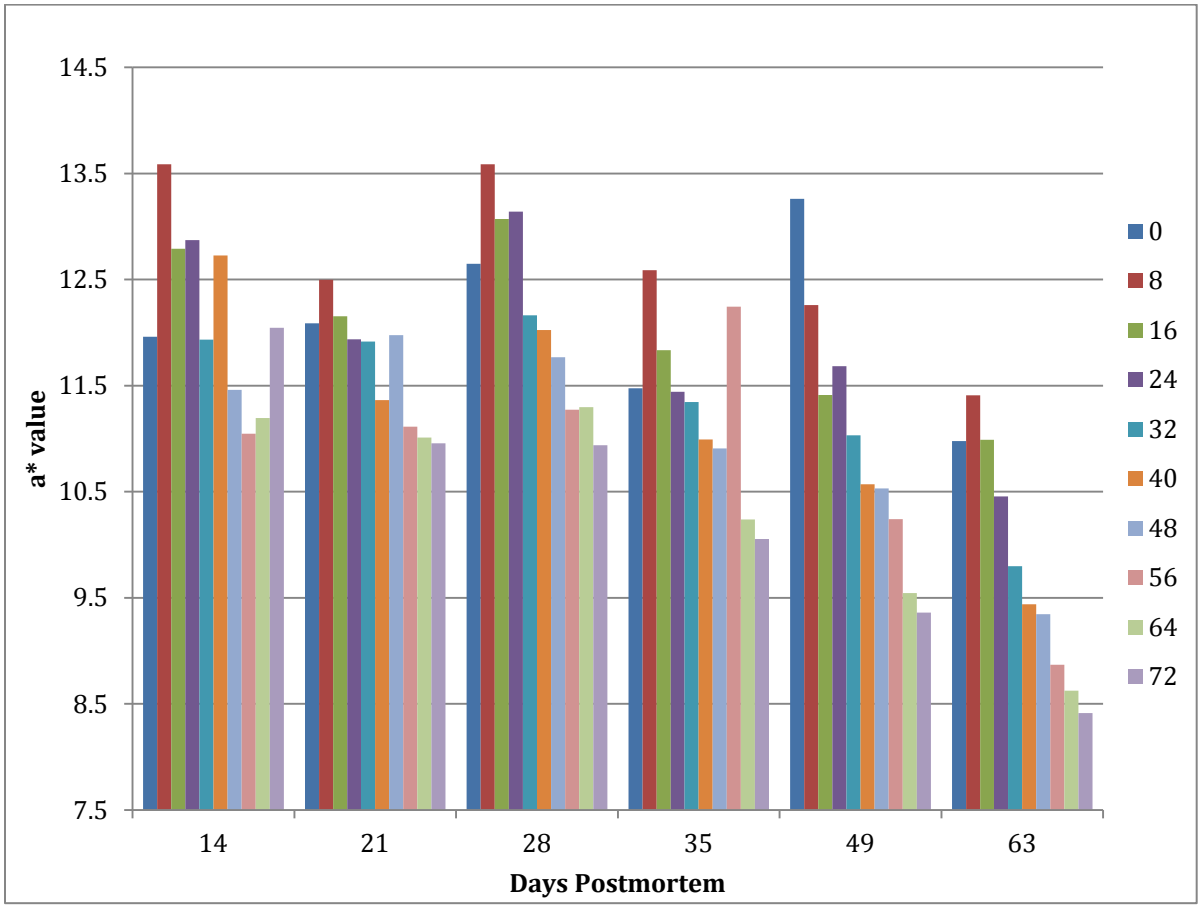



Figure A1.8. Lean a* values for strip loin steaks displayed for 72 hours.

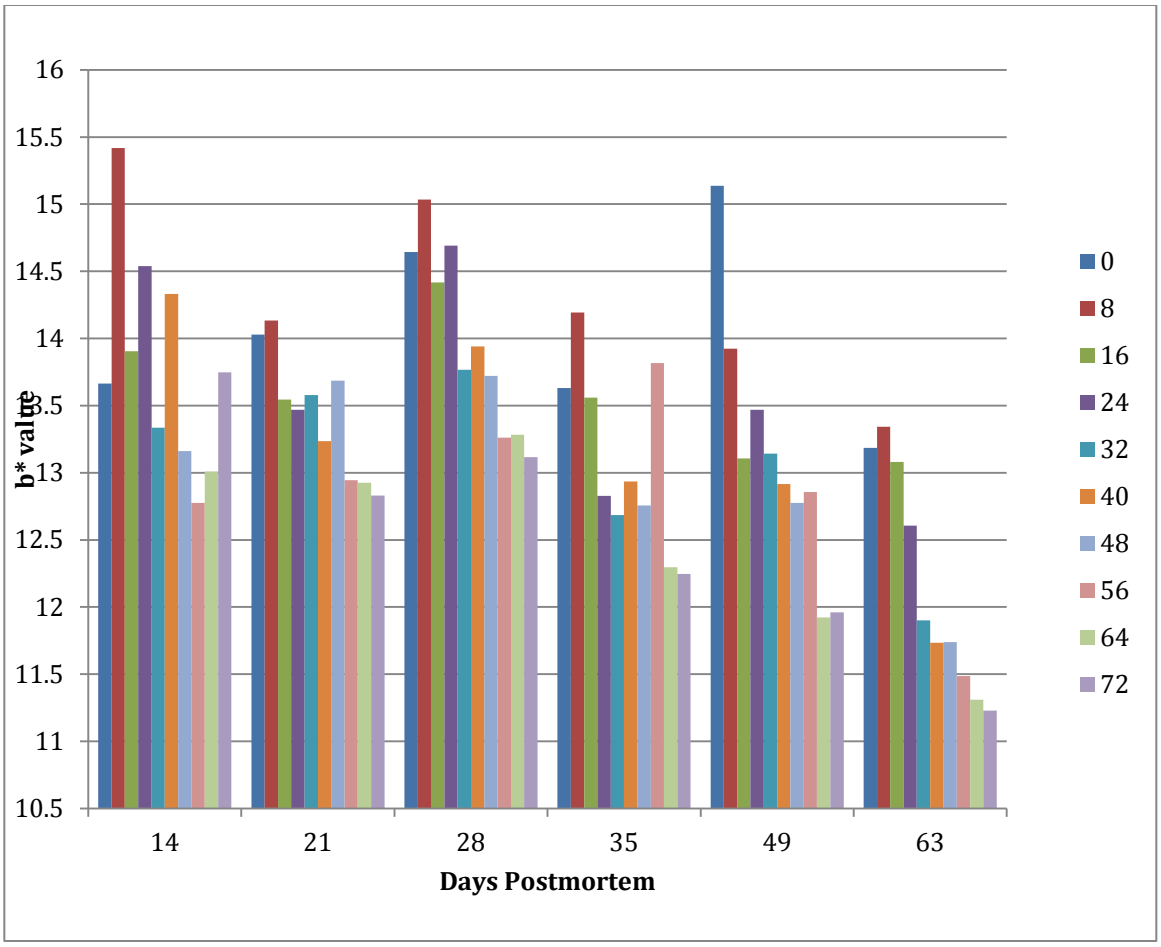



Figure A1.9. Lean b* values for strip loin steaks displayed for 72 hours.

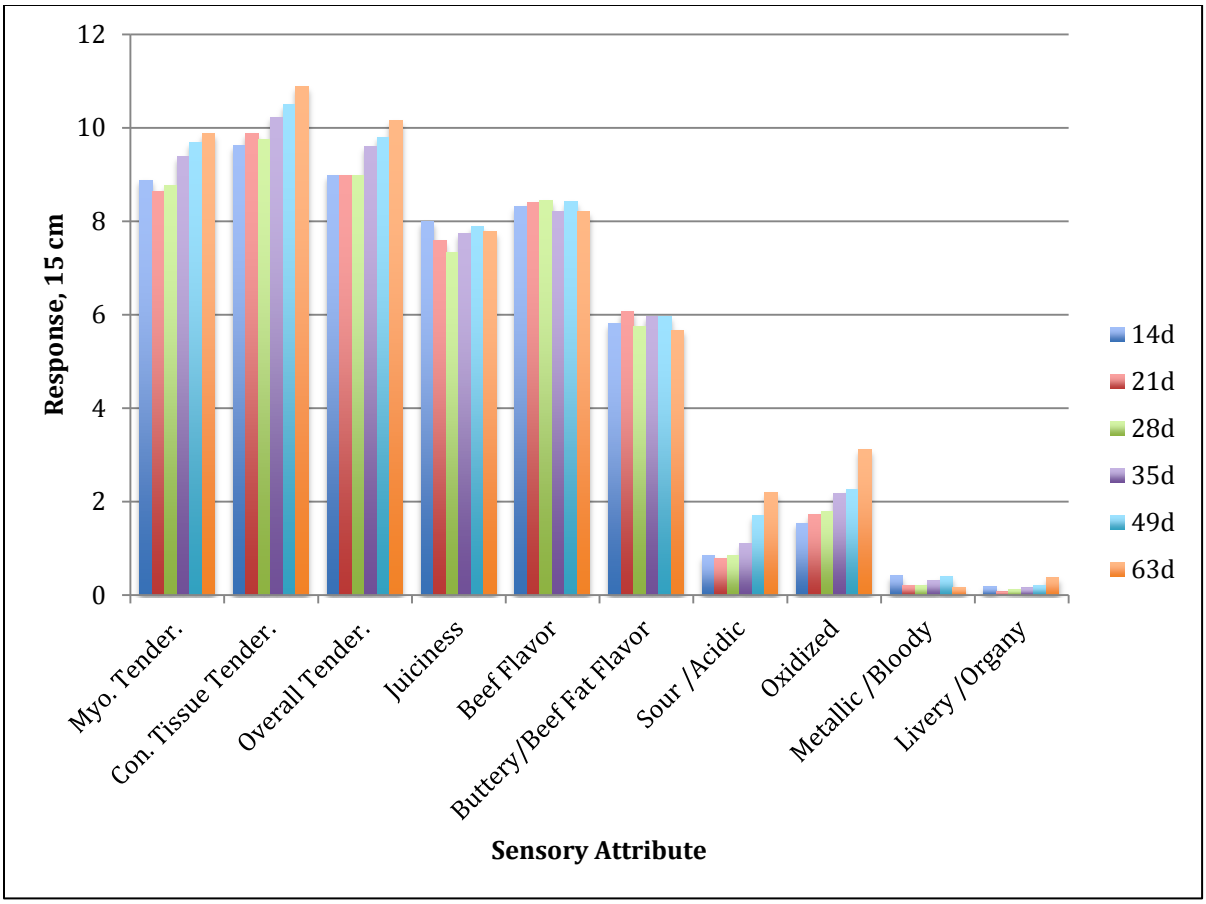



Figure A1.10. Trained sensory panel ratings for strip loin steaks that were displayed for 72 hours.

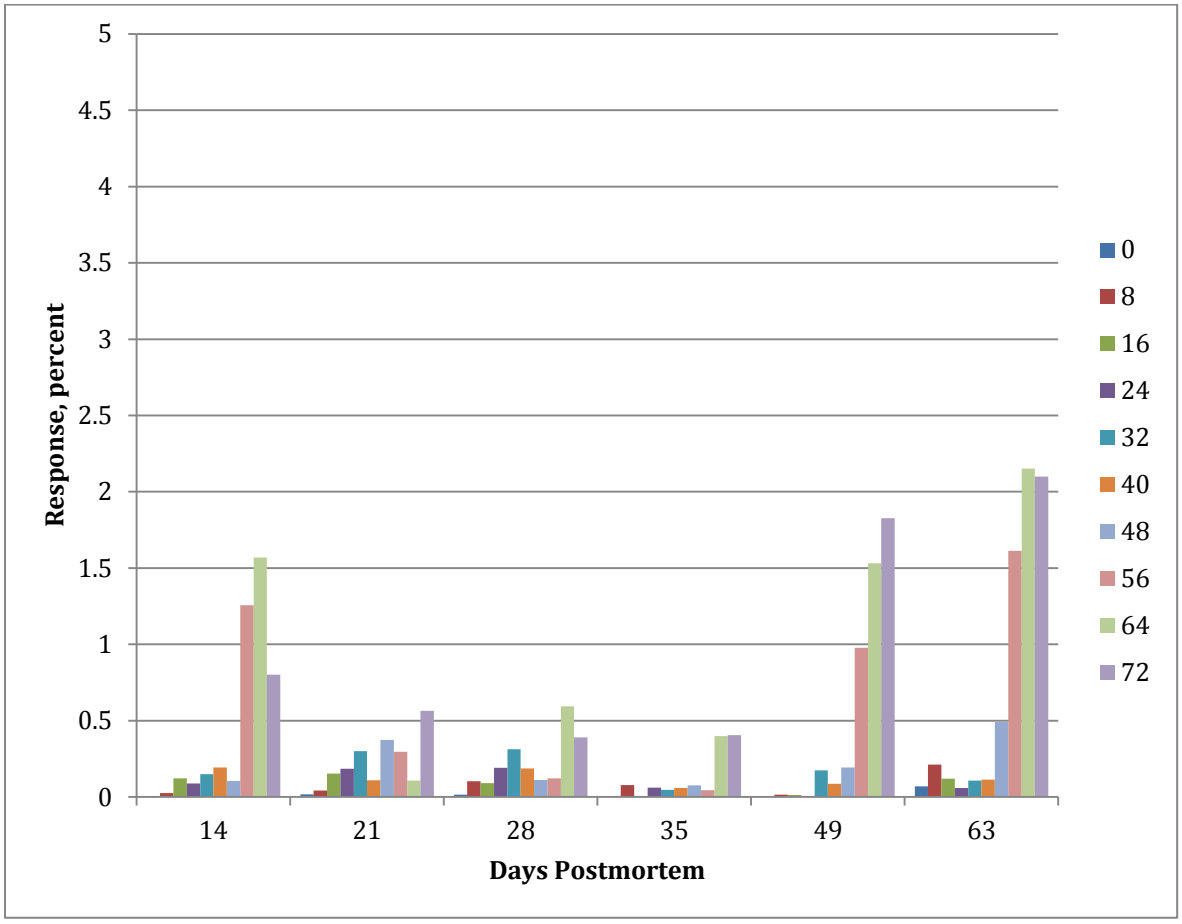



Figure A1.11. Trained color panel percent lean discoloration scores for sirloin steaks displayed for 72 hours

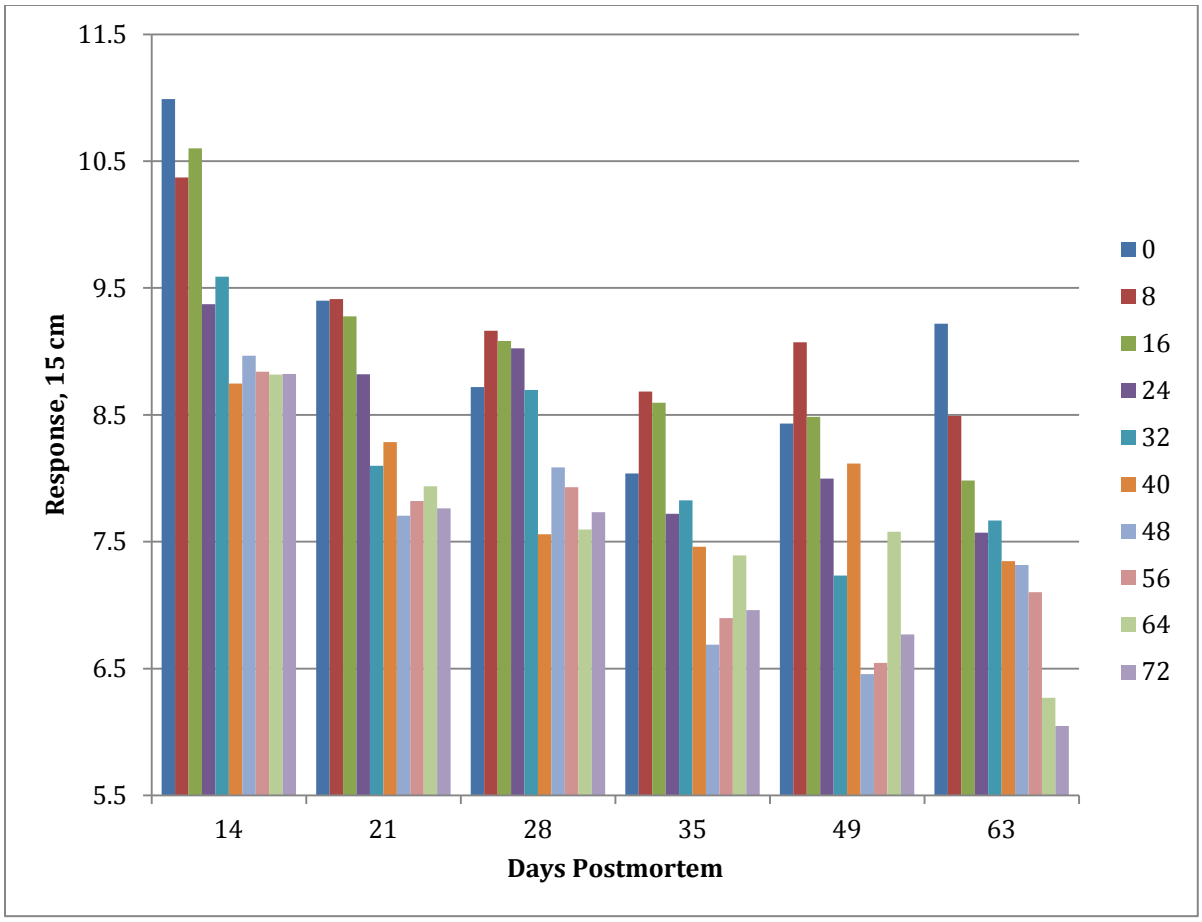



Figure A1.12. Trained color panel lean color scores for sirloin steaks displayed for 72 hours.

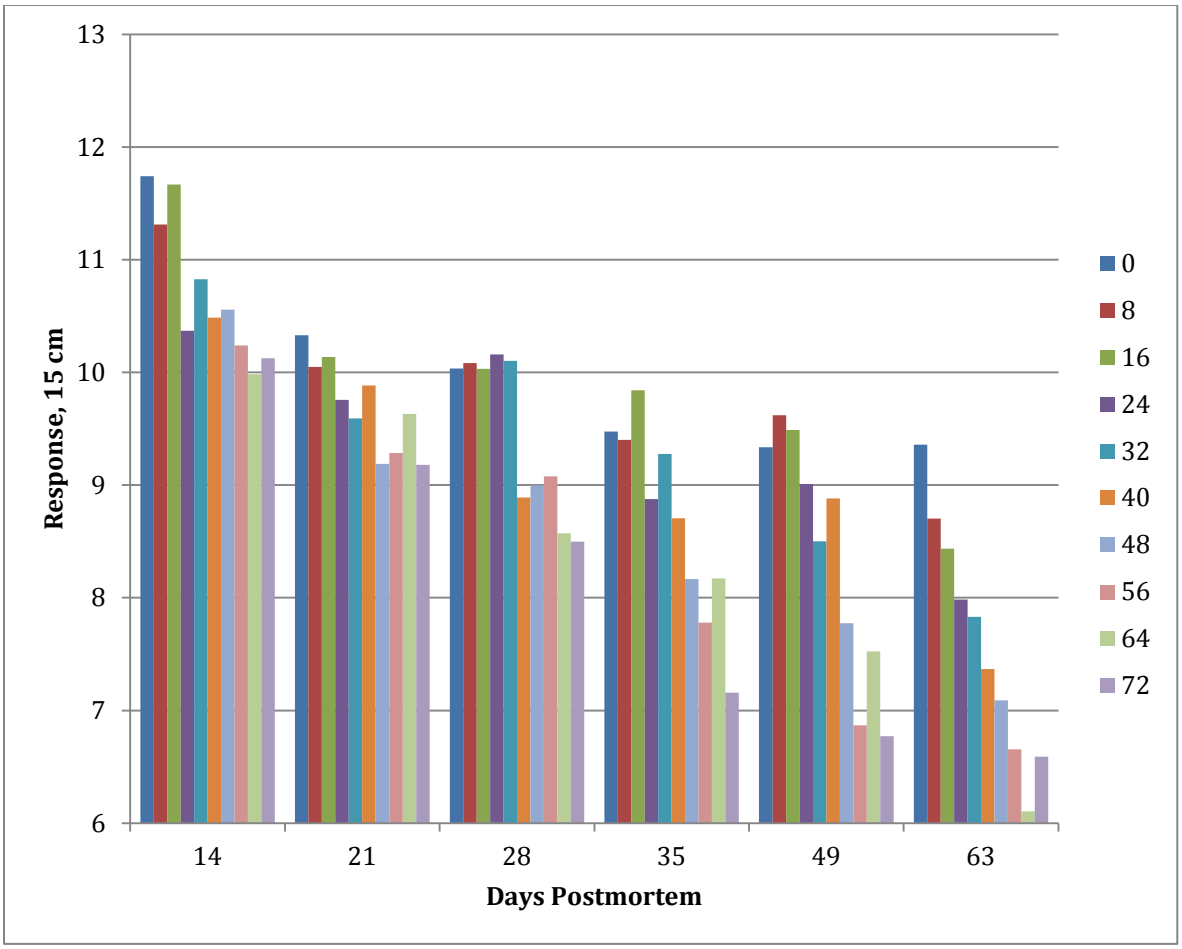



Figure A1.13. Trained color panel external fat color scores for sirloin steaks displayed for 72 hours.

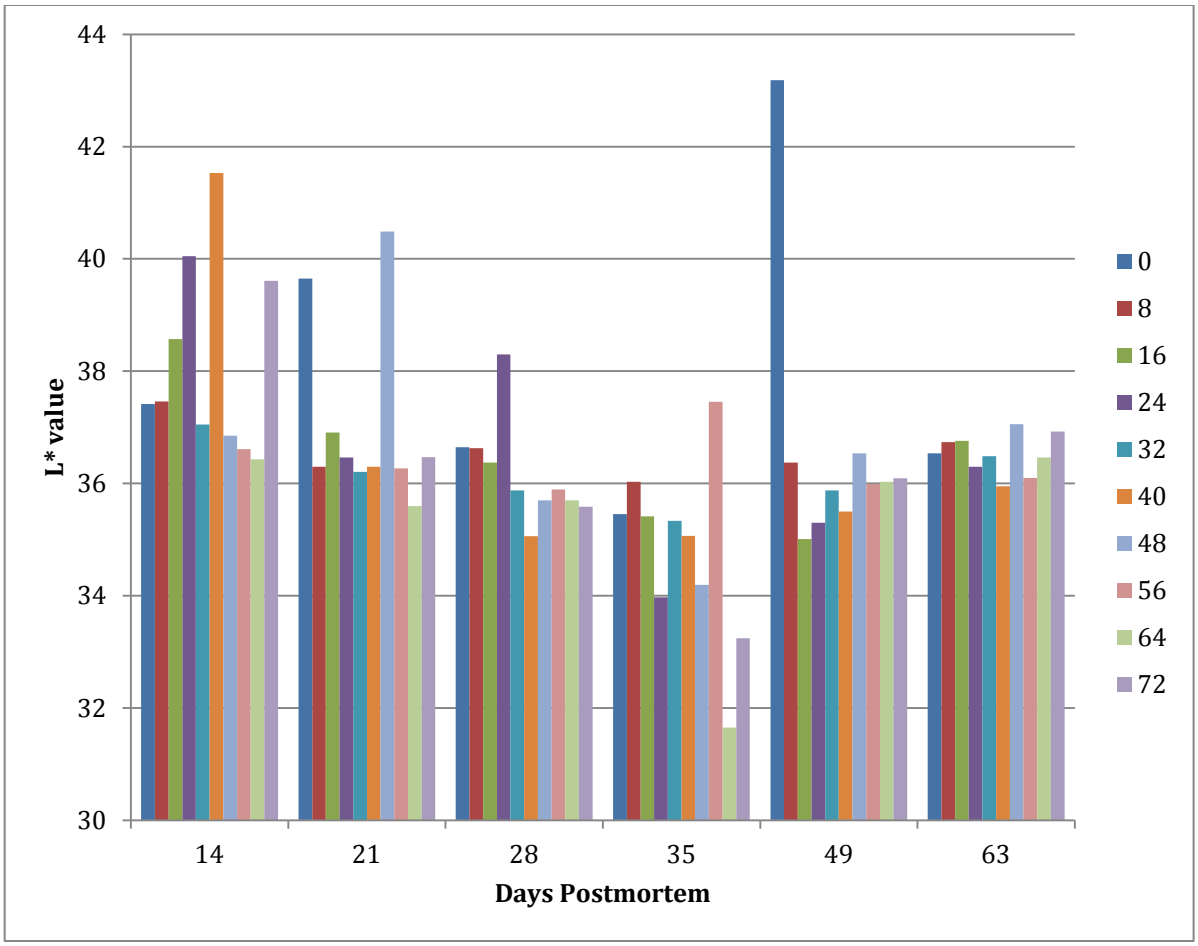


Figure A1.14. Lean L* values for sirloin steaks displayed for 72 hours.

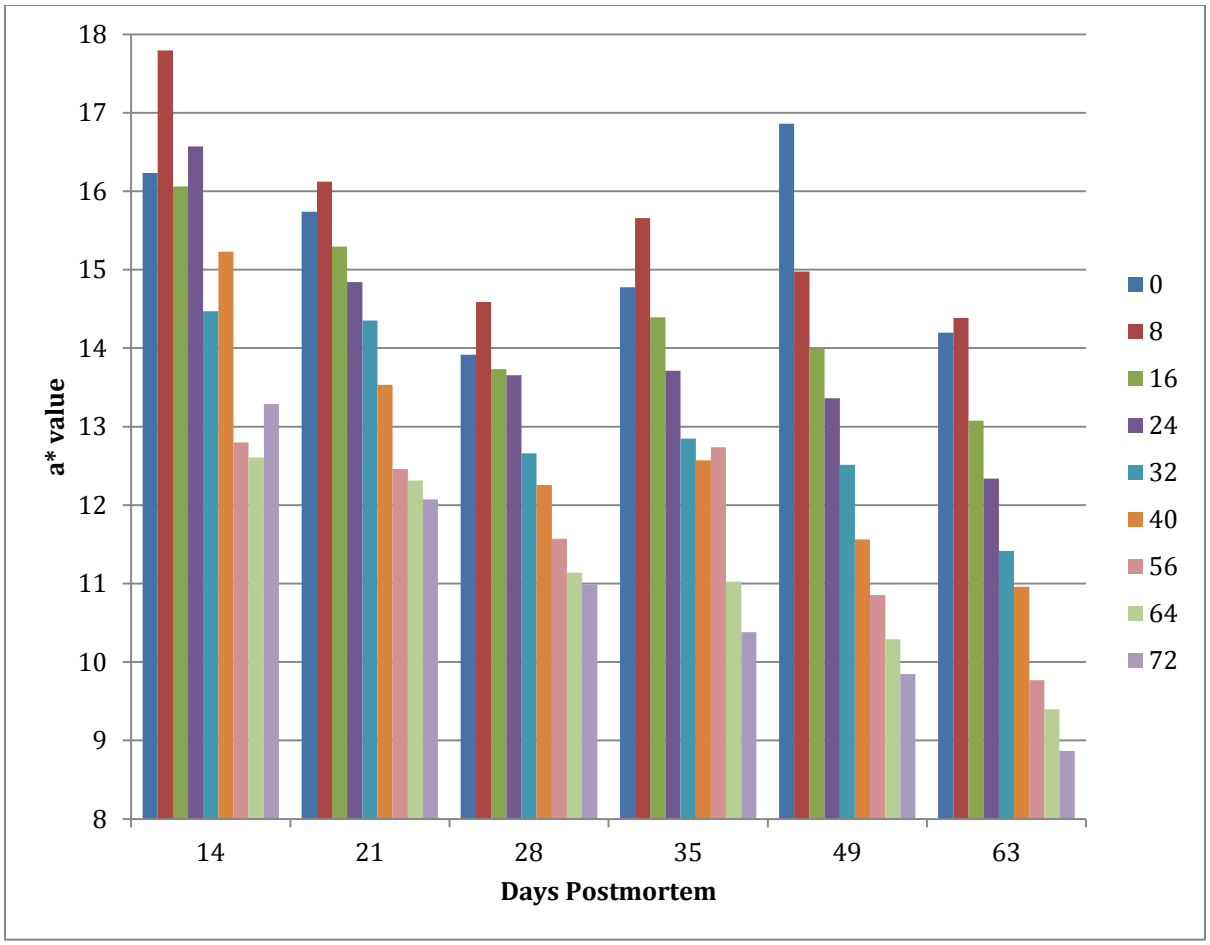


Figure A1.15. Lean a* values for sirloin steaks displayed for 72 hours.

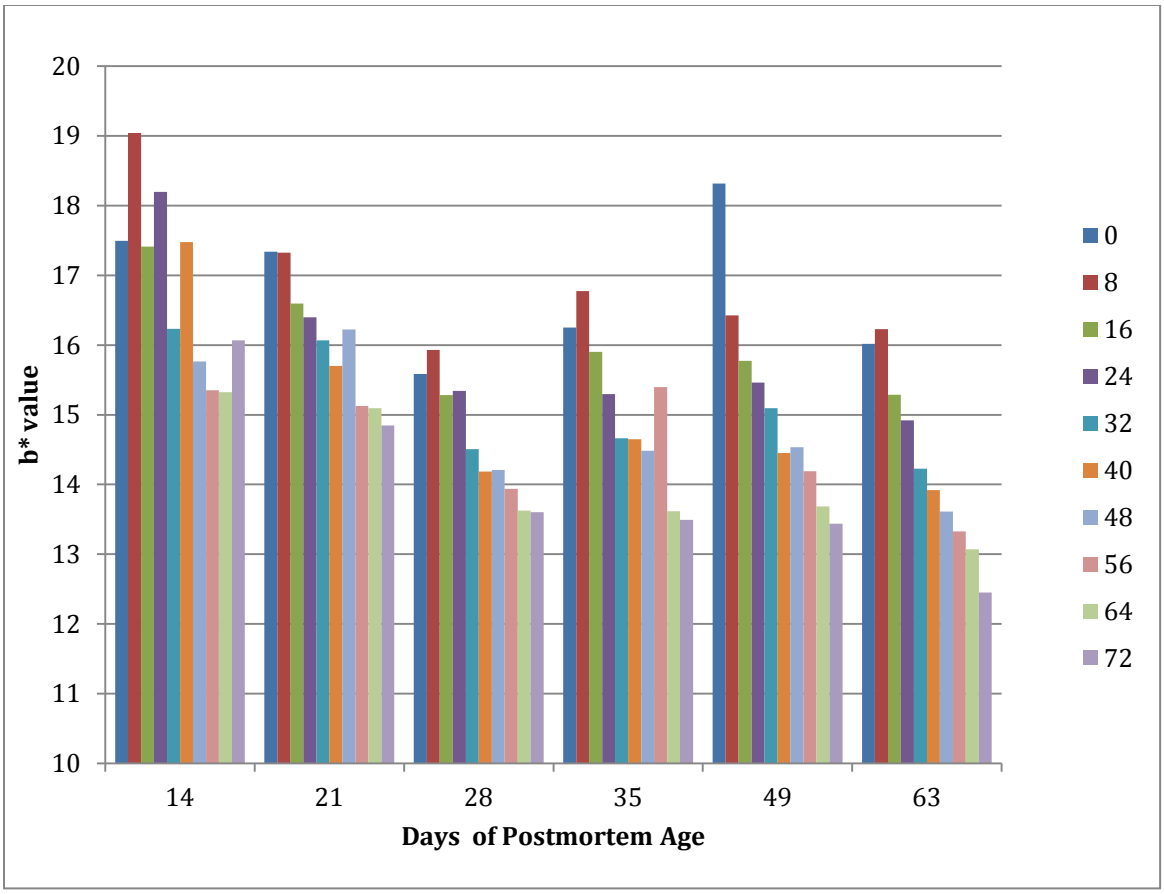



Figure A1.16. Lean b* values for sirloin steaks displayed for 72 hours.

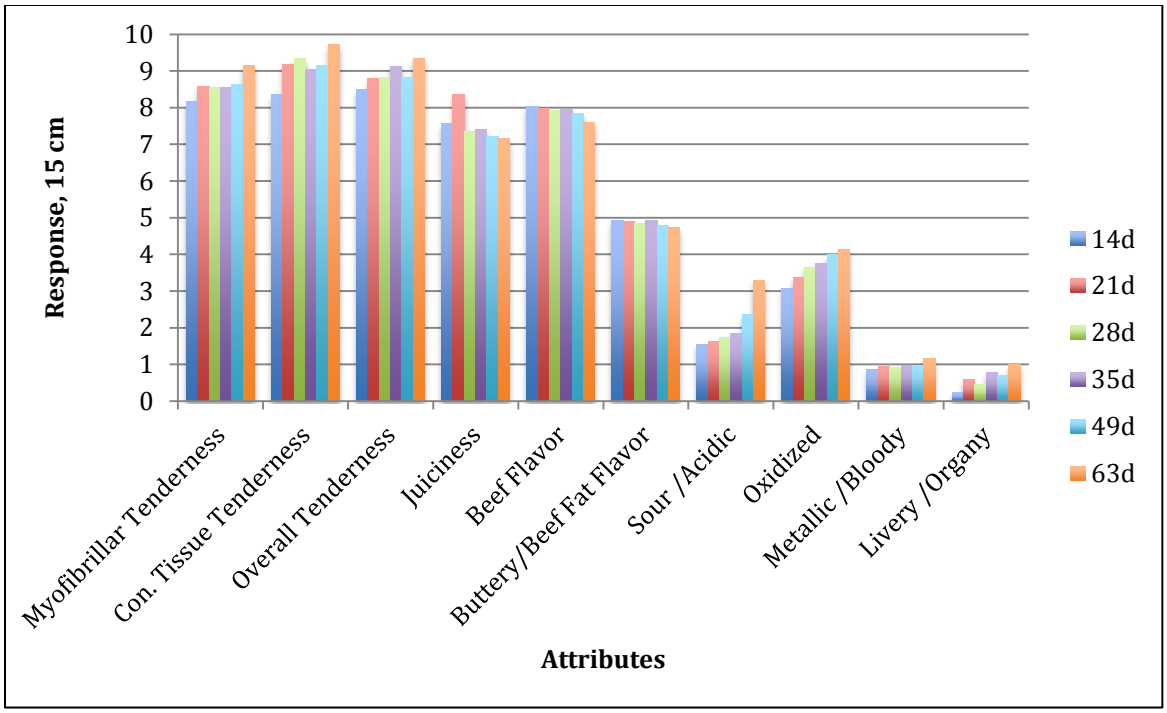



Figure A1.17. Trained sensory panel ratings for strip loin steaks that were displayed for 72 hours.