# BIOCHEMICAL AND PHYSICAL FACTORS AFFECTING COLOR CHARACTERSITICS OF SELECTED BOVINE MUSCLES

A Dissertation

by

DAVID RICHARD MCKENNA

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

December 2003

Major Subject: Animal Science

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Approved as to style and content by:

| | |
|---|---|
| Jeff W. Savell<br>(Chair of Committee) | Dan S. Hale<br>(Member) |
| Stephen B. Smith<br>(Member) | Zerle L. Carpenter<br>(Member) |
| R. Dan Lineberger<br>(Member) | John W. McNeill<br>(Head of Department) |

December 2003

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# ABSTRACT

Biochemical and Physical Factors Affecting Color Characteristics

of Selected Bovine Muscles. (December 2003)

David Richard McKenna,

B.S., Iowa State University;

M.S., Iowa State University

Chair of Advisory Committee: Dr. Jeffery W. Savell

Nineteen bovine muscles were removed from beef carcasses (n = 9). Muscles were trimmed free of fat, cut into 2.54 cm thick steaks, and were packaged in Styrofoam trays with polyvinylchloride overwrap. Steaks were assigned randomly to a day of retail display (0-, 1-, 2-, 3-, 4-, or 5-d). Steaks were evaluated over the course of retail display for objective measures of discoloration (metmyoglobin, oxymyoglobin, L*-, a*-, and b*-values), reducing ability (metmyoglobin reductase activity, resistance to induced metmyoglobin formation, and nitric oxide metmyoglobin reducing ability), oxygen consumption rate, oxygen penetration depth, myoglobin content, oxidative rancidity, and pH. Muscles were grouped according to objective color measures of discoloration. *M. longissimus lumborum*, *M. longissimus thoracis*, *M. semitendinosus*, and *M. tensor fasciae latae* were grouped as "high" color stability muscles, *M. semimembranosus*, *M. rectus femoris*, and *M. vastus lateralis* were grouped as "moderate" color stability

muscles, *M. trapezius*, *M. gluteus medius*, and *M. latissimus dorsi* were grouped as "intermediate" color stability muscles, *M. triceps brachi - long head*, *M. biceps femoris*, *M. pectoralis profundus*, *M. adductor*, *M. triceps brachi - lateral head*, and *M. serratus ventralis* were grouped as "low" color stability muscles, and *M. supraspinatus*, *M. infraspinatus*, and *M. psoas major* were grouped as "very low" color stability muscles. Generally, muscles of high color stability had high resistance to induced metmyoglobin formation, nitric oxide reducing ability, and oxygen penetration depth and possessed low oxygen consumption rates, myoglobin content, and oxidative rancidity. In contrast, muscles of low color stability had high metmyoglobin reductase activity, oxygen consumption rates, myoglobin content, and oxidative rancidity and low resistance to induced metmyoglobin formation, nitric oxide metmyoglobin reducing ability, and oxygen penetration depth. Data indicate that discoloration differences between muscles are related to the amount of reducing activity relative to the oxygen consumption rate.

**DEDICATION**

*To Bailey*

Wh.Nr.

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During my degree program I have had the pleasure of coaching, teaching, and working with many outstanding undergraduate and graduate students too numerous to list. Nonetheless, they have made an indelible mark on me that has only strengthened my love for this university.

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# INTRODUCTION

Meat discoloration is well recognized as one of the leading causes of loss of sales at the retail meat case. Additionally, meat merchandisers discard or devalue millions of dollars worth of product because of discoloration. Thus, meat color is a major driver of retail meat case sales and profitability. Meat color and color stability have been important areas of research for a number of years, and researchers have identified a number of biochemical and physical factors that can affect color and color stability.

Metmyoglobin reducing activity is thought to prolong the color stability of muscles by reducing metmyoglobin to myoglobin. Subsequent oxygenation of myoglobin maintains the bright cherry red color desired by consumers. Reddy and Carpenter (1991) reported that muscles with higher reducing activities also were the muscles that have been traditionally characterized as the most color stable.

Oxygen consumption rate (OCR) was identified as another major color determining characteristic (Madhavi and Carpenter, 1993). Oxygen consumption rate is associated with residual mitochondrial respiration in postmortem muscle (Bendall and Taylor, 1972) and is related to the depth of oxygen penetration into the exposed surface of muscle. Generally, lower OCR allows greater penetration of oxygen into muscle and is associated with more color stable muscles. While OCR and oxygen penetration depth (OPD) are negatively correlated, with OPD increasing as OCR decreases, they are actually two independent measures of color stability as OPD can be affected by higher concentrations of oxygen and fluctuations in partial oxygen pressure (O'Keefe and

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This dissertation follows the style and format of *Meat Science.*

Hood, 1982). The relative role of reducing activity versus OCR in determining color stability of muscles has been the subject of great debate. Some researchers contend that reducing ability of muscle is the primary determinant of color stability (Ledward, 1972). Others have reported that reducing ability is of little importance in determining color stability and have given more credence to oxygen consumption properties (Atkinson and Follett, 1973; O'Keefe and Hood, 1982; Renerre and Labas, 1987). It is expected that both reducing activity and OCR contribute to color stability characteristics of bovine muscles (Madhavi and Carpenter, 1993). Recently, Sammel, Hunt, Kropf, Hachmeister, and Johnson (2002) showed that a relationship existed between reducing activity and OCR ($r = 0.39$ to $0.50$) in *M. semimembranosus* samples. However, the relative contributions of reducing activity and OCR towards color stability in individual muscles needs to be more extensively established.

While reducing activity and OCR are considered the primary endogenous determinants of color stability there are other factors that act independently within muscle . Lipid oxidation and pigment oxidation are closely related in beef, with an increase in one resulting in a similar increase for the other (Faustman and Cassens, 1990). The mechanism behind this system is not completely understood, however, it is thought to be related to direct pigment oxidation or destruction of pigment reducing systems by free radicals during lipid oxidation. pH can also influence the color stability of muscles. Reducing activity, OCR, and OPD are all influenced by changes in pH. Moreover, lower pH conditions favor myoglobin oxidation.

Although our understanding of muscle color and the factors associated with discoloration have progressed during the past three decades, our understanding of the color characteristics of individual muscles and the contribution of reducing activity and OCR in regulating discoloration has not advanced.

In the past few years, a new trend towards marketing individually dissected muscles has resonated throughout the meat industry. A complete bovine carcass muscle profiling project that characterized tenderness and processing traits of each specific muscle within beef carcasses was completed by Jones, Burson, and Calkins (2001). A similar carcass dissection study conducted at Texas A&M University (Belew, Brooks, McKenna, and Savell, 2003) investigated the shear value differences between individual muscles. Both studies showed that individual beef muscles are inherently different in their tenderness and processing characteristics and can be more effectively merchandised by marketing individual muscles towards their most positive characteristics. One of the key drivers to the muscle profile research initiative has been the need to identify and characterize undervalued muscles from the round and chuck. The National Cattlemen's Beef Association has been promoting "Beef Value Cuts" (NCBA, 2001) as a retail merchandising promotion to inform meat market managers about the merchandising opportunities that these underutilized muscles present. However, there are no scientific data that characterize the color stability of these muscles or how they will maintain their color in a retail meat case.

There is a need in the industry for research to characterize the color characteristics of individual bovine muscles and determine how those characteristics

impact the color stability of those muscles. With this information, the beef industry will have a better understanding of parameters affecting product quality characteristics. The objectives of this study were to quantify the biochemical and physical factors that dictate color stability and rate of discoloration of individual bovine muscles and determine the effect of retail display time on biochemical and physical factors that dictate color stability and rate of discoloration of individual bovine muscles

## LITERATURE REVIEW

Color is the primary factor affecting consumer purchasing decisions of meat products. Because of its importance to consumers, much emphasis has been placed on controlling color or more specifically maintaining color (Faustman and Cassens, 1990). Maintaining color becomes particularly challenging for retailers who have to discount or discard meats cuts that discolor before they are sold. This problem results in the loss of millions of dollars annually. Maintaining or extending the stability of meat color entails understanding a number of physical and biochemical factors.

There are many factors that influence color stability of muscles. Reduction of metmyoglobin in meat has been identified by Ledward (1972) as the primary determinant of color stability. However, despite its vigorous study, specific mechanisms for metmyoglobin reduction still have not been conclusively elucidated. A natural metmyoglobin reducing system was identified by Dean and Ball (1960). The enzyme identified as being responsible for reduction of metmyoglobin was named metmyoglobin reductase and has since been partially purified from a number of mammals. Metmyoglobin reductase was only recently localized in bovine skeletal muscle by Arihara, Itoh, and Kondo. (1989). The *in vitro* reaction is NADH-dependent and requires the presence of ferrocyanide. Arihara, Cassens, Greaser, Luchansky, and Mozdziak (1995) identified the mitochondrial fraction of cells as the primary area where metmyoglobin reductase is found, but they noted it was also present at lower levels in the microsomal fraction. Livingston, McLachlan, Lamar, and Brown (1985) determined that metmyoglobin reductase functions by enzymatically reducing cytochrome $b_5$, which

then non-enzymatically reduces metmyoglobin. There has been much discussion about the role of metmyoglobin reductase as a determinant of color stability. Reddy and Carpenter (1993) reported that muscles with higher metmyoglobin reductase activity were also the muscles that have been traditionally characterized as the most color stable. Madhavi and Carpenter (1993) determined that *M. longissimus lumborum* was more color stable than *M. psoas major*, and noted that metmyoglobin reductase activity was one of the main color determining characteristics that differed between the two muscles. Madhavi and Carpenter (1993) concluded that reduction of metmyoglobin and oxygen consumption rate were important biochemical factors involved in determining color stability characteristics of muscles.

Two methods have prevailed as the means for measuring metmyoglobin reducing ability of meat. An assay for metmyoglobin reductase activity was developed by Stewart, Hutchins, Zisper, and Watts (1965a) and involves the complete chemical oxidation of the muscle and the subsequent measure of its ability to reduce metmyoglobin. Aerobic reducing ability, developed by Ledward (1972), involves storing muscle in a 1% oxygen environment to promote metmyoglobin development followed by a subsequent storage period in a normal aerobic environment. Aerobic reducing ability is determined spectrophotometrically by comparing the percentage shift from metmyoglobin to oxymyoglobin. Both procedures offer important means of measuring reducing ability, however, there are concerns that chemical oxidants used in the metmyoglobin reductase activity procedure affect metmyoglobin reduction (Faustman and Cassens, 1990). Each method appears to measure reducing systems.

However, Ledward (1972) has questioned whether metmyoglobin reductase activity and aerobic reducing ability are measuring the same reduction system. Sammel et al. (2002) reported higher metmyoglobin reductase activity and aerobic reducing ability for superficial portions of *M. semimembranosus*, which were more color stable than deep portions. Regardless of whether metmyoglobin reductase activity and aerobic reducing ability are measuring the same reducing system, both procedures serve as valuable measurements of reducing ability. Ledward (1972) suggested that reducing ability was the most important factor in determining metmyoglobin accumulation. Multiple researchers have found little evidence to support the theory that reducing ability is related to meat discoloration or color stability. Atkinson and Follett (1973) found that metmyoglobin reductase activity in lamb was higher than in beef or pork even though the lamb was less color stable. O'Keefe and Hood (1982) reported high metmyoglobin reductase activity was associated with more color stable muscles. However, there was no correlation between metmyoglobin reductase activity and discoloration (as expressed as $(K/S)_{572}/(K/S)_{525}$). Moreover, they concluded that metmyoglobin reductase activity had little effect on metmyoglobin accumulation. Renerre and Labas (1987) observed the highest metmyoglobin reductase activity in diaphragm muscle, the least color stable muscle included in their study. They also measured specifically metmyoglobin reductase activity and found the same trend.

Oxygen-use properties of muscle have been identified as important determinants of color stability. Postmortem oxygen consumption is related to residual mitochondrial activity in the muscle. It has been reported that mitochondria maintain their oxidative

capacity for six days postmortem (Cheah & Cheah, 1971). Bendall and Taylor (1972) reported oxygen consumption rates decreased exponentially in post-rigor muscle stored for 6 days at 2°C and Atkinson and Follet (1973) reported oxygen uptake decreased within increasing retail display time. It is thought that high oxygen consumption rates deter the development of oxymyoglobin (Ashmore, Parker, & Doerr, 1972). O'Keefe and Hood (1982) found that muscles with greater discoloration rates had higher rates of oxygen consumption. They concluded that rate of discoloration was influenced by OCR and tendency of the muscle to oxidation. Renerre and Labas (1987) also reported that muscles with the lowest color stability had the highest OCR (e.g., diaphragm) and the more color stable muscles (e.g., *M. tensor fasciae latae*) had the lowest OCR. They noted a possible relationship between fiber type and discoloration because the diaphragm was comprised of slow-twitch oxidative fibers and the *M. tensor fasciae latae* was primarily composed of fast-twitch glycolytic fibers.

Oxygen penetration depth is thought to be related to oxygen consumption rate. An inverse relationship has been established between the two in that as OCR decreases OPD tends to increase. Morley (1971) reported great variability in oxygen penetration depth of different beef muscles. O'Keefe and Hood (1982) found that *M. longissimus lumborum* muscle had greater OPD at 0 and 10 days postmortem than *M. psoas major*, however, no difference was observed at 2 days postmortem. They concluded that a wide oxymyoglobin layer was a characteristic of muscles with high color stability.

Researchers who believe that reducing potential is the most important factor in determining rate of discoloration have attempted to unequivocally demonstrate that,

whereas scientists investigating the role of OCR in the development of discoloration have championed it as the leading factor. However, there is mounting evidence that both metmyoglobin reductase activity and OCR play an important role in regulating discoloration. The contribution of each of these factors may ultimately determine the color stability of a muscle. Atkinson and Follett (1973) speculated that the ratio between metmyoglobin reductase activity and oxygen uptake in a muscle may be the most important determinant of color stability. They investigated beef, pork, and lamb and found that lamb had the highest metmyoglobin reductase activity but also had the least stable color. This result was unexpected because other studies had linked high metmyoglobin reductase activity with greater color stability. As an explanation, they hypothesized that the ratio of metmyoglobin reductase activity to oxygen uptake was important because more color stable beef and pork had lower metmyoglobin reductase activity than less color stable lamb, but also had lower oxygen uptake resulting in a lower ratio.

pH plays an important role in color stability because it influences many of the factors previously discussed. The effect of pH on color stability is primarily related to the ultimate pH of the muscle, which is usually in the range of 5.4 to 5.8 for beef. Reduced metmyoglobin reductase activity has been associated with lower ultimate pH values (Ledward, 1970). Urbin and Wilson (1958) reported that oxygen uptake increased with increasing pH or temperature. Postmortem storage temperature and pH also affect mitochondrial activity (Bendall, 1972; Bendall and Taylor, 1972). Bendall and Taylor (1972) found that OCR increased as pH increased from 5.6 to 7.2.

Myoglobin is more susceptible to autoxidation and oxidation is more accelerated at lower ultimate pH values (Gotoh & Shikama, 1974; Ledward, 1972; Ledward, Dickinson, Powell, & Shorthose, 1986).

Lipid oxidation has been proposed as a promoter of myoglobin oxidation. Much research has demonstrated that there is a relationship between meat discoloration and lipid oxidation. Faustman et al. (1989b) noted an increase in lipid oxidation is usually related to a similar increase in myoglobin oxidation and vice versa. Hutchins, Liu, and Watts (1967) reported metmyoglobin accumulation and malonaldehyde were positively correlated ($r = 0.73$). Govindarajan, Hultin, and Kotula (1977) found that adding antioxidants to meat improved color stability. Hood (1975) reported improved color stability when sodium ascorbate was injected intravenously at slaughter. Faustman, Cassens, Schaefer, Buege, and Sheller (1989a) found muscles from cattle fed vitamin E (α-tocopherol) had greater color stability. Others have reported that delayed lipid oxidation by antioxidants has not always resulted in decreased myoglobin oxidation.

The current meat industry trend is to move towards merchandising individual muscles. There is a need for a comprehensive study that can characterize the biochemical factors that influence the color stability of beef muscles.

## MATERIAL AND METHODS

### *Raw materials, steak cutting, and packaging*

Beef carcasses (n = 9) were purchased from the Rosenthal Meat Science and Technology Center at Texas A&M University. Carcasses were obtained approximately 72 hrs postmortem, and USDA (1997) quality and yield grade data were collected by trained personnel. Carcasses were dissected into the following individual muscles: *M. adductor*, *M. biceps femoris*, *M. gluteus medius*, *M. infraspinatus*, *M. latissimus dorsi*, *M. longissimus lumborum*, *M. longissimus thoracis*, *M. pectoralis profundus*, *M. psoas major*, *M. rectus femoris*, *M. semimembranosus*, *M. semitendinosus*, *M. serratus ventralis, M. supraspinatus*, *M. tensor fasciae latae*, *M. trapezius*, *M. triceps brachii*-long head, *M. triceps brachii*-lateral head, *M. vastus lateralis*. All muscles were trimmed free of subcutaneous and seam fat, and any visible connective tissue before being vacuum packaged, placed in boxes and stored overnight in a 2 ± 2°C cooler. The following morning, muscles were cut into 2.54 cm thick steaks by cutting perpendicular to the muscle fiber orientation, with the exception of the *M. infraspinatus, M. latissimus dorsi*, and *M. trapezius*. The *M. infraspinatus* was filleted to remove the seam of heavy connective tissue running through the center and then, along with the other thin muscles (*M. latissimus dorsi*, and *M. trapezius*), cut into approximately 7 × 10 cm rectangles. Steaks from each muscle were placed on Styrofoam trays and overwrapped with polyvinylchloride film. Steak packages from each muscle were assigned randomly to a day of retail display (0-, 1-, 2-, 3-, 4- or 5-d). Packages assigned to 0-d retail display were removed and taken immediately for laboratory analysis, whereas all other packages

were placed into retail display cases. Commercial retail meat cases were used to display product, however, display cases were housed in a 2 ± 2°C cooler to minimize temperature fluctuations. Retail display lights were suspended approximately 1 m above each display case above each case and consisted of fluorescent natural white lights (Sylvania F40N, Osram Sylvania, Danvers, MA) that emitted a light intensity of 1200 lux.

***Bovine heart metmyoglobin purification***

Beef hearts were collected 1 d postmortem, trimmed free of fat, epicardial, and endocardial connective tissue and frozen at -10°C. Hearts were thawed at 4°C before metmyoglobin was extracted. Beef hearts were mixed with cold, distilled-deionized water at a ratio of one part beef heart to two parts water and homogenized in a Waring® blender for 60-90 sec. The pH of the homogenate was adjusted to 7.5 using 2 N $NH_4OH$ (Fisher Scientific, Fair Lawn, NJ) and centrifuged for 20 min at 13,700 × g (4°C) (Avanti™ J-25, Beckman Coulter, Inc., Palo Alto, CA). The supernate was collected and brought to 70% saturation with solid $(NH_4)_2SO_4$ (Fisher Scientific, Fair Lawn, NJ). The pH of the supernate was adjusted to 7.5 using 2 N $NH_4OH$, and the solution was allowed to stir for 30 min. After stirring, the solution was centrifuged at 13,700 × g for 15 min (4°C) and the supernate was collected. Solid $(NH_4)_2SO_4$ was added to the supernatant to bring it to 100% saturation and the pH was adjusted to 7.5 using 2 N $NH_4OH$. Celite 545® (Fisher Scientific, Fair Lawn, NJ) was added to the solution (1 g of Celite/ 100 mL of supernate) and the mixture was allowed to stir for 30 min. The supernate was

vacuum-filtered through a coarse porosity glass filter (G/FD, Whatman International, Inc., Maidstone, UK) and the pink filtrate was discarded. Cold water was used to elute the red oxymyoglobin from the glass filter. The oxymyoglobin solution was centrifuged at 20,000 × g for 20 min and the supernatant was collected and filtered through glass wool. The oxymyoglobin solution was oxidized to metmyoglobin using $K_3Fe(CN)_6$ (Fisher Scientific, Fair Lawn, NJ) and stirred for 30 min. The metmyoglobin was poured into 10,000 molecular weight cut-off dialysis tubing (Spectra/Por, Spectrum Industries, Inc., Rancho Dominguez, CA) and dialyzed at 4°C against distilled water with three periodic water changes. The metmyoglobin solution was dialyzed against 2 mM $NaPO_4$ buffer (pH 7.0) and then concentrated to 0.1 mM using Amicon® Bioseparations Centricon® Plus-80 filters (Millipore Corp., Bedford, MA) and stored at 4°C. Bovine heart metmyoglobin was prepared fresh before each weeks use.

***Metmyoglobin reductase activity***

A 4.45 cm diameter core was removed from each steak and the top 1/3 of each core was removed and chopped finely. Five grams of the finely chopped muscle were homogenized with 25 mL of 2 mM phosphate buffer (pH 7.0) for 45 sec in a Waring® blender. The homogenate was centrifuged at 35,000 × g for 30 min (4°C) and the supernatant was filtered through Whatman #541 filter paper. The supernate was oxidized with 1-2 crystals of $K_3Fe(CN)_6$, poured into 10,000 molecular weight cut-off dialysis tubing (Spectra/Por, Spectrum Industries, Inc., Rancho Dominguez, CA, and dialyzed at 4°C against 2 mM phosphate buffer (pH 7.0) with two phosphate buffer

change-overs. After dialysis, 0.2 mL of the muscle extract was placed in a micro-cuvette containing 0.1 mL of 5 mM disodium EDTA, 0.1 mL of 50 mM citrate buffer (pH 5.65), 0.1 mL of 3 mM potassium ferricyanide, 0.3 mL of 0.1 mM bovine metmyoglobin, and 0.1 mL distilled-deionized water. The reaction was initiated by adding 0.1 mL of 10 mM NADH (Sigma-Aldrich Co., St. Louis, MO). The assay was run at 30°C and absorbance at 580 nm was measured. Metmyoglobin redcutase activity was calculated using the linear phase of the reaction using Beer's law with a molar extinction coefficient of 12,000 $M^{-1}$ $cm^{-1}$.

***Myoglobin content***

Myoglobin content was determined using the muscle extract from the metmyoglobin reductase activity assay. Approximately 3 mL of the muscle extract was placed in a standard cuvette and absorbance was read at 572, 565, 545, and 525 nm using a spectrophotometer (DU Series 7000, Beckman Instruments, Inc., Fullerton, CA). Myoglobin content was calculated using the equation described by Kryzwicki (1979).

***Aerobic reducing activity***

A 4.45 cm diameter core was removed from each steak, placed on a mini-Petri dish (47 mm, Millipore Corp., Bedford, MA), and wrapped with an oxygen permeable film (D14, Shield Manufacturing Corporation, Oklahoma City, OK) to prevent surface dehydration. Cores were placed in a 1% oxygen/99% nitrogen environment for 24 hours to induce metmyoglobin formation. Spectral reflectance was recorded between 400 and

700 nm on the surface of each core immediately after removal from the low-oxygen environment using a Hunter MiniScan XE (HunterLabs, Reston, VA). Samples were stored in the dark an additionally 24 hours in an aerobic atmospheric environment and then spectral reflectance from the surface of each sample was recorded. Percentage metmyoglobin was calculated for samples according to AMSA (2003) guidelines. Aerobic reducing activity was calculated by subtracting the percentage of metmyoglobin found in the sample stored for 24 hours in atmospheric conditions from the percentage metmyoglobin found in the sample stored in the 1% oxygen environment for 24 hours.

***Nitric oxide metmyoglobin reducing activity***

A 4.45 cm diameter core was removed from each steak. Cores were placed in 100 mL glass beakers with the exposed surface being the surface displayed in the retail case. Samples were covered with 50 mL of 0.3% sodium nitrite (Fisher Scientific, Fair Lawn, NJ) solution and allowed to soak for 30 min. After soaking, samples were removed and blotted dry with paper towels to remove excess nitrite solution. Samples were placed in bags, maintaining the display side up, and vacuum-packaged immediately. Samples were stored at ambient temperature (approximately 20°C) and spectral data (400 to 700 nm) were collected every 30 min for a total of 3 hours using a Hunter MiniScan XE (HunterLabs, Reston, VA). Nitric oxide metmyoglobin reducing ability was determined by calculating the percentage of metmyoglobin in samples after 3 hours of storage and subtracting that percentage from the initial percentage of metmyoglobin present in samples.

***Oxygen consumption rate***

Polypropylene bottles (250 mL) with modified caps were used to collected oxygen consumption data. Caps for bottles were modified by drilling a hole in the center and then septa were glued to the inside and outside of caps. Cores (4.45 cm diameter) were removed from steaks and placed in the polypropylene bottles so that the exposed surface of each core was the same surface that was exposed in the package. Bottles were flushed with oxygen, and the initial oxygen and carbon dioxide concentration in each bottle was measured using a headspace analyzer (PBI Dansensor Checkpoint, PBI-Dansensor A/S, Ringted, Denmark). Bottles were stored at 4°C for 24 hr and then final oxygen and carbon dioxide concentrations were measured using a headspace analyzer (PBI Dansensor Checkpoint, PBI-Dansensor A/S, Ringted, Denmark). Oxygen consumption rate was determined by subtracting the initial carbon dioxide concentration from the final carbon dioxide concentration.

***Oxygen penetration depth***

To measure oxygen penetration depth, thin slices (approximately 1 cm thick) were removed from steaks at the time of cutting, by cutting perpendicular to the cut surface of steaks. Thin slices were placed immediately between two 5.1 × 5.1 cm glass plates before any oxygenation could occur. Ends of muscle strips that extended outside of the glass plates were cut off and plates were covered with a PVC overwrap to prevent dehydration. Oxygen penetration depth was measured in mm using digital calipers

(Control Company, Friendswood, TX). Ten measurements were taken on each sample and averaged, and each sample was evaluated once per day.

***CIE L*-, a*-, and b*-values and spectral reflectance data***

Objective color values were recorded each day on steaks that were assigned to day 5 of retail display. Color measurements were collected using a Hunter MiniScan XE (HunterLabs, Reston, VA) that was standardized before each use. Illuminate A, 10° standard observer, and a 3.18 cm aperature size were used when collecting values. A total of three readings were taken on each steak and averaged. CIE L*-values (lightness), a*-values (redness), b*-values (yellowness), and spectral reflectance (400-700 nm) data were collected.

***pH***

The remaining portions of steaks were minced into small cubes (approximately 1 $cm^3$). pH of chopped steaks was measured using a handheld pH meter (pHStar, SFK Technologies, Denmark). Two measurements were taken from each steak and averaged.

***2-Thiobarbituric acid reactive substances***

Steaks were evaluated for lipid oxidation by measurement of 2-thiobarbituric acid reactive substances (TBARS) as described by Tarladgis et al. (1960) as modified by Rhee (1978). A 30 g sample from each steak was blended with 40 mL of double distilled water and 15 mL of propyl gallate and ethylenediaminetetracetic acid for 2 min.

Thirty grams of the slurry was sprayed with 316 Silicone Release Spray lubricant (Dow Corning®, Midland, MI, USA) and transferred to distillation flasks and 2.5 mL of 4 N HCl was added to each flask. Samples were distilled until 50 mL of the distillate was collected. Two 5 mL samples were transferred from the distillate into screw cap test tubes and 5 mL of TBA reagent was added to each test tube. The test tubes were boiled for 35 min along with 2 blank test tubes, each containing 5 mL of TBA reagent and 5 mL of distilled-deionized water. The resulting solution was analyzed for optical reflectance at 530 nm using a spectrophotometer (DU Series 7000, Beckman Instruments, Inc., Fullerton, CA). Reflectance values were multiplied by a conversion factor of 7.8 (from the standard curve for the distillation setup in this lab) to arrive at a TBARS value. TBARS values are reported as mg of malonaldehyde per kg of sample.

***Statistical analysis***

Data were analyzed using the GLM procedure of SAS (SAS Institute, Cary, NC). Because of the individual nature of muscles and the complexity of a muscle by retail display day interaction (19 muscles × 6 days = 114 means to separate), it was determined to analyze each muscle individually for changes over display time, thus removing any interactivity. Comparisons between muscles were made by including muscle, retail display time and their interaction (when significant) as main effects in the model. When main effects were determined to be significant ($P < 0.05$), least squares means were generated and separated using a pairwise t-test (pdiff option).

## RESULTS AND DISCUSSION

### *Raw material characterization*

Yield and quality grade factors for carcasses used in this study (Table 1) were slightly lower than national averages reported by McKenna et al. (2002) in the National Beef Quality Audit - 2000. The mix in carcasses showed a normal range in variation with yield grades ranging from 1.1 to 3.5 and marbling scores ranging from Traces[90] to Small[30]. No carcasses with extreme fatness, muscling, or marbling were included in the study, and all carcasses reflect the type of product commonly found in commercial retail markets.

### *Metmyoglobin content*

The ratio of surface reflectance at 572 nm to the reflectance at 525 nm is an important measure used to describe the amount of metmyoglobin accumulated on the surface of a steak. High $(K/S)_{572}/(K/S)_{525}$ values (~1.40-1.30), as were observed on day 1, are indications that a low percentage of metmyoglobin is present and that very little discoloration has occurred (Table 2). As metmyoglobin accumulates, ratios between reflectance values decrease, indicating the presence of greater amounts of metmyoglobin in the surface of steaks. Muscles, such as *M. adductor*, *M. biceps femoris*, *M. infraspinatus*, *M. pectoralis profundus*, *M. psoas major*, *M. rectus femoris*, *M. supraspinatus*, *M. serratus ventralis*, *M. triceps brachi* - long head, and *M. triceps brachi* - lateral head, showed large decreases in $(K/S)_{572}/(K/S)_{525}$ ratios over the retail display period. Of those muscles with substantial losses, *M. psoas major*, *M.*

Table 1
Means, standard deviations (SD), minimum, and maximum values for carcass traits

| Trait | Mean | SD | Minimum | Maximum |
|---|---|---|---|---|
| USDA yield grade | 2.4 | 0.9 | 1.1 | 3.4 |
| Fat thickness, cm | 0.4 | 0.17 | 0.16 | 0.60 |
| Hot carcass weight, kg | 312.8 | 22.2 | 290 | 362 |
| Ribeye area, $cm^2$ | 82.1 | 7.8 | 67.7 | 91.6 |
| Kidney, pelvic, and heart fat, % | 1.8 | 0.6 | 1.0 | 2.5 |
| Marbling score[a] | 347 | 44.4 | 290 | 430 |

[a]Traces[00] = 200, Slight[00] = 300, and Small[00] = 400.

Table 2
Least squares means for $(K/S)_{572}/(K/S)_{525}$ values of steaks from 19 beef muscles over 5 days of retail display

| | Display day | | | | | | |
|---|---|---|---|---|---|---|---|
| Muscle | 0 | 1 | 2 | 3 | 4 | 5 | SEM* |
| *M. adductor* | 1.39[a] | 1.28[b] | 1.17[c] | 1.10[cd] | 1.05[d] | 1.02[d] | 0.030 |
| *M. biceps femoris* | 1.36[a] | 1.29[a] | 1.20[b] | 1.12[bc] | 1.08[cd] | 1.04[d] | 0.028 |
| *M. gluteus medius* | 1.34[a] | 1.31[ab] | 1.22[bc] | 1.18[cd] | 1.14[cd] | 1.12[d] | 0.037 |
| *M. infraspinatus* | 1.36[a] | 1.20[b] | 1.08[c] | 1.01[d] | 0.98[de] | 0.96[e] | 0.017 |
| *M. latissimus dorsi* | 1.33[a] | 1.30[a] | 1.23[b] | 1.17[c] | 1.14[cd] | 1.12[d] | 0.016 |
| *M. longissimus lumborum* | 1.38[a] | 1.35[ab] | 1.33[bc] | 1.32[bcd] | 1.30[cd] | 1.29[d] | 0.014 |
| *M. longissimus thoracis* | 1.39[a] | 1.37[ab] | 1.35[bc] | 1.34[bcd] | 1.31[d] | 1.32[cd] | 0.014 |
| *M. pectoralis profundus* | 1.36[a] | 1.29[ab] | 1.20[bc] | 1.12[cd] | 1.06[d] | 1.02[d] | 0.035 |
| *M. psoas major* | 1.35[a] | 1.23[b] | 1.09[c] | 0.98[d] | 0.94[d] | 0.90[d] | 0.031 |
| *M. rectus femoris* | 1.42[a] | 1.36[ab] | 1.29[bc] | 1.22[cd] | 1.17[de] | 1.12[e] | 0.026 |
| *M. semimembranosus* | 1.37[a] | 1.33[ab] | 1.27[bc] | 1.23[cd] | 1.20[de] | 1.16[e] | 0.022 |
| *M. semitendinosus* | 1.41[a] | 1.37[b] | 1.33[c] | 1.30[cd] | 1.27[de] | 1.26[e] | 0.014 |
| *M. serratus ventralis* | 1.37[a] | 1.24[b] | 1.13[c] | 1.10[cd] | 1.07[d] | 1.06[d] | 0.019 |
| *M. supraspinatus* | 1.37[a] | 1.23[b] | 1.11[c] | 1.03[d] | 1.01[d] | 0.99[d] | 0.023 |
| *M. tensor fasciae latae* | 1.36[a] | 1.32[a] | 1.29[b] | 1.26[bc] | 1.24[c] | 1.23[c] | 0.012 |
| *M. trapezius* | 1.35[a] | 1.31[a] | 1.24[b] | 1.19[bc] | 1.16[cd] | 1.12[d] | 0.018 |
| *M. triceps brachii* – long head | 1.41[a] | 1.31[b] | 1.16[c] | 1.10[cd] | 1.06[d] | 1.03[d] | 0.031 |
| *M. triceps brachii* – lateral head | 1.36[a] | 1.28[b] | 1.16[c] | 1.12[cd] | 1.07[de] | 1.05[e] | 0.022 |
| *M. vastus lateralis* | 1.40[a] | 1.35[a] | 1.25[b] | 1.22[bc] | 1.18[bc] | 1.17[c] | 0.029 |

[a-e]Means within each row lacking a common superscript differ ($P < 0.05$).
*SEM is the standard error of the least squares means.

*infraspinatus*, *M. supraspinatus*, *M. adductor*, and *M. triceps brachi* - long head showed the most severe decreases, and had the lowest $(K/S)_{572}/(K/S)_{525}$ ratios on day 5, indicating that those muscles contained the most metmyoglobin on steak surfaces. Steaks from *M. longissimus lumborum* and *M. longissimus thoracis* showed very small decreases in $(K/S)_{572}/(K/S)_{525}$ ratios over the retail display period and consequently accumulated very little metmyoglobin. Other muscles that showed more moderate decreases in $(K/S)_{572}/(K/S)_{525}$ ratios, hence moderate metmyoglobin accumulation, included *M. tensor fasciae latae*, *M. semitendinosus*, *M. semimembranosus*, *M. latissimus dorsi*, *M. gluteus medius*, and *M. vastus lateralis*.

Stewart, Zisper, and Watts (1965b) established a linear relationship between $(K/S)_{572}/(K/S)_{525}$ and percentage metmyoglobin. They reported that $(K/S)_{572}/(K/S)_{525}$ values equal to 1.40 and 1.30 equated to approximately 0% and 13% metmyoglobin, respectively. Additionally, they reported that $(K/S)_{572}/(K/S)_{525}$ values equal to 1.20, 1.10, 1.00, and 0.90 corresponded to approximately 21%, 33%, 46%, and 59% metmyoglobin, respectively.

Consumers begin discriminating against steaks when approximately 20% metmyoglobin is present (Renerre & Labas, 1987). Other researchers have reported that detectable changes in beef color occur after the $(K/S)_{572}/(K/S)_{525}$ value has decreased by 0.16 units or about 20% metmyoglobin (O'Keefe & Hood, 1982). Based on the linear relationship established by Stewart et al. (1965b) and the standardized unit change in $(K/S)_{572}/(K/S)_{525}$ value, consumer discrimination against steaks would occur at $(K/S)_{572}/(K/S)_{525}$ values between 1.20 and 1.24, depending on what the initial

$(K/S)_{572}/(K/S)_{525}$ value is. Using a conservative estimate of a $(K/S)_{572}/(K/S)_{525}$ value of 1.20 being equivalent to significant discoloration, seven of the 19 muscles investigated (*M. adductor*, *M. infraspinatus*, *M. psoas major*, *M. serratus ventralis*, *M. supraspinatus*, *M. triceps brachi* - long head, *M. triceps brachi* - lateral head) had $(K/S)_{572}/(K/S)_{525}$ values less than 1.20 on day 2. Of those muscles, steaks from *M. infraspinatus*, *M. psoas major*, *M. serratus ventralis*, and *M. supraspinatus* had the lowest $(K/S)_{572}/(K/S)_{525}$ values and showed values that were close to being considered discolored on day 1. *M. biceps femoris*, *M. gluteus medius*, *M. latissimus dorsi*, *M. pectoralis profundus*, and *M. trapezius* had $(K/S)_{572}/(K/S)_{525}$ values below 1.20 on day 3 of retail display, while $(K/S)_{572}/(K/S)_{525}$ values for *M. rectus femoris* and *M. vastus lateralis* dropped below 1.20 on day 4. *M. semimembranosus* $(K/S)_{572}/(K/S)_{525}$ values fell below 1.20 on day 5 of retail display, while $(K/S)_{572}/(K/S)_{525}$ values for *M. longissimus lumborum*, *M. longissimus thoracis*, *M. semitendinosus*, and *M. tensor fasciae latae* exceeded the 1.20 threshold value over the duration of retail display in this study.

Mean $(K/S)_{572}/(K/S)_{525}$ values for each muscle across all display days are presented in Table 3. When $(K/S)_{572}/(K/S)_{525}$ values for muscles are stratified from highest to lowest it appears that the 19 muscles could be segmented in 5 color stability groups. *M. longissimus lumborum*, *M. longissimus thoracis*, *M. semitendinosus*, and *M. tensor fasciae latae* had the highest $(K/S)_{572}/(K/S)_{525}$ values indicating very little accumulation of metmyoglobin and can be classified as having a “high” color stability. *M. semimembranosus*, *M. rectus femoris*, and *M. vastus lateralis* had slightly lower

Table 3
Least squares means for objective color measurements of 19 beef muscles

| Muscle | $\frac{(K/S)_{572}}{(K/S)_{525}}$ | $\frac{(K/S)_{610}}{(K/S)_{525}}$ | L* | a* | b* |
|---|---|---|---|---|---|
| *M. adductor* | $1.17^{f}$ | $0.28^{fgh}$ | $45.06^{de}$ | $24.27^{cde}$ | $19.43^{cd}$ |
| *M. biceps femoris* | $1.18^{ef}$ | $0.28^{fg}$ | $44.02^{gh}$ | $23.97^{de}$ | $18.19^{f}$ |
| *M. gluteus medius* | $1.22^{d}$ | $0.28^{fgh}$ | $43.17^{ji}$ | $24.45^{cde}$ | $17.97^{fg}$ |
| *M. infraspinatus* | $1.10^{gh}$ | $0.32^{ab}$ | $44.87^{ef}$ | $21.14^{hi}$ | $17.35^{gh}$ |
| *M. latissimus dorsi* | $1.21^{de}$ | $0.32^{bc}$ | $46.84^{c}$ | $21.77^{gh}$ | $15.22^{j}$ |
| *M. longissimus lumborum* | $1.33^{a}$ | $0.24^{kl}$ | $42.20^{kl}$ | $27.13^{a}$ | $19.48^{bcd}$ |
| *M. longissimus thoracis* | $1.35^{a}$ | $0.24^{lm}$ | $41.87^{kl}$ | $27.24^{a}$ | $19.62^{bcd}$ |
| *M. pectoralis profundus* | $1.18^{f}$ | $0.29^{ef}$ | $44.98^{ef}$ | $23.41^{ef}$ | $18.08^{f}$ |
| *M. psoas major* | $1.08^{h}$ | $0.34^{a}$ | $45.81^{d}$ | $20.53^{i}$ | $16.87^{h}$ |
| *M. rectus femoris* | $1.26^{b}$ | $0.25^{jkl}$ | $44.24^{fg}$ | $25.76^{b}$ | $19.98^{bc}$ |
| *M. semimembranosus* | $1.26^{bc}$ | $0.24^{lm}$ | $43.17^{ji}$ | $26.93^{a}$ | $20.19^{b}$ |
| *M. semitendinosus* | $1.32^{a}$ | $0.22^{m}$ | $49.17^{a}$ | $27.62^{a}$ | $21.18^{a}$ |
| *M. serratus ventralis* | $1.16^{f}$ | $0.28^{fg}$ | $43.45^{hi}$ | $23.62^{ef}$ | $18.50^{ef}$ |
| *M. supraspinatus* | $1.12^{g}$ | $0.32^{bcd}$ | $44.07^{gh}$ | $21.62^{h}$ | $17.10^{h}$ |
| *M. tensor fasciae latae* | $1.28^{b}$ | $0.26^{hij}$ | $47.75^{b}$ | $25.10^{bc}$ | $18.10^{f}$ |
| *M. trapezius* | $1.23^{cd}$ | $0.30^{de}$ | $46.76^{c}$ | $22.72^{fg}$ | $16.12^{i}$ |
| *M. triceps brachii* – long head | $1.18^{f}$ | $0.27^{ghi}$ | $41.50^{l}$ | $24.50^{cd}$ | $19.53^{bcd}$ |
| *M. triceps brachii* – lateral head | $1.17^{f}$ | $0.30^{cde}$ | $43.50^{ghi}$ | $22.76^{fg}$ | $17.09^{h}$ |
| *M. vastus lateralis* | $1.26^{bc}$ | $0.26^{ijk}$ | $42.53^{jk}$ | $25.69^{b}$ | $19.15^{de}$ |
| SEM* | 0.012 | 0.006 | 0.280 | 0.387 | 0.256 |

[a-m]Means within the column lacking a common letter differ ($P < 0.05$).
*SEM is the standard error of the least squares means.

$(K/S)_{572}/(K/S)_{525}$ values resulting in slightly greater discoloration rates and can be classified as having "moderate" color stability. *M. trapezius*, *M. gluteus medius*, and *M. latissimus dorsi* had lower $(K/S)_{572}/(K/S)_{525}$ values indicating greater discoloration rates and were classified as having "intermediate" color stability. The remaining muscles showed relatively rapid rates of discoloration and were classified accordingly. *M. triceps brachi* - long head, *M. biceps femoris*, *M. pectoralis profundus*, *M. adductor*, *M. triceps brachi* - lateral head, and *M. serratus ventralis* were classified as "low" color stability muscles and *M. supraspinatus*, *M. infraspinatus*, and *M. psoas major* were classified as "very low" color stability muscles.

Previous data showing $(K/S)_{572}/(K/S)_{525}$ values on day of retail display indicated that categorization of muscles into color stability groups would be very similar (Table 2). The debatable area falls within the "low" color stability group where *M. biceps femoris* and *M. pectoralis profundus* show some characteristics of the "intermediate" color stability group and *M. adductor* and *M. serratus ventralis* show some characteristics of the "very low" color stability group. Hood (1980) observed an identical stratification pattern for color stability rankings of steaks from *M. longissimus lumborum*, *M. semitendinosus*, *M. semimembranosus*, *M. vastus lateralis*, *M. gluteus medius*, and *M. psoas major* as was observed in this study. Previous research has characterized *M. psoas major* as having very low color stability and *M. longissimus lumborum* or *M. longissimus thoracis* as having very high color stability (Echevarre, Renerre, & Labas, 1990; Renerre & Labas, 1987; O'Keefe & Hood, 1982; Bendall & Taylor, 1972). Results of this study indicate that the color stability of steaks from *M.*

*longissimus lumborum*, *M. longissimus thoracis*, and *M. tensor fasciae latae* were similar, but Echevarre et al. (1990) reported *M. tensor fasciae latae* color stability was intermediate compared to *M. longissimus lumborum*. The findings of Renerre and Labas (1987) support the findings of this study that *M. tensor fasciae latae* had greater color stability than *M. psoas major*. O'Keefe and Hood (1982) categorized *M. gluteus medius* as an intermediate color stability muscle, *M. semimembranosus* as a high color stability muscle, while Bendall and Taylor (1972) found that steaks from *M. biceps femoris* had relatively unstable color. The findings of this study concur with those observations, with the exception that *M. semimembranosus* was identified as a "moderate" color stable muscle.

***Oxymyoglobin content***

Oxymyoglobin content was measured using the ratio of surface reflectance at 610 nm to surface reflectance at 525 nm. Lower ratios indicate higher levels of oxymyoglobin. With the exception of the *M. gluteus medius*, *M. rectus femoris*, *M. semitendinosus*, and *M. vastus lateralis*, most muscles had some changes in oxymyoglobin content during retail display (Table 4). *M. longissimus lumborum*, *M. longissimus thoracis*, and *M. tensor fasciae latae* had high $(K/S)_{610}/(K/S)_{525}$ values on day 0, which may be related to incomplete oxygenation, but, values throughout the remainder of retail display were much lower and not different from each other. *M. adductor*, *M. biceps femoris*, *M. infraspinatus*, *M. psoas major*, and *M. supraspinatus* all

Table 4
Least squares means for $(K/S)_{610}/(K/S)_{525}$ values of steaks from 19 beef muscles over 5 days of retail display

| | Display day | | | | | | |
|---|---|---|---|---|---|---|---|
| Muscle | 0 | 1 | 2 | 3 | 4 | 5 | SEM* |
| *M. adductor* | 0.21$^{d}$ | 0.23$^{cd}$ | 0.27$^{bc}$ | 0.30$^{ab}$ | 0.31$^{a}$ | 0.33$^{a}$ | 0.014 |
| *M. biceps femoris* | 0.25$^{c}$ | 0.25$^{c}$ | 0.28$^{bc}$ | 0.29$^{ab}$ | 0.31$^{ab}$ | 0.33$^{a}$ | 0.013 |
| *M. gluteus medius* | 0.27 | 0.25 | 0.27 | 0.29 | 0.30 | 0.31 | 0.015 |
| *M. infraspinatus* | 0.28$^{c}$ | 0.29$^{c}$ | 0.32$^{b}$ | 0.34$^{ab}$ | 0.35$^{a}$ | 0.35$^{a}$ | 0.008 |
| *M. latissimus dorsi* | 0.33$^{a}$ | 0.28$^{b}$ | 0.31$^{a}$ | 0.33$^{a}$ | 0.33$^{a}$ | 0.33$^{a}$ | 0.009 |
| *M. longissimus lumborum* | 0.28$^{a}$ | 0.24$^{b}$ | 0.24$^{b}$ | 0.23$^{b}$ | 0.23$^{b}$ | 0.23$^{b}$ | 0.007 |
| *M. longissimus thoracis* | 0.28$^{a}$ | 0.24$^{b}$ | 0.23$^{bc}$ | 0.23$^{bc}$ | 0.23$^{bc}$ | 0.22$^{c}$ | 0.006 |
| *M. pectoralis profundus* | 0.27$^{c}$ | 0.25$^{bc}$ | 0.28$^{bc}$ | 0.30$^{ab}$ | 0.32$^{ab}$ | 0.33$^{a}$ | 0.016 |
| *M. psoas major* | 0.27$^{c}$ | 0.28$^{c}$ | 0.33$^{b}$ | 0.36$^{ab}$ | 0.38$^{a}$ | 0.40$^{a}$ | 0.014 |
| *M. rectus femoris* | 0.26 | 0.23 | 0.24 | 0.25 | 0.26 | 0.28 | 0.010 |
| *M. semimembranosus* | 0.23$^{bc}$ | 0.21$^{c}$ | 0.23$^{bc}$ | 0.25$^{ab}$ | 0.25$^{ab}$ | 0.26$^{a}$ | 0.010 |
| *M. semitendinosus* | 0.23 | 0.21 | 0.22 | 0.22 | 0.22 | 0.23 | 0.007 |
| *M. serratus ventralis* | 0.26$^{b}$ | 0.26$^{b}$ | 0.29$^{a}$ | 0.29$^{a}$ | 0.30$^{a}$ | 0.29$^{a}$ | 0.009 |
| *M. supraspinatus* | 0.28$^{c}$ | 0.28$^{c}$ | 0.32$^{b}$ | 0.34$^{ab}$ | 0.34$^{ab}$ | 0.35$^{a}$ | 0.010 |
| *M. tensor fasciae latae* | 0.29$^{a}$ | 0.25$^{b}$ | 0.26$^{b}$ | 0.26$^{b}$ | 0.26$^{b}$ | 0.26$^{b}$ | 0.006 |
| *M. trapezius* | 0.31$^{ab}$ | 0.27$^{c}$ | 0.29$^{bc}$ | 0.31$^{ab}$ | 0.31$^{ab}$ | 0.33$^{a}$ | 0.009 |
| *M. triceps brachii* – long head | 0.25$^{bc}$ | 0.24$^{c}$ | 0.27$^{abc}$ | 0.28$^{ab}$ | 0.29$^{a}$ | 0.30$^{a}$ | 0.013 |
| *M. triceps brachii* – lateral head | 0.28$^{bc}$ | 0.27$^{c}$ | 0.31$^{ab}$ | 0.31$^{ab}$ | 0.32$^{ab}$ | 0.33$^{a}$ | 0.013 |
| *M. vastus lateralis* | 0.26 | 0.23 | 0.26 | 0.26 | 0.27 | 0.27 | 0.011 |

[a-d]Means within each row lacking a common superscript differ ($P < 0.05$).
*SEM is the standard error of the least squares means.

showed substantial increases in $(K/S)_{610}/(K/S)_{525}$ values with increasing days of retail display, indicating a loss of oxymyoglobin over the course of retail display. Other muscles, such as *M. latissimus dorsi*, *M. pectoralis profundus*, *M. semimembranosus*, *M. serratus ventralis*, *M. triceps brachi* - long head, *M. triceps brachi* - lateral head, and *M. trapezius*, showed only moderate increases in $(K/S)_{610}/(K/S)_{525}$ values over the retail display period.

Stratification of muscles by $(K/S)_{610}/(K/S)_{525}$ values showed a similar pattern as was observed for $(K/S)_{572}/(K/S)_{525}$ values (Table 3). Separations for grouping muscles were not as defined as they were with $(K/S)_{572}/(K/S)_{525}$ values, however, *M. longissimus thoracis*, *M. longissimus lumborum*, and *M. semitendinosus* had the lowest values indicative of the highest oxymyoglobin content. In contrast, *M. psoas major*, *M. infraspinatus*, and *M. supraspinatus* had the highest $(K/S)_{610}/(K/S)_{525}$ values indicating the lowest amount of oxymyoglobin. Previous research has not reported $(K/S)_{610}/(K/S)_{525}$ values for steaks, probably because it is not as direct a measure of discoloration as $(K/S)_{572}/(K/S)_{525}$ values and because changes are not as substantial as those observed in $(K/S)_{572}/(K/S)_{525}$ values.

Correlation data (Table 5) also showed a strong relationship between $(K/S)_{572}/(K/S)_{525}$ and $(K/S)_{610}/(K/S)_{525}$ ($r = -0.82$, $P < 0.001$). Clearly, the relationship between $(K/S)_{572}/(K/S)_{525}$ and $(K/S)_{610}/(K/S)_{525}$ fits most muscles, however, slight anomalies were noted for *M. serratus ventralis* and *M. trapezius*. In the case of *M. serratus ventralis*, increases in $(K/S)_{610}/(K/S)_{525}$ were not as large as what would have been expected looking at $(K/S)_{572}/(K/S)_{525}$ data. Likewise, *M. trapezius* showed

Table 5
Correlation coefficients of biochemical, physical, and objective color measurements for all muscles

| | MRA | RIMF | NORA | OCR | OPD | MetMb | OxMb | L* | a* | b* | Myogl. | TBA |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| RIMF | -0.32*** | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- |
| NORA | 0.30*** | -0.57*** | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- |
| OCR | 0.35*** | -0.55*** | 0.35*** | -- | -- | -- | -- | -- | -- | -- | -- | -- |
| OPD | -0.55*** | 0.31*** | -0.30*** | -0.53*** | -- | -- | -- | -- | -- | -- | -- | -- |
| MetMb | 0.23*** | -0.67*** | 0.61*** | 0.42*** | -0.12*** | -- | -- | -- | -- | -- | -- | -- |
| OxMb | -0.10** | 0.38*** | -0.44*** | -0.14*** | -0.08** | -0.82*** | -- | -- | -- | -- | -- | -- |
| L* | -0.24*** | -0.11*** | 0.08* | 0.04 | 0.15*** | 0.16*** | -0.06 | -- | -- | -- | -- | -- |
| a* | 0.15*** | -0.50*** | 0.50*** | 0.28*** | 0.01 | 0.90*** | -0.97*** | 0.06 | -- | -- | -- | -- |
| b* | -0.11*** | -0.13*** | 0.16*** | 0.00 | 0.23*** | 0.47*** | -0.82*** | 0.06 | 0.76*** | -- | -- | -- |
| Myogl. | 0.40*** | -0.03 | -0.05 | 0.20*** | -0.25*** | -0.06* | 0.07* | -0.43*** | -0.03 | -0.12*** | -- | -- |
| TBA | -0.25*** | 0.40*** | -0.32*** | -0.39*** | 0.42*** | -0.30*** | 0.08* | -0.02 | -0.18*** | 0.05 | -0.12*** | -- |
| pH | 0.32*** | -0.03 | 0.05 | -0.03 | -0.17*** | -0.02 | 0.05 | -0.11*** | -0.06 | -0.12*** | 0.02 | -0.03 |

MRA = metmyoglobin reductase activity; RIMF = resistance to induced metmyoglobin formation; NORA = nitric oxide metmyoglobin reducing ability; OCR = oxygen consumption rate; OPD = oxygen penetration depth; MetMb = (K/S)572/(K/S)525; OxMb = (K/S)610/(K/S)525; Myogl. = myoglobin content; TBA = 2-thiobarbituric acid reactive substances.

*$P < 0.05$.

**$P < 0.01$.

***$P < 0.001$.

moderate decreases in $(K/S)_{572}/(K/S)_{525}$ values over retail display, but virtually no changes in $(K/S)_{610}/(K/S)_{525}$ values and high $(K/S)_{610}/(K/S)_{525}$ values. We expect some of the differences observed in *M. trapezius* are related to how it was cut into "steaks" and presented in the retail display case.

***L*-values***

Generally, changes in L*-values over retail display were very subtle (Table 6). Steaks from *M. biceps femoris*, *M. psoas major*, *M. rectus femoris*, and *M. triceps brachi - long head*, showed decreases in L*-values after day 1 of retail display, with no subsequent changes thereafter. In contrast, steaks from *M. adductor*, *M. infraspinatus*, *M. pectoralis profundus*, and *M. vastus lateralis* showed more incremental decreases in L*-values with increasing days of retail display.

Mean L*-values for muscles over all days of retail display showed that *M. semitendinosus* and *M. tensor fasciae latae* had the highest L* values, whereas *M. longissimus lumborum*, *M. longissimus thoracis*, and *M. triceps brachi - long head* had the lowest L*-values (Table 3). Lightness (i.e., L*-value) appears to play a minimal role in color stability as *M. semitendinosus*, *M. tensor fasciae latae*, *M. longissimus lumborum*, and *M. longissimus thoracis* were all previously classified as "high" color stability muscles, yet they occupy opposing ends of the spectrum of L*-values found in the muscles investigated. Additionally, correlations coefficients (Table 5) between L*-value and $(K/S)_{572}/(K/S)_{525}$ ($r = 0.16$, $P < 0.001$) and L*-value and $(K/S)_{610}/(K/S)_{525}$ ($r = 0.06$, $P > 0.05$) were low and not significant.

Table 6
Least squares means for L*-values of steaks from 19 beef muscles over 5 days of retail display

| | Display day | | | | | | |
|---|---|---|---|---|---|---|---|
| Muscle | 0 | 1 | 2 | 3 | 4 | 5 | SEM* |
| *M. adductor* | 46.35[a] | 46.09[ab] | 44.60[c] | 44.42[c] | 44.07[c] | 44.85[bc] | 0.473 |
| *M. biceps femoris* | 45.20[a] | 45.18[a] | 43.51[b] | 43.07[b] | 43.46[b] | 43.67[b] | 0.491 |
| *M. gluteus medius* | 43.71 | 43.69 | 42.92 | 42.70 | 42.81 | 43.17 | 0.444 |
| *M. infraspinatus* | 45.83[a] | 46.02[a] | 45.11[ab] | 44.22[bc] | 44.42[bc] | 43.63[c] | 0.318 |
| *M. latissimus dorsi* | 48.32 | 47.01 | 46.73 | 46.44 | 46.45 | 46.11 | 0.504 |
| *M. longissimus lumborum* | 42.50[ab] | 43.39[a] | 42.24[bc] | 41.45[c] | 41.83[bc] | 41.80[bc] | 0.351 |
| *M. longissimus thoracis* | 41.50[b] | 42.99[a] | 41.82[b] | 41.35[b] | 41.99[b] | 41.57[b] | 0.303 |
| *M. pectoralis profundus* | 46.05[a] | 46.03[a] | 44.91[ab] | 44.34[b] | 44.15[b] | 44.42[b] | 0.466 |
| *M. psoas major* | 47.33[a] | 46.74[a] | 45.54[b] | 44.79[b] | 45.21[b] | 45.25[b] | 0.407 |
| *M. rectus femoris* | 45.58[a] | 45.16[a] | 44.12[b] | 43.69[b] | 43.52[b] | 43.36[b] | 0.352 |
| *M. semimembranosus* | 43.08 | 43.38 | 43.36 | 43.35 | 42.78 | 43.08 | 0.382 |
| *M. semitendinosus* | 48.90[b] | 49.86[a] | 49.37[ab] | 48.78[b] | 48.69[b] | 49.39[ab] | 0.250 |
| *M. serratus ventralis* | 43.88 | 44.37 | 43.61 | 42.66 | 43.20 | 42.95 | 0.457 |
| *M. supraspinatus* | 44.92[a] | 44.71[a] | 44.03[ab] | 43.18[b] | 43.52[b] | 44.03[ab] | 0.311 |
| *M. tensor fasciae latae* | 47.58 | 48.35 | 47.50 | 47.50 | 47.44 | 48.12 | 0.416 |
| *M. trapezius* | 47.69[a] | 47.93[a] | 47.01[ab] | 46.42[bc] | 45.67[c] | 45.86[c] | 0.398 |
| *M. triceps brachii* – long head | 42.79[a] | 42.94[a] | 41.10[b] | 40.63[b] | 40.86[b] | 40.68[b] | 0.364 |
| *M. triceps brachii* – lateral head | 43.89 | 44.17 | 44.00 | 42.87 | 42.91 | 43.14 | 0.389 |
| *M. vastus lateralis* | 43.38[a] | 43.09[ab] | 42.49[abc] | 41.99[c] | 42.00[c] | 42.22[bc] | 0.402 |

[a-c]Means within each row lacking a common superscript differ ($P < 0.05$).
*SEM is the standard error of the least squares means.

***a*-values***

Many differences in a*-values were observed both between muscles and over the retail display period (Table 7). In a number of cases, an increase in a*-values was observed within muscles from day 0 to day 1. This was unexpected since steaks were allowed to oxygenate for at least 2 hours on day 0 before objective color measurements were taken. Ledward (1992) noted that muscle typically oxygenates very rapidly upon exposure to oxygen, however, muscle that is less than 96 hrs postmortem has a relatively high oxygen consumption rate that can inhibit steaks from fully oxygenating. Hood (1980) reported a similar phenomenon in fresh meat compared to meat aged for several days. Steaks from *M. longissimus lumborum*, *M. longissimus thoracis*, *M. semitendinosus*, and *M. tensor fasciae latae* showed no changes in a*-values over the course of retail display. In contrast, *M. adductor* and *M. psoas major* showed nearly a 10 unit decrease in a*-value from day 0 to day 5. Interesting trends in a*-values were observed in *M. serratus ventralis* and *M. vastus lateralis*, with initial decreases in a*-values occurring early in retail display with no subsequent decreases for the remainder of retail display. $(K/S)_{610}/(K/S)_{525}$ values for *M. serratus ventralis* appear to mirror changes associated with a*-values, while $(K/S)_{572}/(K/S)_{525}$ values indicate that steaks from *M. serratus ventralis* would have accumulated enough metmyoglobin by day 2 of retail display to be considered discolored. In contrast, the observed changes in a*-values for *M. vastus lateralis* do not match changes in $(K/S)_{610}/(K/S)_{525}$ values or $(K/S)_{572}/(K/S)_{525}$ values. It is unclear why this is the case and what consumer perceptions of these color changes would be.

Table 7
Least squares means for a*-values of steaks from 19 beef muscles over 5 days of retail display

| | Display day | | | | | | |
|---|---|---|---|---|---|---|---|
| Muscle | 0 | 1 | 2 | 3 | 4 | 5 | SEM* |
| *M. adductor* | 30.04[a] | 27.26[b] | 24.49[c] | 22.40[cd] | 21.30[d] | 20.11[d] | 0.858 |
| *M. biceps femoris* | 27.71[a] | 26.80[a] | 24.44[b] | 22.80[bc] | 21.53[cd] | 20.56[d] | 0.781 |
| *M. gluteus medius* | 26.69[a] | 26.99[a] | 24.80[ab] | 23.61[b] | 22.48[b] | 22.10[b] | 0.979 |
| *M. infraspinatus* | 25.80[a] | 23.36[b] | 20.76[c] | 19.56[cd] | 18.72[d] | 18.65[d] | 0.441 |
| *M. latissimus dorsi* | 22.37[b] | 24.44[a] | 22.12[bc] | 20.83[bcd] | 20.64[cd] | 20.23[d] | 0.577 |
| *M. longissimus lumborum* | 25.77 | 27.89 | 27.47 | 27.63 | 27.26 | 27.36 | 0.462 |
| *M. longissimus thoracis* | 25.68[b] | 27.50[a] | 27.49[a] | 27.72[a] | 27.32[a] | 27.74[a] | 0.391 |
| *M. pectoralis profundus* | 26.19[a] | 26.52[a] | 24.12[ab] | 22.33[bc] | 21.11[c] | 20.18[c] | 0.978 |
| *M. psoas major* | 26.30[a] | 23.98[b] | 20.63[c] | 18.45[cd] | 17.28[d] | 16.53[d] | 0.762 |
| *M. rectus femoris* | 26.79[ab] | 27.79[a] | 26.48[abc] | 25.24[bcd] | 24.74[cd] | 23.55[d] | 0.710 |
| *M. semimembranosus* | 28.87[ab] | 29.37[a] | 27.32[bc] | 25.77[cd] | 25.61[cd] | 24.64[d] | 0.670 |
| *M. semitendinosus* | 28.08 | 28.83 | 27.78 | 27.30 | 27.03 | 26.71 | 0.504 |
| *M. serratus ventralis* | 27.11[a] | 25.20[b] | 22.73[c] | 22.55[c] | 22.00[c] | 22.11[c] | 0.573 |
| *M. supraspinatus* | 25.96[a] | 24.04[b] | 21.47[c] | 19.81[cd] | 19.56[d] | 18.86[d] | 0.598 |
| *M. tensor fasciae latae* | 24.65 | 26.07 | 25.34 | 24.87 | 24.84 | 24.83 | 0.417 |
| *M. trapezius* | 23.96[ab] | 24.84[a] | 23.38[bc] | 22.03[cd] | 21.51[de] | 20.60[e] | 0.482 |
| *M. triceps brachii* – long head | 27.93[a] | 27.14[a] | 24.51[b] | 23.25[bc] | 22.46[bc] | 21.69[c] | 0.846 |
| *M. triceps brachii* – lateral head | 25.75[a] | 25.44[a] | 22.39[b] | 21.76[bc] | 20.96[bc] | 20.28[c] | 0.717 |
| *M. vastus lateralis* | 27.18[ab] | 27.86[a] | 25.68[abc] | 25.08[bc] | 24.29[c] | 24.05[c] | 0.772 |

[a-e]Means within each row lacking a common superscript differ ($P < 0.05$).
*SEM is the standard error of the least squares means.

Stratification of muscles based upon a*-values closely mimics stratification of muscles based upon $(K/S)_{610}/(K/S)_{525}$ values with *M. semitendinosus*, *M. longissimus lumborum*, *M. longissimus thoracis*, and *M. semimembranosus* having the highest a*-values and *M. psoas major*, *M. infraspinatus*, *M. supraspinatus*, and *M. latissimus dorsi* having the lowest values (Table 3). Perhaps this is not completely unexpected as oxymyoglobin is characterized by a bright red color and a*-values measure the redness of a muscle. Correlation data (Table 5) showed a very strong relationship between these two measures ($r = -0.97$, $P < 0.001$).

***b*-values***

Few differences were noted in b*-values (Table 8). Of those observed, most appeared to be related to relatively low b*-values on day 0, with subsequent increases observed on day 1 and very subtle changes thereafter. The notable exception to this was *M. adductor*, which had a decrease of approximately 3.5 b*-units over the entire display period.

The relationship between color stability and b*-values was not very clear (Table 3). Most of the high color stability muscles, such as *M. semitendinosus*, *M. longissimus lumborum*, and *M. longissimus thoracis*, had b*-values that were somewhat high, whereas steaks from *M. tensor fasciae latae* had low b*-values. Most lower color stability muscles had b*-values that occupied the bottom half of all muscles investigated, although, *M. triceps brachi* - long head and *M. adductor* both had relatively high b*-values.

Table 8
Least squares means for b*-values of steaks from 19 beef muscles over 5 days of retail display

| | Display day | | | | | | |
|---|---|---|---|---|---|---|---|
| Muscle | 0 | 1 | 2 | 3 | 4 | 5 | SEM* |
| *M. adductor* | 21.54[a] | 20.39[ab] | 19.47[bc] | 18.62[cd] | 18.64[cd] | 17.92[d] | 0.513 |
| *M. biceps femoris* | 18.75 | 19.20 | 18.18 | 17.92 | 17.58 | 17.49 | 0.445 |
| *M. gluteus medius* | 17.78 | 18.99 | 17.92 | 17.89 | 17.64 | 17.60 | 0.593 |
| *M. infraspinatus* | 17.66[ab] | 18.33[a] | 17.16[b] | 17.11[b] | 16.87[b] | 16.97[b] | 0.296 |
| *M. latissimus dorsi* | 13.86[c] | 16.80[a] | 15.37[b] | 14.85[b] | 15.28[b] | 15.14[b] | 0.327 |
| *M. longissimus lumborum* | 17.06[b] | 19.23[a] | 19.68[a] | 20.34[a] | 20.23[a] | 20.37[a] | 0.420 |
| *M. longissimus thoracis* | 16.91[c] | 19.50[b] | 19.87[ab] | 20.39[ab] | 20.36[ab] | 20.72[a] | 0.397 |
| *M. pectoralis profundus* | 17.25 | 19.36 | 18.31 | 17.93 | 18.84 | 17.76 | 0.600 |
| *M. psoas major* | 17.67[a] | 17.68[a] | 16.63[b] | 16.53[b] | 16.36[b] | 16.35[b] | 0.312 |
| *M. rectus femoris* | 18.22[b] | 20.63[a] | 20.45[a] | 20.21[a] | 20.34[a] | 20.01[a] | 0.430 |
| *M. semimembranosus* | 20.26 | 21.49 | 20.11 | 19.53 | 20.20 | 19.56 | 0.491 |
| *M. semitendinosus* | 20.07 | 21.64 | 21.25 | 21.38 | 21.56 | 21.19 | 0.372 |
| *M. serratus ventralis* | 18.64 | 19.04 | 17.85 | 18.49 | 18.36 | 18.63 | 0.428 |
| *M. supraspinatus* | 17.24 | 18.01 | 17.09 | 16.75 | 17.02 | 16.49 | 0.370 |
| *M. tensor fasciae latae* | 16.00[b] | 18.60[a] | 18.33[a] | 18.33[a] | 18.65[a] | 18.67[a] | 0.336 |
| *M. trapezius* | 14.83[d] | 17.55[a] | 16.71[ab] | 16.04[bc] | 16.16[bc] | 15.44[cd] | 0.354 |
| *M. triceps brachii* – long head | 19.33 | 20.22 | 19.47 | 19.50 | 19.52 | 19.16 | 0.555 |
| *M. triceps brachii* – lateral head | 16.88 | 18.38 | 16.63 | 17.02 | 17.02 | 16.62 | 0.458 |
| *M. vastus lateralis* | 18.20 | 20.05 | 18.94 | 19.30 | 19.17 | 19.22 | 0.495 |

[a-d]Means within each row lacking a common superscript differ ($P < 0.05$).
*SEM is the standard error of the least squares means.

***Metmyoglobin reductase activity***

Metmyoglobin reductase activity reacted consistently within most muscles (Table 9). Generally, all muscles maintained their initial levels of metmyoglobin reductase activity through day 3 of retail display, before activity levels decreased. Lanari and Cassens (1991) reported no decrease in MRA over time. Others (Bekhit, Geesink, Morton, & Bickerstaffe, 2001) reported that MRA is stable during postmortem storage and is not the principal determinant of color stability. It was expected that different rates of MRA loss would show up between different muscles. Sammel et al. (2002) hypothesized that MRA can only be used to differentiate reducing differences between muscles and not within a muscle across display time because the rate limiting factor for the reaction (NADH) is present in excess. Findings from this study support their hypothesis.

Differences in metmyoglobin reductase activity were observed between muscles (Table 10). *M. infraspinatus*, *M. supraspinatus*, and *M. serratus ventralis* were determined to have the highest MRA values while *M. semitendinosus* and *M. rectus femoris* were found to have the lowest MRA values. Generally, muscles with low color stability had the highest MRA, whereas more color stable muscles, such as *M. semitendinosus*, *M. semimembranosus*, *M. rectus femoris*, and *M. tensor fasciae latae* had lower MRA. There were exceptions to this as *M. longissimus lumborum*, a color stable muscle, had a relatively high MRA, whereas *M. psoas major*, a low color stability muscle, had a low MRA. Reddy and Carpenter (1991) reported that

Table 9
Least squares means for metmyoglobin reductase activity (nmoles/min·g) of steaks from 19 beef muscles over 5 days of retail display

| | Display day | | | | | | |
|---|---|---|---|---|---|---|---|
| Muscle | 0 | 1 | 2 | 3 | 4 | 5 | SEM* |
| *M. adductor* | 242.8$^{a}$ | 234.4$^{a}$ | 252.5$^{a}$ | 233.5$^{a}$ | 188.4$^{b}$ | 175.2$^{b}$ | 13.76 |
| *M. biceps femoris* | 241.7$^{a}$ | 252.4$^{a}$ | 234.9$^{a}$ | 230.9$^{ab}$ | 195.8$^{bc}$ | 180.1$^{c}$ | 12.49 |
| *M. gluteus medius* | 239.4$^{ab}$ | 242.5$^{ab}$ | 247.7$^{a}$ | 240.2$^{ab}$ | 206.3$^{bc}$ | 182.9$^{c}$ | 12.78 |
| *M. infraspinatus* | 292.7$^{a}$ | 275.2$^{a}$ | 297.0$^{a}$ | 266.5$^{a}$ | 211.3$^{b}$ | 199.1$^{b}$ | 14.98 |
| *M. latissimus dorsi* | 241.1$^{a}$ | 245.7$^{a}$ | 228.7$^{a}$ | 225.6$^{a}$ | 162.0$^{b}$ | 173.6$^{b}$ | 12.38 |
| *M. longissimus lumborum* | 257.8$^{a}$ | 242.6$^{a}$ | 241.1$^{a}$ | 234.8$^{a}$ | 197.5$^{b}$ | 189.3$^{b}$ | 11.84 |
| *M. longissimus thoracis* | 239.3$^{a}$ | 246.1$^{a}$ | 233.0$^{a}$ | 228.8$^{a}$ | 190.9$^{b}$ | 179.1$^{b}$ | 11.62 |
| *M. pectoralis profundus* | 248.2$^{a}$ | 227.3$^{a}$ | 219.0$^{a}$ | 218.9$^{a}$ | 163.2$^{b}$ | 170.1$^{b}$ | 11.61 |
| *M. psoas major* | 238.2$^{a}$ | 237.0$^{a}$ | 223.5$^{a}$ | 228.1$^{a}$ | 178.5$^{b}$ | 160.8$^{b}$ | 12.46 |
| *M. rectus femoris* | 207.7$^{a}$ | 217.5$^{a}$ | 211.6$^{a}$ | 201.7$^{a}$ | 142.3$^{b}$ | 141.1$^{b}$ | 14.35 |
| *M. semimembranosus* | 225.8$^{a}$ | 228.2$^{a}$ | 212.3$^{a}$ | 212.0$^{a}$ | 168.0$^{b}$ | 167.1$^{b}$ | 12.53 |
| *M. semitendinosus* | 201.2$^{a}$ | 196.4$^{a}$ | 199.6$^{a}$ | 196.9$^{a}$ | 140.7$^{b}$ | 154.0$^{b}$ | 12.88 |
| *M. serratus ventralis* | 283.2$^{a}$ | 254.0$^{ab}$ | 290.4$^{a}$ | 275.3$^{a}$ | 192.9$^{c}$ | 220.0$^{bc}$ | 18.40 |
| *M. supraspinatus* | 271.4$^{a}$ | 273.9$^{a}$ | 248.7$^{ab}$ | 268.2$^{a}$ | 189.8$^{c}$ | 204.1$^{bc}$ | 17.30 |
| *M. tensor fasciae latae* | 244.2$^{a}$ | 225.5$^{a}$ | 224.7$^{a}$ | 212.5$^{a}$ | 167.7$^{b}$ | 158.0$^{b}$ | 11.13 |
| *M. trapezius* | 255.4$^{a}$ | 252.3$^{a}$ | 247.1$^{a}$ | 233.5$^{a}$ | 163.7$^{b}$ | 178.5$^{b}$ | 14.32 |
| *M. triceps brachii* – long head | 243.3$^{a}$ | 222.2$^{ab}$ | 261.9$^{a}$ | 235.3$^{a}$ | 181.1$^{b}$ | 176.4$^{b}$ | 16.31 |
| *M. triceps brachii* – lateral head | 245.4$^{a}$ | 245.6$^{a}$ | 238.3$^{a}$ | 226.3$^{a}$ | 175.5$^{b}$ | 178.5$^{b}$ | 11.99 |
| *M. vastus lateralis* | 249.7$^{a}$ | 220.9$^{a}$ | 230.9$^{a}$ | 208.3$^{ab}$ | 167.4$^{bc}$ | 162.0$^{c}$ | 14.57 |

$^{a\text{-}c}$Means within a row lacking a common letter differ ($P < 0.05$).
*SEM is the standard error of the least squares means.

Table 10
Least squares means for metmyoglobin reductase activity (MRA), resistance to induced metmyoglobin formation (RIMF), and nitric oxide metmyoglobin reducing ability (NORA) for 19 beef muscles

| Muscle | MRA (nmoles/min·g) | RIMF (% metmyoglobin) | NORA (Δ % metmyoglobin) |
|---|---|---|---|
| *M. adductor* | 221.1$^{bcde}$ | 75.3$^{a}$ | 29.1$^{g}$ |
| *M. biceps femoris* | 222.6$^{bc}$ | 71.3$^{abc}$ | 46.4$^{bcde}$ |
| *M. gluteus medius* | 226.5$^{b}$ | 65.0$^{bcde}$ | 45.1$^{bcdef}$ |
| *M. infraspinatus* | 256.9$^{a}$ | 73.5$^{ab}$ | 41.2$^{f}$ |
| *M. latissimus dorsi* | 212.8$^{bcdefg}$ | 61.0$^{de}$ | 47.2$^{bcd}$ |
| *M. longissimus lumborum* | 227.2$^{b}$ | 42.7$^{h}$ | 58.0$^{a}$ |
| *M. longissimus thoracis* | 219.5$^{bcdef}$ | 42.7$^{h}$ | 59.6$^{a}$ |
| *M. pectoralis profundus* | 207.8$^{defg}$ | 67.8$^{abcd}$ | 44.5$^{cdef}$ |
| *M. psoas major* | 210.8$^{cdefg}$ | 76.0$^{a}$ | 29.4$^{g}$ |
| *M. rectus femoris* | 187.0$^{h}$ | 57.0$^{efg}$ | 43.1$^{def}$ |
| *M. semimembranosus* | 202.2$^{g}$ | 60.6$^{def}$ | 41.7$^{ef}$ |
| *M. semitendinosus* | 181.5$^{h}$ | 48.6$^{gh}$ | 59.9$^{a}$ |
| *M. serratus ventralis* | 252.4$^{a}$ | 65.0$^{bcde}$ | 40.9$^{f}$ |
| *M. supraspinatus* | 243.2$^{a}$ | 67.9$^{abcd}$ | 46.9$^{bcd}$ |
| *M. tensor fasciae latae* | 205.4$^{fg}$ | 52.0$^{fg}$ | 58.0$^{a}$ |
| *M. trapezius* | 221.7$^{bcd}$ | 57.4$^{ef}$ | 48.2$^{bc}$ |
| *M. triceps brachii* – long head | 220.0$^{bcdef}$ | 69.2$^{abcd}$ | 47.1$^{bcd}$ |
| *M. triceps brachii* – lateral head | 218.3$^{bcdef}$ | 70.2$^{abc}$ | 47.0$^{bcd}$ |
| *M. vastus lateralis* | 206.5$^{efg}$ | 64.5$^{cde}$ | 49.5$^{b}$ |
| SEM* | 5.32 | 3.15 | 1.79 |

[a-h]Means within the column lacking a common letter differ ($P < 0.05$).
*SEM is the standard error of the least squares means.

metmyoglobin reductase activity for five muscles was *M. tensor fasciae latae* > *M. longissimus lumborum* > *M. gluteus medius* > *M. semimembranosus* = *M. psoas major*. Lanari and Cassens (1991) found *M. gluteus medius* had greater MRA than *M. longissimus lumborum*, and *M. gluteus medius* was less color stable. As was found in this study, Renerre and Labas (1987) noted no differences in metmyoglobin reductase activity between *M. psoas major* and *M. tensor fasciae latae* even though *M. psoas major* had much greater discoloration during retail display.

Initial investigations into metmyoglobin reductase activity theorized that more color stable muscles would have greater reductase activities, hence their ability to maintain a greater percentage of oxymyoglobin for a greater period of time. However, results from various studies have yielded conflicting results. Echevarre et al. (1990) reported that metmyoglobin reductase activity was highest in the least color stable muscles. Their findings were similar to what was observed in this study. Furthermore, Atkinson and Follett (1973) found that metmyoglobin reductase activity was not related to discoloration in beef, pork, or lamb. Correlation data from this study (Table 5) also showed a low correlation between MRA and $(K/S)_{572}/(K/S)_{525}$ ($r = 0.23$, $P < 0.001$), $(K/S)_{610}/(K/S)_{525}$ ($r = - 0.10$, $P < 0.01$), and a*-values ($r = 0.15$, $P < 0.001$). O'Keefe and Hood (1982) characterized muscles of low color stability as having lower metmyoglobin reducing ability (as opposed to measuring specific reductase activity).

The utility of MRA as a measure of reducing activity must be questioned. A lack of continuity in procedures has created numerous variants that offer conflicting results and disparate values. Other researchers have questioned the validity of the

metmyoglobin reductase assay based on evidence that the potassium ferricyanide used in the procedure interfered with the reducing reaction. Van den Oord (1974) determined that ferricyanide does interfere with the reducing reaction both in myoglobin extracts and in beef muscle. Furthermore, Van den Oord (1974) speculated that true reduction of metmyoglobin was unlikely to occur in beef and any reduction occurring in the presence of ferricyanide would be exhausted rapidly when steaks were exposed to oxygen. Recent insights by Sammel et al. (2002) suggest that metmyoglobin reductase activity can be used to differentiate reducing activity between muscles, but can not differentiate differences within muscles over display times because NADH, the rate limiting substance, is present in excess. This presents a methodological challenge because NADH is essential for metmyoglobin reductase to function. Other measures of reducing activity (i.e., aerobic reducing ability, resistance to induced metmyoglobin formation or nitric oxide metmyoglobin reducing ability) indicate that metmyoglobin reduction occurs, and it decreases with display time. If metmyoglobin reductase activity was consistent in postmortem muscle, then discoloration would be very difficult to explain because OCR decreases with display time. It seems logical that reducing ability must decrease at a rate that is greater than OCR, otherwise it would be difficult for metmyoglobin to accumulate and cause discoloration.

***Resistance to induced metmyoglobin formation***

Aerobic reducing ability (ARA) was measured as described by Ledward (1972). However, upon analysis, it was determined that aerobic reducing ability patterns were

unusual both within and between muscles. Further investigation revealed that the metmyoglobin state that was supposed to be induced on the surface of muscle samples by the 1% oxygen environment was resisted to varying levels by different muscles. O'Keefe and Hood (1982) observed a similar phenomenon when they measured aerobic reducing ability. They reported that resistance to oxidation appeared to be a better indicator of color stability than percentage reductions, because percentage reductions were based upon the initial level of metmyoglobin induced on the surface of samples. Moreover, the actual metmyoglobin reduced was the same for all muscles. As suggested by O'Keefe and Hood (1982), it was determined to measure the resistance to induced metmyoglobin formation (RIMF) as an indirect measure of reducing ability within a muscle (Table 11). Muscles of low color stability, such as *M. psoas major* and *M. adductor*, were susceptible to high levels of induced metmyoglobin early in retail display, with close to 70% metmyoglobin induced on the surface at day 1. *M. biceps femoris*, *M. infraspinatus*, *M. pectoralis profundus*, *M. supraspinatus*, *M. triceps brachi* - long head, *M. triceps brachi* - lateral head were initially more resistant to induced metmyoglobin formation than *M. psoas major* and *M. adductor*, but all exceeded 70% induced metmyoglobin on day 2. *M. longissimus lumborum* and *M. longissimus thoracis* were very resistant to induced metmyoglobin formation and carried resistance over the duration of retail display as only slightly greater than 60% metmyoglobin was induced on day 5. *M. semitendinosus* and *M. tensor fasciae latae* were moderately resistant to induced metmyoglobin formation as they did not exceed 70% metmyoglobin until day 5, which was slightly greater than *M. longissimus lumborum* or *M. longissimus thoracis*.

Table 11
Least squares means for resistance to induced metmyoglobin formation (% metmyoglobin) of steaks from 19 beef muscles over 5 days of retail display

| | Display day | | | | | | |
|---|---|---|---|---|---|---|---|
| Muscle | 0 | 1 | 2 | 3 | 4 | 5 | SEM* |
| *M. adductor* | 56.6$^{d}$ | 70.7$^{bcd}$ | 69.3$^{cd}$ | 78.6$^{abc}$ | 89.0$^{a}$ | 87.3$^{ab}$ | 6.03 |
| *M. biceps femoris* | 35.5$^{d}$ | 55.9$^{c}$ | 76.2$^{b}$ | 83.6$^{ab}$ | 87.5$^{a}$ | 88.8$^{a}$ | 3.81 |
| *M. gluteus medius* | 25.2$^{c}$ | 54.0$^{b}$ | 62.7$^{b}$ | 80.4$^{a}$ | 83.6$^{a}$ | 83.9$^{a}$ | 3.55 |
| *M. infraspinatus* | 37.1$^{d}$ | 59.0$^{c}$ | 78.2$^{b}$ | 84.4$^{ab}$ | 89.5$^{a}$ | 92.7$^{a}$ | 3.57 |
| *M. latissimus dorsi* | 33.5$^{c}$ | 49.7$^{b}$ | 58.2$^{b}$ | 73.4$^{a}$ | 75.0$^{a}$ | 76.2$^{a}$ | 3.66 |
| *M. longissimus lumborum* | 15.7$^{d}$ | 32.6$^{c}$ | 41.8$^{bc}$ | 50.9$^{ab}$ | 53.3$^{ab}$ | 61.8$^{a}$ | 5.66 |
| *M. longissimus thoracis* | 18.1$^{c}$ | 28.7$^{c}$ | 43.9$^{b}$ | 55.0$^{ab}$ | 49.6$^{ab}$ | 60.7$^{a}$ | 4.57 |
| *M. pectoralis profundus* | 31.4$^{e}$ | 57.3$^{d}$ | 71.8$^{c}$ | 75.0$^{bc}$ | 84.4$^{ab}$ | 87.2$^{a}$ | 3.42 |
| *M. psoas major* | 44.2$^{c}$ | 68.3$^{b}$ | 74.7$^{b}$ | 87.7$^{a}$ | 89.7$^{a}$ | 91.4$^{a}$ | 4.36 |
| *M. rectus femoris* | 28.4$^{c}$ | 54.0$^{b}$ | 51.2$^{b}$ | 75.1$^{a}$ | 66.2$^{ab}$ | 67.2$^{ab}$ | 7.05 |
| *M. semimembranosus* | 30.3$^{c}$ | 54.5$^{b}$ | 60.6$^{ab}$ | 67.8$^{ab}$ | 73.4$^{a}$ | 76.9$^{a}$ | 6.21 |
| *M. semitendinosus* | 10.7$^{c}$ | 39.8$^{b}$ | 49.9$^{b}$ | 58.9$^{ab}$ | 59.9$^{ab}$ | 72.1$^{a}$ | 7.73 |
| *M. serratus ventralis* | 32.4$^{e}$ | 47.5$^{d}$ | 66.5$^{c}$ | 77.6$^{b}$ | 78.0$^{b}$ | 87.9$^{a}$ | 3.42 |
| *M. supraspinatus* | 37.7$^{c}$ | 46.8$^{c}$ | 73.5$^{b}$ | 72.6$^{b}$ | 86.0$^{a}$ | 91.1$^{a}$ | 4.17 |
| *M. tensor fasciae latae* | 28.6$^{b}$ | 38.6$^{b}$ | 42.5$^{b}$ | 61.2$^{a}$ | 65.0$^{a}$ | 76.3$^{a}$ | 5.74 |
| *M. trapezius* | 41.6$^{d}$ | 47.3$^{cd}$ | 52.0$^{bc}$ | 59.1$^{b}$ | 71.0$^{a}$ | 73.5$^{a}$ | 3.47 |
| *M. triceps brachii* – long head | 28.0$^{d}$ | 57.7$^{c}$ | 73.5$^{b}$ | 83.3$^{ab}$ | 86.1$^{a}$ | 86.4$^{a}$ | 3.82 |
| *M. triceps brachii* – lateral head | 36.3$^{d}$ | 53.9$^{c}$ | 76.0$^{b}$ | 80.5$^{ab}$ | 86.9$^{a}$ | 87.6$^{a}$ | 3.05 |
| *M. vastus lateralis* | 24.3$^{d}$ | 55.7$^{c}$ | 65.6$^{bc}$ | 75.4$^{ab}$ | 79.2$^{a}$ | 86.8$^{a}$ | 4.68 |

[a-e]Means within a row lacking a common letter differ ($P < 0.05$).
*SEM is the standard error of the least squares means.

Differences in resistance to induced metmyoglobin formation were observed between muscles (Table 10). *M. longissimus lumborum*, *M. longissimus thoracis*, *M. semitendinosus* and *M. tensor fasciae latae* showed the greatest resistance to induced metmyoglobin formation, whereas *M. psoas major*, *M. adductor*, and *M. infraspinatus* were the least resistant to induced metmyoglobin formation. *M. pectoralis profundus*, *M. supraspinatus*, *M. triceps brachi* - long head, *M. triceps brachi* - lateral head and *M. biceps femoris* showed low resistance to induced metmyoglobin formation. Generally, initial findings from this study agree with O'Keefe and Hood (1982). They characterized *M. longissimus lumborum* steaks as resistant to oxidation and found *M. semimembranosus* had higher RIMF than *M. psoas major* or *M. gluteus medius*. Rankings for RIMF closely mimicked $(K/S)_{572}/(K/S)_{525}$ rankings for metmyoglobin accumulation. This may not be unexpected because muscles that are more susceptible to induced metmyoglobin formation probably accumulate greater amounts of metmyoglobin under normal retail display conditions. Muscles of high color stability appear to possess an ability to rapidly reduce metmyoglobin, even when conditions favor metmyoglobin formation. Van den Oord (1974) criticized ARA measures of reducing ability because the artificial induction of metmyoglobin on the surface of steaks does not correspond with the natural formation of metmyoglobin, making it unlikely that the true reducing capacity of the muscle is captured. Sammel et al. (2002) and Faustman and Cassens (1990) defended ARA measures by suggesting that because no chemicals are used as oxidizing agents the inherent reducing system would be minimally altered. Additionally, they described it as one of the better measures of reducing activity. In this

study, there was a strong correlation (r = -0.67, $P < 0.001$) between RIMF and discoloration as measured by $(K/S)_{572}/(K/S)_{525}$ (Table 5), which corresponds closely with the correlation O'Keefe and Hood (1982) found between ARA and rate of discoloration (r = -0.70).

***Nitric oxide metmyoglobin reducing ability***

All muscles showed a decrease in nitric oxide reducing ability with increasing days of retail display, with the exception of *M. trapezius* (Table 12). *M. psoas major* and *M. adductor* had the lowest NORA values within each day of retail display. *M. adductor* showed a sharp decrease in NORA after day 1 of retail display, whereas *M. psoas major* showed incremental decreases in NORA with increasing days of retail display. *M. longissimus lumborum*, *M. longissimus thoracis*, *M. semitendinosus*, and *M. tensor fasciae latae* had the highest NORA percentages on day 5 of retail display, and only exhibited 26.2%, 19.9%, 33.7%, and 33.7% decreases, respectively, in NORA over the retail display period. In contrast, *M. psoas major* and *M. adductor* exhibited 62.1% and 56.4% decreases, respectively, in NORA over the retail display period. Because there were such large differences in NORA values between muscles on day 0 it was difficult to determine if it was best to look at percentage decreases in NORA or the actual reduction in NORA. For example, *M. serratus ventralis* and *M. supraspinatus*, two muscles of low color stability, had greater percentage decreases in NORA over retail display than *M. tensor fasciae latae* (a more color stable muscle), but had lower decreases in actual NORA. It is expected that percentage decrease is more important

because initial NORA levels are inherent to the muscles and not something that can necessarily be standardized or manipulated.

NORA evaluations showed that *M. semitendinosus*, *M. longissimus lumborum*, *M. longissimus thoracis*, and *M. tensor fasciae latae* had much higher NORA reducing abilities than the other muscles that were evaluated (Table 10). In contrast, *M. psoas major* and *M. adductor* had the lowest NORA values, while *M. serratus ventralis*, *M. infraspinatus*, and *M. semimembranosus* all exhibited low NORA values. *M. triceps brachi* - long head, *M. triceps brachi* - lateral head, and *M. supraspinatus* had higher NORA values than steaks from *M. gluteus medius*, *M. rectus femoris*, and *M. semimembranosus*, which was surprising because muscles that exhibited high MRA values (i.e., *M. infraspinatus*, *M. supraspinatus*, *M. serratus ventralis*) typically had low NORA values. Sammel et al. (2002) found the superficial portion of *M. semimembranosus* (which is more color stable) had higher NORA than the less color stable deep portion of *M. semimembranosus*. Correlation data (Table 5) showed that NORA had a strong relationship to $(K/S)_{572}/(K/S)_{525}$ ($r = 0.61$, $P < 0.001$) and a*-values ($r = 0.50$, $P < 0.001$). Sammel et al. (2002) reported strong correlations between NORA and measures of discoloration. NORA may be the best measure of reducing activity because it requires a mild oxidant (sodium nitrite) relative to the metmyoglobin reductase activity assay (potassium ferricyanide).

Table 12
Least squares means for nitric oxide metmyoglobin reducing ability (Δ% metmyoglobin) of steaks from 19 beef muscles over 5 days of retail display

| | Display day | | | | | | |
|---|---|---|---|---|---|---|---|
| Muscle | 0 | 1 | 2 | 3 | 4 | 5 | SEM* |
| *M. adductor* | 44.3$^{a}$ | 39.9$^{a}$ | 25.8$^{b}$ | 24.3$^{b}$ | 20.8$^{b}$ | 19.1$^{b}$ | 4.63 |
| *M. biceps femoris* | 61.9$^{a}$ | 63.6$^{a}$ | 53.7$^{a}$ | 37.6$^{b}$ | 31.5$^{b}$ | 29.6$^{b}$ | 5.05 |
| *M. gluteus medius* | 61.5$^{a}$ | 56.7$^{ab}$ | 47.8$^{bc}$ | 40.6$^{cd}$ | 34.4$^{d}$ | 29.6$^{d}$ | 4.34 |
| *M. infraspinatus* | 53.6$^{a}$ | 47.4$^{ab}$ | 43.1$^{bc}$ | 37.5$^{cd}$ | 36.2$^{cd}$ | 29.2$^{d}$ | 3.12 |
| *M. latissimus dorsi* | 62.5$^{a}$ | 55.9$^{ab}$ | 46.7$^{bc}$ | 40.5$^{cd}$ | 44.6$^{bcd}$ | 33.0$^{d}$ | 4.09 |
| *M. longissimus lumborum* | 64.6$^{a}$ | 65.7$^{a}$ | 62.1$^{a}$ | 54.4$^{b}$ | 53.6$^{b}$ | 47.7$^{b}$ | 2.57 |
| *M. longissimus thoracis* | 69.5$^{a}$ | 64.4$^{ab}$ | 59.0$^{bc}$ | 57.3$^{bc}$ | 52.1$^{c}$ | 55.7$^{bc}$ | 3.48 |
| *M. pectoralis profundus* | 59.8$^{a}$ | 54.7$^{ab}$ | 46.4$^{bc}$ | 36.4$^{c}$ | 35.3$^{c}$ | 34.6$^{c}$ | 4.28 |
| *M. psoas major* | 46.7$^{a}$ | 38.4$^{b}$ | 31.2$^{bc}$ | 24.3$^{cd}$ | 18.4$^{d}$ | 17.7$^{d}$ | 2.58 |
| *M. rectus femoris* | 61.3$^{a}$ | 38.9$^{b}$ | 42.6$^{b}$ | 44.4$^{b}$ | 38.5$^{b}$ | 32.8$^{b}$ | 5.84 |
| *M. semimembranosus* | 56.7$^{a}$ | 51.5$^{a}$ | 47.4$^{ab}$ | 32.7$^{bc}$ | 33.1$^{bc}$ | 28.9$^{c}$ | 5.38 |
| *M. semitendinosus* | 79.6$^{a}$ | 64.8$^{ab}$ | 59.7$^{bc}$ | 53.9$^{bc}$ | 48.3$^{c}$ | 52.8$^{bc}$ | 5.52 |
| *M. serratus ventralis* | 54.9$^{a}$ | 47.9$^{b}$ | 39.0$^{c}$ | 38.2$^{c}$ | 30.6$^{d}$ | 34.6$^{cd}$ | 2.30 |
| *M. supraspinatus* | 55.8$^{a}$ | 55.9$^{a}$ | 51.1$^{ab}$ | 45.5$^{bc}$ | 40.3$^{de}$ | 33.1$^{d}$ | 3.29 |
| *M. tensor fasciae latae* | 69.2$^{a}$ | 67.2$^{a}$ | 62.4$^{ab}$ | 54.7$^{bc}$ | 48.5$^{c}$ | 45.9$^{c}$ | 3.54 |
| *M. trapezius* | 53.0 | 51.7 | 47.5 | 53.9 | 44.4 | 38.8 | 4.14 |
| *M. triceps brachii* – long head | 61.7$^{a}$ | 59.1$^{a}$ | 46.2$^{b}$ | 43.0$^{b}$ | 38.2$^{b}$ | 34.2$^{b}$ | 4.31 |
| *M. triceps brachii* – lateral head | 62.5$^{a}$ | 55.3$^{a}$ | 51.9$^{a}$ | 39.2$^{b}$ | 37.7$^{b}$ | 35.2$^{b}$ | 3.87 |
| *M. vastus lateralis* | 70.0$^{a}$ | 50.9$^{b}$ | 50.2$^{b}$ | 45.8$^{b}$ | 41.1$^{b}$ | 39.3$^{b}$ | 4.97 |

$^{a\text{-}e}$Means within a row lacking a common letter differ ($P < 0.05$).
*SEM is the standard error of the least squares means.

***Oxygen consumption rate***

Oxygen consumption rates were determined by measuring the amount of carbon dioxide respired by muscle samples in a closed system. As expected, respiration rates decreased with increasing days of retail display for all muscles included in this study (Table 13). *M. latissimus dorsi* and *M. trapezius* portions had the lowest respiration rates observed on day 0, however, it is unclear if this is an artifact of these muscles being cut and displayed as flat muscle sections as opposed to thick steaks as was the case with other muscles. A number of muscles, including *M. biceps femoris*, *M. infraspinatus*, *M. pectoralis profundus*, *M. psoas major*, *M. supraspinatus*, *M. serratus ventralis*, and *M. trapezius*, showed high residual respiration rates over the retail display period. O'Keefe and Hood (1982) reported that *M. psoas major* had higher initial and residual OCR than *M. longissimus lumborum*/*M. longissimus thoracis* during display. Additionally, Bendall and Taylor (1972) observed high OCR in steaks from *M. biceps femoris*.

Data showed differences in OCR between muscles (Table 14). Generally, muscles of high color stability had low OCRs, whereas muscles of low color stability had high OCRs. The notable exceptions to these generalizations were steaks from *M. adductor* and *M. semitendinosus*. *M. adductor* had the second lowest OCR, yet was one of the least color stable muscles, while *M. semitendinosus* was one of the most color stable muscles, but had a much higher OCR than other muscles of similar color stability (i.e., *M. longissimus lumborum*, *M. longissimus thoracis*, and *M. tensor fasciae latae*). Previous studies showed conflicting results from what was observed in muscle to muscle differences in this study. Lanari and Cassens (1991) found *M. gluteus medius* had

Table 13
Least squares means for oxygen consumption rate (Δ% $CO_2$) of steaks from 19 beef muscles over 5 days of retail display

| | Display day | | | | | | |
|---|---|---|---|---|---|---|---|
| Muscle | 0 | 1 | 2 | 3 | 4 | 5 | SEM* |
| *M. adductor* | 2.59[a] | 1.32[b] | 0.62[bc] | 0.81[c] | 0.33[c] | 0.40[c] | 0.189 |
| *M. biceps femoris* | 2.92[a] | 1.74[b] | 1.04[c] | 0.68[cd] | 0.36[d] | 0.28[d] | 0.148 |
| *M. gluteus medius* | 2.72[a] | 1.57[b] | 0.83[c] | 0.57[cd] | 0.36[d] | 0.39[d] | 0.143 |
| *M. infraspinatus* | 2.74[a] | 1.89[b] | 1.26[c] | 0.91[cd] | 0.84[cd] | 0.53[d] | 0.167 |
| *M. latissimus dorsi* | 1.91[a] | 1.60[a] | 0.83[b] | 0.60[bc] | 0.55[bc] | 0.47[c] | 0.156 |
| *M. longissimus lumborum* | 2.23[a] | 1.54[b] | 0.94[c] | 0.63[c] | 0.53[c] | 0.45[c] | 0.196 |
| *M. longissimus thoracis* | 2.53[a] | 1.56[b] | 0.89[c] | 0.64[cd] | 0.39[d] | 0.44[d] | 0.104 |
| *M. pectoralis profundus* | 2.57[a] | 1.44[b] | 1.05[bc] | 0.92[cd] | 0.55[cd] | 0.75[cd] | 0.148 |
| *M. psoas major* | 2.90[a] | 1.59[b] | 0.88[c] | 0.71[c] | 0.71[c] | 0.53[c] | 0.205 |
| *M. rectus femoris* | 2.81[a] | 1.50[b] | 0.89[c] | 0.54[c] | 0.37[c] | 0.65[c] | 0.189 |
| *M. semimembranosus* | 2.71[a] | 1.82[b] | 0.91[c] | 0.66[d] | 0.38[e] | 0.39[e] | 0.075 |
| *M. semitendinosus* | 2.79[a] | 1.55[b] | 0.95[c] | 0.75[c] | 0.38[d] | 0.45[d] | 0.096 |
| *M. serratus ventralis* | 2.99[a] | 1.99[b] | 1.13[c] | 0.96[c] | 0.69[c] | 0.60[c] | 0.232 |
| *M. supraspinatus* | 3.51[a] | 1.82[b] | 1.33[c] | 1.01[cd] | 0.66[de] | 0.46[e] | 0.171 |
| *M. tensor fasciae latae* | 2.23[a] | 1.40[b] | 0.79[c] | 0.67[cd] | 0.44[cd] | 0.47[d] | 0.112 |
| *M. trapezius* | 2.07[a] | 1.65[b] | 0.84[c] | 0.83[c] | 0.74[c] | 0.61[c] | 0.122 |
| *M. triceps brachii* – long head | 3.01[a] | 1.74[b] | 0.81[c] | 0.60[c] | 0.52[c] | 0.50[c] | 0.124 |
| *M. triceps brachii* – lateral head | 2.79[a] | 1.95[b] | 0.80[c] | 0.69[c] | 0.52[c] | 0.44[c] | 0.167 |
| *M. vastus lateralis* | 2.73[a] | 1.45[b] | 1.01[c] | 0.69[cd] | 0.42[d] | 0.34[d] | 0.133 |

[a-e]Means within a row lacking a common letter differ ($P < 0.05$).
*SEM is the standard error of the least squares means.

Table 14
Least squares means for oxygen consumption rate (OCR), oxygen penetration depth (OPD), myoglobin content, 2-thiobarbituric acid reactive substances (TBARS), and pH for 19 beef muscles

| Muscle | OCR ($\Delta$% $CO_2$) | OPD (mm) | Myoglobin (mg/g) | TBARS (mg/kg) | pH |
|---|---|---|---|---|---|
| *M. adductor* | 1.01$^{e}$ | 4.11$^{efghi}$ | 5.14$^{bc}$ | 0.37$^{abc}$ | 5.73$^{efgh}$ |
| *M. biceps femoris* | 1.15$^{cde}$ | 4.12$^{efgh}$ | 5.41$^{ab}$ | 0.42$^{a}$ | 5.69$^{h}$ |
| *M. gluteus medius* | 1.06$^{cde}$ | 4.53$^{cd}$ | 5.62$^{a}$ | 0.33$^{bcd}$ | 5.69$^{h}$ |
| *M. infraspinatus* | 1.38$^{ab}$ | 2.94$^{j}$ | 5.20$^{bc}$ | 0.29$^{cdef}$ | 5.93$^{a}$ |
| *M. latissimus dorsi* | 1.02$^{de}$ | 4.01$^{fghi}$ | 3.97$^{g}$ | 0.24$^{efgh}$ | 5.74$^{defg}$ |
| *M. longissimus lumborum* | 1.05$^{cde}$ | 4.80$^{bc}$ | 4.62$^{de}$ | 0.19$^{gh}$ | 5.77$^{cdef}$ |
| *M. longissimus thoracis* | 1.08$^{cde}$ | 5.04$^{c}$ | 4.48$^{e}$ | 0.16$^{h}$ | 5.78$^{cd}$ |
| *M. pectoralis profundus* | 1.17$^{cde}$ | 3.84$^{ghi}$ | 4.35$^{ef}$ | 0.26$^{defg}$ | 5.73$^{fgh}$ |
| *M. psoas major* | 1.22$^{bc}$ | 4.47$^{cde}$ | 4.10$^{fg}$ | 0.39$^{ab}$ | 5.73$^{fgh}$ |
| *M. rectus femoris* | 1.13$^{cde}$ | 4.21$^{defg}$ | 4.35$^{ef}$ | 0.28$^{def}$ | 5.82$^{bc}$ |
| *M. semimembranosus* | 1.13$^{cde}$ | 4.73$^{bc}$ | 4.90$^{cd}$ | 0.26$^{defg}$ | 5.70$^{gh}$ |
| *M. semitendinosus* | 1.11$^{cde}$ | 5.61$^{a}$ | 3.60$^{h}$ | 0.24$^{efgh}$ | 5.73$^{efgh}$ |
| *M. serratus ventralis* | 1.39$^{ab}$ | 3.09$^{j}$ | 5.47$^{ab}$ | 0.26$^{defg}$ | 5.92$^{a}$ |
| *M. supraspinatus* | 1.45$^{a}$ | 3.74$^{i}$ | 5.35$^{ab}$ | 0.28$^{def}$ | 5.84$^{b}$ |
| *M. tensor fasciae latae* | 1.01$^{e}$ | 4.98$^{b}$ | 4.01$^{fg}$ | 0.24$^{efg}$ | 5.78$^{cde}$ |
| *M. trapezius* | 1.20$^{c}$ | 3.30$^{j}$ | 4.04$^{fg}$ | 0.23$^{fgh}$ | 5.93$^{a}$ |
| *M. triceps brachii* – long head | 1.19$^{cd}$ | 3.74$^{hi}$ | 5.43$^{ab}$ | 0.33$^{bcd}$ | 5.75$^{defg}$ |
| *M. triceps brachii* – lateral head | 1.22$^{bc}$ | 3.85$^{fghi}$ | 4.93$^{cd}$ | 0.32$^{bcde}$ | 5.77$^{def}$ |
| *M. vastus lateralis* | 1.10$^{cde}$ | 4.22$^{def}$ | 5.34$^{ab}$ | 0.33$^{abcd}$ | 5.71$^{gh}$ |
| SEM* | 0.063 | 0.137 | 0.124 | 0.030 | 0.017 |

[a-l]Means within a column lacking a common superscript differ ($P < 0.05$).
*SEM is the standard error of the least squares means.

greater OCR than *M. longissimus lumborum*, whereas they were determined to be equivalent in this study. Likewise, Bendall and Taylor (1972) determined that the order of OCR for five muscles was *M. biceps femoris>M. longissimus lumborum>M. tensor fasciae latae>M. vastus lateralis>M. rectus femoris*. This study found *M. biceps femoris* had the highest OCR of those muscles, but *M. tensor fasciae latae* and *M. longissimus lumborum* had lower OCRs than *M. rectus femoris* and *M. vastus lateralis*. O'Keefe and Hood (1982) and Atkinson and Follett (1973) concluded that high OCR is a defining characteristic of muscles with low color stability. Likewise, Renerre and Labas (1987) described muscles having the poorest color stability as having the highest oxidative activities. Sammel et al. (2002) concluded that a very high or very low OCR could have a negative impact on color stability. In the case of low OCR, they speculated that low OCR would result in low mitochondrial generation of NADH, limiting the amount of reduction that could occur. In the case of high OCR, they speculated that, high OCR sufficiently reduces partial oxygen pressure resulting in a thin oxymyoglobin layer, thus allowing greater expression of the underlying metmyoglobin layer. This hypothesis could only be valid if a strong relationship between OCR and reducing activity was established. Reviewing correlation data (Table 5) it was noticed that OCR had a moderate correlation to measures of reducing ability (MRA, $r = 0.35$, $P < 0.001$; RIMF, $r = -0.55$, $P < 0.001$; NORA, $r = 0.35$, $P < 0.001$). Nonetheless, a number of unique relationships with different muscles that question the role of OCR as described by Sammel et al. (2002). Based on their hypothesis, *M. tensor fasciae latae* and *M. adductor*, which have identically low OCRs, therefore producing equivalent amounts of

NADH resulting in equivalent reducing activities. Clearly, this is not the case because *M. tensor fasciae latae* and *M. adductor* were divergent within all measures of reducing activity. In the case of MRA, *M. tensor fasciae latae* was low as hypothesized by Sammel et al. (2002), but *M. adductor* was much higher. Likewise, in contrast to what was hypothesized, *M. tensor fasciae latae* had some of the highest NORA and RIMF values, whereas *M. adductor* had some of the lowest. Thus, even though OCR was the same, ability to reduce was quite different. Perhaps MRA is truly a function of NADH production and offers little differentiation of the reducing capacity of muscle because the rate limiting substrate (NADH) is present in excess.

An alternate, theoretical explanation for the relationship between OCR and reducing ability may be that color stability is governed by the OCR relative to the reducing ability of the muscle. In the case of *M. adductor*, its reducing ability is sufficiently low that it can not keep up with the oxidative stress imposed by the OCR, even though the oxidative stress is at a low level. *M. tensor fasciae latae*, which has an almost identical OCR to *M. adductor*, had much more color stability because its reducing ability was high relative to its low OCR. Likewise, *M. semitendinosus* has a high enough reducing system that it could more than compensate for the oxidative stress imposed by its high OCR. Atkinson and Follet (1973) hypothesized the same relationship between OCR and reducing activity when they compared the color stability of beef, pork, and lamb.

Crude analysis of the ratio of OCR to NORA showed that there appears to be some validity to this hypothesis (data not shown in tabular form). *M. adductor* and *M.*

*psoas major* had the highest ratios, followed closely by *M. serratus ventralis*, *M. infraspinatus*, and *M. supraspinatus*, all of which have been characterized as low color stability muscles. Furthermore, all of the high color stability muscles (*M. tensor fasciae latae*, *M. longissimus lumborum*, *M. longissimus thoracis*, and *M. semitendinosus*) had the lowest ratios. OCR to NORA ratios for *M. rectus femoris* and *M. semimembranosus* were high, but these muscles did not show the same extent of metmyoglobin accumulation as muscles with similar OCR to NORA ratios.

***Oxygen penetration depth***

Oxygen penetration depth increased with increasing days of retail display (Table 15). Traditionally color labile muscles, such as *M. adductor* and *M. psoas major*, showed a 2 to 3 day lag phase before significant increases in OPD were detected. Steaks from *M. gluteus medius*, *M. latissimus dorsi*, *M. pectoralis profundus*, and *M. serratus ventralis* showed similar OPD patterns as *M. adductor* and *M. psoas major* except they had slightly shorter lag periods before significant increases in OPD were observed. Color stable muscles, such as *M. longissimus lumborum*, *M. longissimus thoracis*, *M. semitendinosus*, and *M. tensor fasciae latae*, showed incremental increases in OPD with increasing days of retail display. In addition, the total change in OPD from day 0 to day 5 was greater in the traditionally color stable muscles than the total change observed in less color stable muscles. O'Keefe and Hood (1982) also reported incremental increases in OPD with increased display time, and noted that OPD was greater in muscles that had greater postmortem age.

Table 15
Least squares means for oxygen penetration depth (mm) of steaks from 19 beef muscles over 5 days of retail display

| | Display day | | | | | | |
|---|---|---|---|---|---|---|---|
| Muscle | 0 | 1 | 2 | 3 | 4 | 5 | SEM* |
| *M. adductor* | 3.18$^{c}$ | 3.23$^{c}$ | 3.11$^{c}$ | 3.84$^{c}$ | 5.13$^{b}$ | 6.17$^{a}$ | 0.323 |
| *M. biceps femoris* | 2.72$^{e}$ | 3.15$^{de}$ | 3.61$^{d}$ | 4.21$^{c}$ | 5.12$^{b}$ | 5.89$^{a}$ | 0.170 |
| *M. gluteus medius* | 3.01$^{c}$ | 3.52$^{c}$ | 3.66$^{c}$ | 4.70$^{b}$ | 5.84$^{a}$ | 6.45$^{a}$ | 0.228 |
| *M. infraspinatus* | 2.02$^{e}$ | 2.31$^{de}$ | 2.67$^{cd}$ | 2.91$^{c}$ | 3.56$^{b}$ | 4.19$^{a}$ | 0.134 |
| *M. latissimus dorsi* | 2.58$^{c}$ | 2.99$^{c}$ | 3.28$^{c}$ | 4.19$^{b}$ | 5.35$^{a}$ | 5.66$^{a}$ | 0.252 |
| *M. longissimus lumborum* | 2.93$^{d}$ | 3.60$^{cd}$ | 4.08$^{c}$ | 4.95$^{b}$ | 6.38$^{a}$ | 6.83$^{a}$ | 0.273 |
| *M. longissimus thoracis* | 3.06$^{d}$ | 3.65$^{cd}$ | 4.20$^{c}$ | 5.22$^{b}$ | 6.92$^{a}$ | 7.20$^{a}$ | 0.344 |
| *M. pectoralis profundus* | 2.78$^{c}$ | 2.88$^{c}$ | 3.15$^{bc}$ | 3.85$^{b}$ | 4.99$^{a}$ | 5.38$^{a}$ | 0.251 |
| *M. psoas major* | 2.78$^{c}$ | 3.31$^{c}$ | 3.38$^{bc}$ | 4.69$^{b}$ | 6.40$^{a}$ | 6.25$^{a}$ | 0.475 |
| *M. rectus femoris* | 2.75$^{d}$ | 3.33$^{cd}$ | 3.75$^{bc}$ | 4.24$^{b}$ | 5.46$^{a}$ | 5.74$^{a}$ | 0.232 |
| *M. semimembranosus* | 3.03$^{d}$ | 3.70$^{cd}$ | 4.27$^{bc}$ | 4.97$^{b}$ | 6.09$^{a}$ | 6.32$^{a}$ | 0.246 |
| *M. semitendinosus* | 3.23$^{d}$ | 4.19$^{cd}$ | 4.88$^{bc}$ | 5.63$^{b}$ | 7.34$^{a}$ | 8.39$^{a}$ | 0.411 |
| *M. serratus ventralis* | 2.37$^{c}$ | 2.49$^{c}$ | 2.74$^{bc}$ | 3.04$^{b}$ | 3.75$^{a}$ | 4.18$^{a}$ | 0.182 |
| *M. supraspinatus* | 2.25$^{d}$ | 2.83$^{c}$ | 3.50$^{b}$ | 3.73$^{b}$ | 4.85$^{a}$ | 5.26$^{a}$ | 0.147 |
| *M. tensor fasciae latae* | 2.97$^{d}$ | 3.59$^{d}$ | 4.33$^{c}$ | 5.17$^{b}$ | 6.61$^{a}$ | 7.20$^{a}$ | 0.222 |
| *M. trapezius* | 2.17$^{c}$ | 2.68$^{bc}$ | 2.80$^{b}$ | 3.20$^{b}$ | 4.32$^{a}$ | 4.62$^{a}$ | 0.199 |
| *M. triceps brachii* – long head | 2.40$^{d}$ | 2.83$^{cd}$ | 3.15$^{c}$ | 3.77$^{b}$ | 4.91$^{a}$ | 5.40$^{a}$ | 0.198 |
| *M. triceps brachii* – lateral head | 2.31$^{d}$ | 2.79$^{cd}$ | 3.25$^{c}$ | 3.98$^{b}$ | 5.25$^{a}$ | 5.56$^{a}$ | 0.235 |
| *M. vastus lateralis* | 2.75$^{d}$ | 3.02$^{cd}$ | 3.51$^{c}$ | 4.26$^{b}$ | 5.67$^{a}$ | 6.11$^{a}$ | 0.222 |

[a-e]Means within a row lacking a common superscript differ ($P < 0.05$).
*SEM is the standard error of the least squares means.

Mean OPD values for muscles over the retail display period showed that *M. semitendinosus*, *M. longissimus thoracis*, *M. tensor fasciae latae*, *M. longissimus lumborum*, and *M. semimembranosus* had the highest OPD values (Table 14). Research findings have suggested that OPD values for *M. psoas major* were lower than those reported for *M. longissimus lumborum* (Bendall and Taylor, 1972; MacDougall and Taylor, 1975). Findings from this study showed that OPD values from *M. psoas major* were lower, but comparable to OPD values for *M. longissimus lumborum* and *M. gluteus medius*. Nonetheless, oxygen penetration depth appears to play an important role in determining color stability with the most color stable muscles (i.e., *M. longissimus lumborum*, *M. longissimus thoracis*, *M. semitendinosus*, and *M. tensor fasciae latae*) having the greatest OPD values. OPD may be less important in muscles of low color stability as *M. psoas major* and *M. adductor* were in the middle of the stratification. Even so, a number of muscles of low color stability, such as *M. infraspinatus*, *M. serratus ventralis*, *M. supraspinatus*, and *M. triceps brachi* - long head, had the lowest OPD values. Bendall and Taylor (1972) concluded that OPD was important because it masked underlying metmyoglobin formation which occurs at the metmyoglobin/oxymyoglobin interface where partial pressure oxygen is optimal for oxymyoglobin autoxidation. Correlation data (Table 5) indicated a strong relationship between OPD and OCR (r = -0.53), which is supported by findings from other researchers (O'Keefe and Hood, 1982). O'Keefe and Hood (1982) found that thin layers of oxymyoglobin resulted when high OCRs reduced partial oxygen pressure at the surface of meat cuts.

***Myoglobin content***

Approximately half of the muscles included in this study showed a decrease in myoglobin content with increasing days of retail display (Table 16). It is unclear if losses in myoglobin are related to oxidation or degradation of myoglobin, but this seems unlikely since nearly all muscles showed a decrease in myoglobin content to some extent over the retail display period, coupled with the fact that some highly oxidized muscles, like *M. psoas major* and *M. supraspinatus* (as determined by $(K/S)_{572}/(K/S)_{525}$ values), did not exhibit statistically significant decreases in myoglobin content. It is possible that decreases in myoglobin content may be a result of a loss of sarcoplasmic fluid (i.e., purge). Muscles traditionally characterized by large losses in purge during retail display, such as *M. semimembranosus* and *M. biceps femoris*, showed large decreases in myoglobin content, but large standard errors prevented detecting significant differences in myoglobin content. Unfortunately purge loss was not measured in this study.

Muscle differences in myoglobin content did not have any discernable trends indicating a relationship between myoglobin content and color stability (Table 14). Stratification of muscles based upon myoglobin content showed *M. semitendinosus* had the lowest myoglobin content and *M. gluteus medius* had the highest myoglobin content. In agreement, MacDougall and Taylor (1975) found *M. psoas major* had less myoglobin than *M. longissimus lumborum et thoracis*, which had less myoglobin than *M. gluteus medius*. Reddy and Carpenter (1991) found *M. tensor fasciae latae* had less myoglobin than *M. psoas major*, which had less myoglobin than *M. longissimus lumborum et*

Table 16
Least squares means for myoglobin content (mg/g) of steaks from 19 beef muscles over 5 days of retail display

| | Display day | | | | | | |
|---|---|---|---|---|---|---|---|
| Muscle | 0 | 1 | 2 | 3 | 4 | 5 | SEM* |
| *M. adductor* | 5.58[a] | 5.55[a] | 5.00[ab] | 5.36[a] | 5.05[a] | 4.33[ab] | 0.241 |
| *M. biceps femoris* | 5.81 | 5.40 | 5.34 | 5.73 | 5.03 | 5.14 | 0.309 |
| *M. gluteus medius* | 6.22[ab] | 6.51[a] | 5.30[c] | 5.41[bc] | 5.57[bc] | 4.74[c] | 0.311 |
| *M. infraspinatus* | 6.26[a] | 5.12[b] | 5.20[b] | 4.95[b] | 4.95[b] | 4.70[b] | 0.272 |
| *M. latissimus dorsi* | 4.39 | 4.10 | 3.82 | 4.40 | 3.64 | 3.50 | 0.263 |
| *M. longissimus lumborum* | 5.07[a] | 5.01[ab] | 4.38[bc] | 4.81[ab] | 4.35[bc] | 4.08[c] | 0.242 |
| *M. longissimus thoracis* | 4.85[a] | 4.43[ab] | 4.42[ab] | 4.37[ab] | 4.85[a] | 3.96[b] | 0.190 |
| *M. pectoralis profundus* | 4.47[ab] | 4.94[a] | 4.26[bc] | 4.39[ab] | 4.41[ab] | 3.66[c] | 0.226 |
| *M. psoas major* | 4.61 | 4.27 | 3.91 | 4.12 | 3.88 | 3.83 | 0.240 |
| *M. rectus femoris* | 4.65[ab] | 5.25[a] | 4.40[ab] | 4.54[ab] | 3.90[bc] | 3.33[c] | 0.312 |
| *M. semimembranosus* | 5.59 | 5.09 | 4.57 | 4.81 | 4.93 | 4.44 | 0.352 |
| *M. semitendinosus* | 3.99 | 4.04 | 3.53 | 3.30 | 3.56 | 3.18 | 0.353 |
| *M. serratus ventralis* | 5.45 | 5.13 | 5.53 | 5.79 | 5.48 | 5.44 | 0.263 |
| *M. supraspinatus* | 5.45 | 6.08 | 4.95 | 5.57 | 5.10 | 4.92 | 0.313 |
| *M. tensor fasciae latae* | 4.24[ab] | 4.62[a] | 3.93[ab] | 3.95[b] | 4.03[b] | 3.29[c] | 0.191 |
| *M. trapezius* | 4.09[ab] | 4.50[a] | 4.09[ab] | 3.94[b] | 3.99[b] | 3.64[b] | 0.165 |
| *M. triceps brachii* – long head | 5.07[bc] | 6.66[a] | 5.44[bc] | 4.98[bc] | 5.94[ab] | 4.52[c] | 0.380 |
| *M. triceps brachii* – lateral head | 4.66 | 5.43 | 5.01 | 4.96 | 4.59 | 4.91 | 0.300 |
| *M. vastus lateralis* | 6.43[a] | 5.96[ab] | 5.25[abc] | 5.14[abc] | 4.83[bc] | 4.43[c] | 0.453 |

[a-c]Means within a row lacking a common superscript differ ($P < 0.05$).
*SEM is the standard error of the least squares means.

*thoracis*, *M. gluteus medius*, and *M. semimembranosus*, but there was little difference in myoglobin content between those three muscles. This is in contrast to the findings of this study which found myoglobin content in *M. tensor fasciae latae* and *M. psoas major* were comparable and *M. gluteus medius* had greater myoglobin content than *M. longissimus lumborum*, *M. longissimus thoracis*, and *M. semimembranosus*.

Steaks from muscles that were low in myoglobin content had the highest L*-values. Correlation data (Table 5) confirmed this trend by showing a moderately strong relationship between myoglobin content and L*-value ($r = -0.43$, $P < 0.001$). This is probably a function of the predominant fiber type within those muscles, as white fibers are characterized by less myoglobin and a lighter appearance. Researchers have speculated that muscles of lower myoglobin content have greater rates of discoloration because greater frequency of autoxidation of oxymyoglobin to metmyoglobin (O'Keefe & Hood, 1982). Thus requiring a more frequent reducing turnover to maintain color. However, results from this study do not support this theory as many color stable muscles had lower myoglobin levels.

***2-Thiobarbituric acid reactive substances***

Expectedly, TBARS values increased with increasing days of retail display, however, all values were below the arbitrary threshold level of 1 used to establish the development off-flavors associated with oxidative rancidity (Table 17). *M. vastus lateralis*, *M. psoas major*, *M. adductor*, *M. biceps femoris*, *M. infraspinatus*, and *M.*

Table 17
Least squares means for 2-thiobarbituric acid reactive substances (mg/kg) of steaks from 19 beef muscles over 5 days of retail display

| | Display day | | | | | | |
|---|---|---|---|---|---|---|---|
| Muscle | 0 | 1 | 2 | 3 | 4 | 5 | SEM* |
| *M. adductor* | 0.16$^{c}$ | 0.16$^{c}$ | 0.36$^{b}$ | 0.26$^{bc}$ | 0.56$^{a}$ | 0.72$^{a}$ | 0.062 |
| *M. biceps femoris* | 0.15$^{c}$ | 0.13$^{c}$ | 0.32$^{bc}$ | 0.41$^{b}$ | 0.70$^{a}$ | 0.80$^{a}$ | 0.075 |
| *M. gluteus medius* | 0.16$^{c}$ | 0.16$^{c}$ | 0.22$^{c}$ | 0.25$^{c}$ | 0.46$^{b}$ | 0.74$^{a}$ | 0.056 |
| *M. infraspinatus* | 0.18$^{bc}$ | 0.11$^{c}$ | 0.33$^{b}$ | 0.26$^{bc}$ | 0.30$^{b}$ | 0.54$^{a}$ | 0.057 |
| *M. latissimus dorsi* | 0.18$^{b}$ | 0.09$^{b}$ | 0.17$^{b}$ | 0.21$^{b}$ | 0.26$^{b}$ | 0.54$^{a}$ | 0.060 |
| *M. longissimus lumborum* | 0.17 | 0.06 | 0.22 | 0.21 | 0.14 | 0.33 | 0.061 |
| *M. longissimus thoracis* | 0.16$^{b}$ | 0.06$^{b}$ | 0.12$^{b}$ | 0.14$^{b}$ | 0.16$^{b}$ | 0.31$^{a}$ | 0.046 |
| *M. pectoralis profundus* | 0.17$^{b}$ | 0.11$^{b}$ | 0.19$^{b}$ | 0.13$^{b}$ | 0.41$^{a}$ | 0.53$^{a}$ | 0.061 |
| *M. psoas major* | 0.13$^{c}$ | 0.15$^{c}$ | 0.28$^{c}$ | 0.39$^{bc}$ | 0.58$^{ab}$ | 0.82$^{a}$ | 0.092 |
| *M. rectus femoris* | 0.14$^{c}$ | 0.18$^{c}$ | 0.22$^{bc}$ | 0.25$^{bc}$ | 0.39$^{ab}$ | 0.49$^{a}$ | 0.058 |
| *M. semimembranosus* | 0.16 | 0.30 | 0.26 | 0.17 | 0.29 | 0.39 | 0.086 |
| *M. semitendinosus* | 0.12$^{c}$ | 0.16$^{bc}$ | 0.28$^{abc}$ | 0.17$^{bc}$ | 0.30$^{ab}$ | 0.41$^{a}$ | 0.062 |
| *M. serratus ventralis* | 0.16 | 0.32 | 0.24 | 0.20 | 0.27 | 0.35 | 0.065 |
| *M. supraspinatus* | 0.17 | 0.23 | 0.20 | 0.23 | 0.33 | 0.49 | 0.080 |
| *M. tensor fasciae latae* | 0.21 | 0.13 | 0.10 | 0.23 | 0.33 | 0.47 | 0.086 |
| *M. trapezius* | 0.15$^{b}$ | 0.17$^{b}$ | 0.15$^{b}$ | 0.21$^{b}$ | 0.17$^{b}$ | 0.53$^{a}$ | 0.072 |
| *M. triceps brachii* – long head | 0.15$^{c}$ | 0.19$^{c}$ | 0.18$^{c}$ | 0.34$^{bc}$ | 0.48$^{ab}$ | 0.67$^{a}$ | 0.095 |
| *M. triceps brachii* – lateral head | 0.14$^{b}$ | 0.23$^{b}$ | 0.21$^{b}$ | 0.30$^{b}$ | 0.36$^{b}$ | 0.64$^{a}$ | 0.085 |
| *M. vastus lateralis* | 0.12$^{c}$ | 0.12$^{c}$ | 0.21$^{c}$ | 0.30$^{bc}$ | 0.54$^{ab}$ | 0.70$^{a}$ | 0.089 |

$^{a-c}$Means within a row lacking a common superscript differ ($P < 0.05$).
*SEM is the standard error of the least squares means.

*rectus femoris* showed greater susceptibility to autoxidation at earlier days during retail display, whereas *M. gluteus medius*, *M. latissimus dorsi*, *M. longissimus lumborum*, *M. longissimus thoracis*, *M. pectoralis profundus*, *M. semimembranosus*, *M. supraspinatus*, *M. serratus ventralis*, *M. triceps brachi* - long head, *M. tensor fasciae latae*, and *M. trapezius* showed longer lag phases before oxidative rancidity by-products began accumulating.

Mean TBARS values for muscles across all days of retail display were low (Table 14). Generally, more color stable muscles (i.e., *M. longissimus lumborum*, *M. longissimus thoracis*, *M. semitendinosus*, and *M. tensor fasciae latae*) had lower TBARS and less color stable muscles (i.e., *M. psoas major* and *M. adductor*) had higher TBARS values. Faustman and Cassens (1990) reported a strong relationship between lipid oxidation and myoglobin oxidation, however, it is unclear if oxidation of myoglobin catalyzes lipid oxidation or vice versa.

***pH***

Very few differences in pH values were observed within muscles over the display period (Table 18). When differences were observed, pH increased approximately 0.1 units from day 0 to day 5. Such a small change in pH is likely negligible and not of practical importance.

Stratification of muscles by pH value showed that *M. gluteus medius*, *M. biceps femoris*, *M. semimembranosus*, and *M. vastus lateralis* had the lowest pH values and *M. infraspinatus*, *M. trapezius*, and *M. serratus ventralis* had the highest pH values (Table

Table 18
Least squares means for pH values of steaks from 19 beef muscles over 5 days of retail display

| | Display day | | | | | | |
|---|---|---|---|---|---|---|---|
| Muscle | 0 | 1 | 2 | 3 | 4 | 5 | SEM* |
| *M. adductor* | 5.72 | 5.71 | 5.72 | 5.73 | 5.74 | 5.77 | 0.0182 |
| *M. biceps femoris* | 5.66 | 5.67 | 5.70 | 5.70 | 5.67 | 5.72 | 0.0156 |
| *M. gluteus medius* | 5.67 | 5.67 | 5.71 | 5.71 | 5.68 | 5.70 | 0.0166 |
| *M. infraspinatus* | 5.87$^{c}$ | 5.91$^{bc}$ | 5.91$^{bc}$ | 5.96$^{ab}$ | 5.95$^{ab}$ | 5.98$^{a}$ | 0.0203 |
| *M. latissimus dorsi* | 5.73 | 5.73 | 5.73 | 5.80 | 5.74 | 5.74 | 0.0197 |
| *M. longissimus lumborum* | 5.74 | 5.77 | 5.79 | 5.79 | 5.77 | 5.79 | 0.0162 |
| *M. longissimus thoracis* | 5.75$^{b}$ | 5.75$^{b}$ | 5.81$^{a}$ | 5.82$^{a}$ | 5.78$^{ab}$ | 5.81$^{a}$ | 0.0181 |
| *M. pectoralis profundus* | 5.72$^{ab}$ | 5.70$^{b}$ | 5.75$^{a}$ | 5.72$^{ab}$ | 5.69$^{b}$ | 5.76$^{a}$ | 0.0146 |
| *M. psoas major* | 5.75 | 5.78 | 5.50 | 5.80 | 5.70 | 5.71 | 0.1438 |
| *M. rectus femoris* | 5.80$^{b}$ | 5.78$^{b}$ | 5.80$^{b}$ | 5.85$^{a}$ | 5.80$^{b}$ | 5.90$^{a}$ | 0.0179 |
| *M. semimembranosus* | 5.70 | 5.67 | 5.70 | 5.70 | 5.70 | 5.74 | 0.0158 |
| *M. semitendinosus* | 5.70$^{c}$ | 5.69$^{c}$ | 5.75$^{ab}$ | 5.76$^{a}$ | 5.71$^{bc}$ | 5.76$^{a}$ | 0.0159 |
| *M. serratus ventralis* | 5.87 | 5.90 | 5.93 | 5.95 | 5.91 | 5.98 | 0.0342 |
| *M. supraspinatus* | 5.82 | 5.81 | 5.84 | 5.87 | 5.84 | 5.88 | 0.0184 |
| *M. tensor fasciae latae* | 5.77$^{b}$ | 5.74$^{b}$ | 5.79$^{b}$ | 5.79$^{b}$ | 5.77$^{b}$ | 5.85$^{a}$ | 0.0186 |
| *M. trapezius* | 5.90$^{c}$ | 5.91$^{c}$ | 5.92$^{bc}$ | 6.00$^{ab}$ | 5.97$^{abc}$ | 6.03$^{a}$ | 0.0308 |
| *M. triceps brachii* – long head | 5.67$^{c}$ | 5.73$^{bc}$ | 5.75$^{ab}$ | 5.78$^{ab}$ | 5.73$^{bc}$ | 5.79$^{a}$ | 0.0186 |
| *M. triceps brachii* – lateral head | 5.77 | 5.73 | 5.75 | 5.80 | 5.78 | 5.82 | 0.0221 |
| *M. vastus lateralis* | 5.76 | 5.74 | 5.59 | 5.64 | 5.70 | 5.75 | 0.0880 |

[a-c]Means within a row lacking a common superscript differ ($P < 0.05$).
*SEM is the standard error of the least squares means.

14). Previous research (O'Grady, Monohan, Moody, 2001; Brown and Mebine, 1969) has suggested that increased oxidation of oxymyoglobin occurs at lower pH values. However, results from this study showed a low correlation between pH and measures of discoloration (Table 5). Moreover, some of the muscles of the lowest color stability (*M. infraspinatus*, *M. supraspinatus*, and *M. serratus ventralis*) had the highest pHs. Hood (1980) determined that differences in rates of discoloration between muscles were not related to pH. Lawrie (1979) found that OCR increased with increasing pH. Correlation data show a low correlation between OCR and pH, however, many of the muscles exhibiting high pH values also had high OCR values (*M. infraspinatus*, *M. serratus ventralis*, *M. supraspinatus*, *M. trapezius*). Exceptions to this trend were *M. tensor fasciae latae*, *M. longissimus lumborum*, and *M. longissimus thoracis*.

# CONCLUSIONS

Color stability and rates of discoloration varied among muscles. This study confirmed the high color stability characteristics that have historically been associated with steaks from *M. longissimus lumborum* and *M. longissimus thoracis* and also identified *M. semitendinosus* and *M. tensor fasciae latae* as muscles of high color stability. Likewise, the very low color stability associated with *M. psoas major* was confirmed and *M. adductor*, *M. infraspinatus*, and *M. supraspinatus* were identified as muscles with very low color stability.

Color stability is not determined solely by reducing activity or oxygen consumption rate, rather, it appears that color stability is determined by the proportion of those two components. Muscles with low color stability may have high or low oxygen consumption rates but their reducing activity is proportionally low compared to their oxygen consumption rates. In contrast, muscles of high color stability may have high or low oxygen consumption rates, but have reducing activity that proportionally exceeds their oxygen consumption rates.

This study will serve as a valuable benchmark for determining the color stability characteristics of individual bovine muscles, and provides insights into the oxidative and reductive challenges associated with various muscles. With better knowledge of color stability characteristics the beef industry may develop packaging strategies to maximize the color shelf-life of individual muscles and enhance the value of underutilized beef muscles.

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# APPENDIX A

## CORRELATION COEFFICIENTS OF COLOR STABILITY CHARACTERISTICS FOR INDIVIDUAL MUSCLES

The following tables (A – 1 through A – 19) contain correlation data for color stability characteristics and objective color measures for individual muscles.

Appendix A - 1
Correlation coefficients of biochemical, physical, and objective color measurements for *M. adductor* steaks

| | MRA | RIMF | NORA | OCR | OPD |
|---|---|---|---|---|---|
| MetMb | 0.37** | -0.44*** | 0.61*** | 0.61*** | -0.39** |
| OxyMb | -0.32* | 0.36** | -0.47*** | -0.43** | 0.30* |
| L* | -0.18 | -0.10 | 0.05 | 0.06 | 0.11 |
| a* | 0.34* | -0.39** | 0.54*** | 0.54*** | -0.32* |
| b* | 0.10 | -0.23 | 0.27* | 0.36** | -0.06 |
| OPD | -0.67*** | 0.38** | -0.37** | -0.32* | -- |
| OCR | 0.33* | -0.40** | 0.48*** | -- | -- |
| NORA | 0.37** | -0.50*** | -- | -- | -- |
| RIMF | -0.34* | -- | -- | -- | -- |

MRA = metmyoglobin reductase activity; RIMF = resistance to induced metmyoglobin formation; NORA = nitric oxide reducing ability; OCR = oxygen consumption rate; OPD = oxygen penetration depth; MetMb = $(K/S)_{572}/(K/S)_{525}$; OxyMb = $(K/S)_{610}/(K/S)_{525}$.

*$P < 0.05$.

**$P < 0.01$.

***$P < 0.001$.

Appendix A - 2

Correlation coefficients of biochemical, physical, and objective color measurements for *M. biceps femoris*

| | MRA | RIMF | NORA | OCR | OPD |
|---|---|---|---|---|---|
| MetMb | 0.44*** | -0.78*** | 0.79*** | 0.61*** | -0.21 |
| OxyMb | -0.35** | 0.53*** | -0.67*** | -0.35** | 0.01 |
| L* | -0.22 | -0.18 | 0.11 | 0.11 | 0.16 |
| a* | 0.41** | -0.67*** | 0.74*** | 0.50*** | -0.12 |
| b* | 0.08 | -0.34* | 0.45*** | 0.24 | 0.06 |
| OPD | -0.40** | 0.44*** | -0.37** | -0.64*** | -- |
| OCR | 0.42** | -0.82*** | 0.55*** | -- | -- |
| NORA | -0.51*** | -0.68*** | -- | -- | -- |
| RIMF | -0.44*** | -- | -- | -- | -- |

MRA = metmyoglobin reductase activity; RIMF = resistance to induced metmyoglobin formation; NORA = nitric oxide reducing ability; OCR = oxygen consumption rate; OPD = oxygen penetration depth; MetMb = $(K/S)_{572}/(K/S)_{525}$; OxyMb = $(K/S)_{610}/(K/S)_{525}$.

*$P < 0.05$.

**$P < 0.01$.

***$P < 0.001$.

Appendix A - 3
Correlation coefficients of biochemical, physical, and objective color measurements for *M. gluteus medius*

| | MRA | RIMF | NORA | OCR | OPD |
|---|---|---|---|---|---|
| MetMb | 0.43** | -0.63*** | 0.65*** | 0.46*** | -0.09 |
| OxyMb | -0.40** | 0.39** | -0.56*** | -0.23 | -0.05 |
| L* | -0.27* | -0.07 | 0.06 | 0.04 | 0.28* |
| a* | 0.41** | -0.52*** | 0.61*** | 0.40** | -0.03 |
| b* | 0.01 | -0.18 | 0.21 | 0.13 | 0.21 |
| OPD | -0.48*** | 0.53*** | -0.51*** | -0.60*** | -- |
| OCR | 0.30* | -0.76*** | 0.53*** | -- | -- |
| NORA | 0.49*** | -0.63*** | -- | -- | -- |
| RIMF | -0.33* | -- | -- | -- | -- |

MRA = metmyoglobin reductase activity; RIMF = resistance to induced metmyoglobin formation; NORA = nitric oxide reducing ability; OCR = oxygen consumption rate; OPD = oxygen penetration depth; MetMb = $(K/S)_{572}/(K/S)_{525}$; OxyMb = $(K/S)_{610}/(K/S)_{525}$.

*$P < 0.05$.

**$P < 0.01$.

***$P < 0.001$.

Appendix A - 4

Correlation coefficients of biochemical, physical, and objective color measurements for *M. infraspinatus*

| | MRA | RIMF | NORA | OCR | OPD |
|---|---|---|---|---|---|
| MetMb | 0.45*** | -0.78*** | 0.50*** | 0.54*** | -0.59*** |
| OxyMb | -0.44** | 0.59*** | -0.49*** | -0.38** | 0.47*** |
| L* | 0.12 | -0.28* | 0.48*** | 0.16 | -0.38** |
| a* | 0.44 | -0.73*** | 0.51*** | 0.53*** | -0.56*** |
| b* | 0.02 | -0.12 | 0.21 | 0.15 | -0.08 |
| OPD | -0.70*** | 0.62*** | -0.69*** | -0.57*** | -- |
| OCR | 0.24 | -0.76*** | 0.38** | -- | -- |
| NORA | 0.55*** | -0.59*** | -- | -- | -- |
| RIMF | -0.47*** | -- | -- | -- | -- |

MRA = metmyoglobin reductase activity; RIMF = resistance to induced metmyoglobin formation; NORA = nitric oxide reducing ability; OCR = oxygen consumption rate; OPD = oxygen penetration depth; MetMb = $(K/S)_{572}/(K/S)_{525}$; OxyMb = $(K/S)_{610}/(K/S)_{525}$.

*$P < 0.05$.

**$P < 0.01$.

***$P < 0.001$.

Appendix A - 5
Correlation coefficients of biochemical, physical, and objective color measurements for *M. latissimus dorsi*

| | MRA | RIMF | NORA | OCR | OPD |
|---|---|---|---|---|---|
| MetMb | 0.49*** | -0.72*** | 0.63*** | 0.61*** | -0.52*** |
| OxyMb | -0.21 | 0.27* | -0.29* | -0.31* | 0.12 |
| L* | -0.25 | 0.05 | 0.06 | 0.04 | 0.00 |
| a* | 0.39** | -0.51*** | 0.48*** | 0.52*** | -0.35** |
| b* | -0.06 | -0.03 | 0.03 | 0.11 | 0.09 |
| OPD | -0.75*** | 0.66*** | -0.57*** | -0.57*** | -- |
| OCR | 0.49*** | -0.62*** | 0.49*** | -- | -- |
| NORA | 0.52*** | -0.66*** | -- | -- | -- |
| RIMF | -0.59*** | -- | -- | -- | -- |

MRA = metmyoglobin reductase activity; RIMF = resistance to induced metmyoglobin formation; NORA = nitric oxide reducing ability; OCR = oxygen consumption rate; OPD = oxygen penetration depth; MetMb = $(K/S)_{572}/(K/S)_{525}$; OxyMb = $(K/S)_{610}/(K/S)_{525}$.

*$P < 0.05$.

**$P < 0.01$.

***$P < 0.001$.

Appendix A - 6
Correlation coefficients of biochemical, physical, and objective color measurements for *M. longissimus lumborum*

| | MRA | RIMF | NORA | OCR | OPD |
|---|---|---|---|---|---|
| MetMb | -0.11 | -0.48*** | 0.11 | 0.23 | 0.18 |
| OxyMb | 0.41** | -0.13 | 0.27* | 0.33* | -0.64*** |
| L* | -0.24 | -0.28* | 0.09 | 0.18 | 0.25 |
| a* | -0.32* | -0.05 | -0.19 | -0.19 | 0.56*** |
| b* | -0.44*** | 0.15 | -0.25 | -0.35* | 0.56*** |
| OPD | -0.52*** | 0.41** | -0.61*** | -0.54*** | -- |
| OCR | 0.28* | -0.54*** | 0.36** | -- | -- |
| NORA | 0.30* | -0.41** | -- | -- | -- |
| RIMF | -0.32* | -- | -- | -- | -- |

MRA = metmyoglobin reductase activity; RIMF = resistance to induced metmyoglobin formation; NORA = nitric oxide reducing ability; OCR = oxygen consumption rate; OPD = oxygen penetration depth; MetMb = $(K/S)_{572}/(K/S)_{525}$; OxyMb = $(K/S)_{610}/(K/S)_{525}$.

*$P < 0.05$.

**$P < 0.01$.

***$P < 0.001$.

Appendix A - 7
Correlation coefficients of biochemical, physical, and objective color measurements for *M. longissimus thoracis*

| | MRA | RIMF | NORA | OCR | OPD |
|---|---|---|---|---|---|
| MetMb | 0.12 | -0.43** | 0.12 | 0.33* | -0.02 |
| OxyMb | 0.31* | -0.30* | 0.27 | 0.46*** | -0.52*** |
| L* | -0.39** | -0.21 | 0.02 | -0.03 | 0.30* |
| a* | -0.22 | 0.08 | -0.20 | -0.25 | 0.43** |
| b* | -0.29* | 0.30* | -0.17 | -0.44*** | 0.39** |
| OPD | -0.59*** | 0.39** | -0.54*** | -0.65*** | -- |
| OCR | 0.41** | -0.68*** | -0.46*** | -- | -- |
| NORA | 0.37** | -0.35* | -- | -- | -- |
| RIMF | -0.37** | -- | -- | -- | -- |

MRA = metmyoglobin reductase activity; RIMF = resistance to induced metmyoglobin formation; NORA = nitric oxide reducing ability; OCR = oxygen consumption rate; OPD = oxygen penetration depth; MetMb = $(K/S)_{572}/(K/S)_{525}$; OxyMb = $(K/S)_{610}/(K/S)_{525}$.

*$P < 0.05$.

**$P < 0.01$.

***$P < 0.001$.

Appendix A - 8
Correlation coefficients of biochemical, physical, and objective color measurements for *M. pectoralis profundus*

| | MRA | RIMF | NORA | OCR | OPD |
|---|---|---|---|---|---|
| MetMb | 0.71*** | -0.72*** | 0.65*** | 0.38** | -0.56*** |
| OxyMb | -0.66*** | 0.40** | -0.61*** | -0.13 | 0.49*** |
| L* | -0.24 | -0.06 | -0.23 | 0.11 | 0.23 |
| a* | 0.70*** | -0.54*** | 0.64*** | 0.28* | -0.55*** |
| b* | 0.33* | -0.07 | 0.42** | -0.02 | -0.28* |
| OPD | -0.67*** | 0.52*** | -0.56*** | -0.44*** | -- |
| OCR | 0.39** | -0.71*** | 0.40** | -- | -- |
| NORA | 0.67*** | -0.63*** | -- | -- | -- |
| RIMF | -0.54*** | -- | -- | -- | -- |

MRA = metmyoglobin reductase activity; RIMF = resistance to induced metmyoglobin formation; NORA = nitric oxide reducing ability; OCR = oxygen consumption rate; OPD = oxygen penetration depth; MetMb = $(K/S)_{572}/(K/S)_{525}$; OxyMb = $(K/S)_{610}/(K/S)_{525}$.

*$P < 0.05$.

**$P < 0.01$.

***$P < 0.001$.

Appendix A - 9
Correlation coefficients of biochemical, physical, and objective color measurements for *M. psoas major*

| | MRA | RIMF | NORA | OCR | OPD |
|---|---|---|---|---|---|
| MetMb | 0.31$^{*}$ | -0.67$^{***}$ | 0.78$^{***}$ | 0.54$^{***}$ | -0.36$^{**}$ |
| OxyMb | -0.33$^{*}$ | 0.57$^{***}$ | -0.73$^{***}$ | -0.45$^{***}$ | 0.35$^{**}$ |
| L* | -0.28$^{*}$ | -0.25 | 0.24 | 0.28$^{*}$ | 0.16 |
| a* | 0.33$^{*}$ | -0.65$^{***}$ | 0.76$^{***}$ | 0.53$^{***}$ | -0.38$^{**}$ |
| b* | -0.05 | -0.30$^{*}$ | 0.34$^{*}$ | 0.33$^{*}$ | -0.01 |
| OPD | -0.62$^{***}$ | 0.41$^{**}$ | -0.46$^{***}$ | -0.39$^{**}$ | -- |
| OCR | 0.27$^{*}$ | -0.54$^{***}$ | 0.36$^{**}$ | -- | -- |
| NORA | 0.35$^{*}$ | -0.71$^{***}$ | -- | -- | -- |
| RIMF | -0.40$^{**}$ | -- | -- | -- | -- |

MRA = metmyoglobin reductase activity; RIMF = resistance to induced metmyoglobin formation; NORA = nitric oxide reducing ability; OCR = oxygen consumption rate; OPD = oxygen penetration depth; MetMb = $(K/S)_{572}/(K/S)_{525}$; OxyMb = $(K/S)_{610}/(K/S)_{525}$.

$^{*}P < 0.05$.

$^{**}P < 0.01$.

$^{***}P < 0.001$.

Appendix A - 10
Correlation coefficients of biochemical, physical, and objective color measurements for *M. rectus femoris*

| | MRA | RIMF | NORA | OCR | OPD |
|---|---|---|---|---|---|
| MetMb | 0.42** | -0.56*** | 0.37** | 0.43** | -0.44*** |
| OxyMb | -0.33* | 0.23 | -0.10 | -0.01 | 0.10 |
| L* | -0.28* | -0.02 | 0.09 | 0.13 | 0.01 |
| a* | 0.37** | -0.36** | 0.18 | 0.18 | -0.22 |
| b* | 0.07 | 0.02 | -0.21 | -0.19 | 0.24 |
| OPD | -0.63*** | 0.27 | -0.31* | -0.55*** | -- |
| OCR | 0.26 | -0.41** | 0.27* | -- | -- |
| NORA | 0.30* | -0.29* | -- | -- | -- |
| RIMF | -0.26 | -- | -- | -- | -- |

MRA = metmyoglobin reductase activity; RIMF = resistance to induced metmyoglobin formation; NORA = nitric oxide reducing ability; OCR = oxygen consumption rate; OPD = oxygen penetration depth; MetMb = $(K/S)_{572}/(K/S)_{525}$; OxyMb = $(K/S)_{610}/(K/S)_{525}$.

*$P < 0.05$.

**$P < 0.01$.

***$P < 0.001$.

Appendix A - 11
Correlation coefficients of biochemical, physical, and objective color measurements for *M. semimembranosus*

| | MRA | RIMF | NORA | OCR | OPD |
|---|---|---|---|---|---|
| MetMb | 0.36** | -0.61*** | 0.48*** | 0.43** | -0.01 |
| OxyMb | -0.12 | 0.36** | -0.31* | -0.12 | -0.23 |
| L* | -0.18 | -0.10 | -0.08 | -0.15 | 0.44*** |
| a* | 0.23 | -0.50*** | 0.41** | 0.30* | 0.10 |
| b* | -0.14 | -0.15 | 0.10 | -0.04 | 0.30* |
| OPD | -0.42** | 0.26 | -0.44 | -0.68*** | -- |
| OCR | 0.44*** | -0.61*** | 0.50*** | -- | -- |
| NORA | 0.36** | -0.38** | -- | -- | -- |
| RIMF | -0.37** | -- | -- | -- | -- |

MRA = metmyoglobin reductase activity; RIMF = resistance to induced metmyoglobin formation; NORA = nitric oxide reducing ability; OCR = oxygen consumption rate; OPD = oxygen penetration depth; MetMb = $(K/S)_{572}/(K/S)_{525}$; OxyMb = $(K/S)_{610}/(K/S)_{525}$.

*$P < 0.05$.

**$P < 0.01$.

***$P < 0.001$.

Appendix A - 12
Correlation coefficients of biochemical, physical, and objective color measurements for *M. semitendinosus*

| | MRA | RIMF | NORA | OCR | OPD |
|---|---|---|---|---|---|
| MetMb | 0.05 | -0.63*** | 0.43** | 0.50*** | -0.16 |
| OxyMb | 0.20 | 0.04 | -0.01 | 0.11 | -0.33* |
| L* | -0.32* | -0.18 | -0.15 | -0.05 | 0.41** |
| a* | -0.02 | -0.21 | 0.25 | 0.16 | 0.06 |
| b* | -0.29* | 0.13 | -0.16 | -0.28* | 0.43** |
| OPD | -0.50*** | 0.33* | -0.43** | -0.65*** | -- |
| OCR | 0.41** | -0.61*** | 0.46*** | -- | -- |
| NORA | 0.24 | -0.32* | -- | -- | -- |
| RIMF | -0.34* | -- | -- | -- | -- |

MRA = metmyoglobin reductase activity; RIMF = resistance to induced metmyoglobin formation; NORA = nitric oxide reducing ability; OCR = oxygen consumption rate; OPD = oxygen penetration depth; MetMb = $(K/S)_{572}/(K/S)_{525}$; OxyMb = $(K/S)_{610}/(K/S)_{525}$.

*$P < 0.05$.

**$P < 0.01$.

***$P < 0.001$.

Appendix A - 13
Correlation coefficients of biochemical, physical, and objective color measurements for *M. serratus ventralis*

| | MRA | RIMF | NORA | OCR | OPD |
|---|---|---|---|---|---|
| MetMb | 0.31* | -0.76*** | 0.63*** | 0.61*** | -0.36** |
| OxyMb | -0.11 | 0.47*** | -0.54*** | -0.31* | 0.14 |
| L* | -0.08 | -0.05 | -0.27 | 0.00 | -0.12 |
| a* | 0.22 | -0.66*** | 0.63*** | 0.50*** | -0.28* |
| b* | -0.10 | -0.11 | 0.12 | 0.17 | -0.01 |
| OPD | -0.42** | 0.63*** | -0.42** | -0.46*** | -- |
| OCR | 0.24 | -0.61*** | 0.30* | -- | -- |
| NORA | 0.31* | -0.70*** | -- | -- | -- |
| RIMF | -0.39** | -- | -- | -- | -- |

MRA = metmyoglobin reductase activity; RIMF = resistance to induced metmyoglobin formation; NORA = nitric oxide reducing ability; OCR = oxygen consumption rate; OPD = oxygen penetration depth; MetMb = $(K/S)_{572}/(K/S)_{525}$; OxyMb = $(K/S)_{610}/(K/S)_{525}$.

*$P < 0.05$.

**$P < 0.01$.

***$P < 0.001$.

Appendix A - 14
Correlation coefficients of biochemical, physical, and objective color measurements for *M. supraspinatus*

| | MRA | RIMF | NORA | OCR | OPD |
|---|---|---|---|---|---|
| MetMb | 0.50*** | -0.68*** | 0.52*** | 0.66*** | -0.53*** |
| OxyMb | -0.48*** | 0.58*** | -0.51*** | -0.49*** | 0.40** |
| L* | -0.13 | -0.20 | 0.42** | 0.11 | -0.01 |
| a* | 0.50*** | -0.67*** | 0.52*** | 0.64*** | -0.52*** |
| b* | 0.07 | -0.30* | 0.13 | 0.30* | -0.24 |
| OPD | -0.45*** | 0.64*** | -0.49*** | -0.66*** | -- |
| OCR | 0.31* | -0.70*** | 0.33* | -- | -- |
| NORA | 0.51*** | -0.50*** | -- | -- | -- |
| RIMF | -0.56*** | -- | -- | -- | -- |

MRA = metmyoglobin reductase activity; RIMF = resistance to induced metmyoglobin formation; NORA = nitric oxide reducing ability; OCR = oxygen consumption rate; OPD = oxygen penetration depth; MetMb = $(K/S)_{572}/(K/S)_{525}$; OxyMb = $(K/S)_{610}/(K/S)_{525}$.

*$P < 0.05$.

**$P < 0.01$.

***$P < 0.001$.

Appendix A - 15
Correlation coefficients of biochemical, physical, and objective color measurements for *M. tensor fasciae latae*

| | MRA | RIMF | NORA | OCR | OPD |
|---|---|---|---|---|---|
| MetMb | 0.25 | -0.47*** | 0.50*** | 0.55*** | -0.36** |
| OxyMb | 0.22 | -0.23 | -0.05 | 0.25 | -0.19 |
| L* | -0.53*** | 0.01 | 0.18 | -0.07 | 0.15 |
| a* | 0.06 | -0.03 | 0.28* | 0.08 | -0.06 |
| b* | -0.25 | 0.22 | 0.00 | -0.32* | 0.20 |
| OPD | -0.63*** | 0.64*** | -0.54*** | -0.70*** | -- |
| OCR | 0.52*** | -0.52*** | 0.46*** | -- | -- |
| NORA | 0.37** | -0.61*** | -- | -- | -- |
| RIMF | -0.43** | -- | -- | -- | -- |

MRA = metmyoglobin reductase activity; RIMF = resistance to induced metmyoglobin formation; NORA = nitric oxide reducing ability; OCR = oxygen consumption rate; OPD = oxygen penetration depth; MetMb = $(K/S)_{572}/(K/S)_{525}$; OxyMb = $(K/S)_{610}/(K/S)_{525}$.

*$P < 0.05$.

**$P < 0.01$.

***$P < 0.001$.

Appendix A - 16
Correlation coefficients of biochemical, physical, and objective color measurements for *M. trapezius*

| | MRA | RIMF | NORA | OCR | OPD |
|---|---|---|---|---|---|
| MetMb | 0.45*** | -0.62*** | 0.46*** | 0.53*** | -0.72*** |
| OxyMb | -0.23 | 0.39** | -0.44*** | -0.13 | 0.44*** |
| L* | -0.31* | 0.08 | 0.25 | 0.14 | 0.12 |
| a* | 0.37** | -0.52*** | 0.45*** | 0.32* | -0.58*** |
| b* | 0.06 | -0.15 | 0.33* | -0.03 | -0.11 |
| OPD | -0.69*** | 0.74*** | -0.42** | -0.50*** | -- |
| OCR | 0.28* | -0.38** | 0.10 | -- | --- |
| NORA | 0.18 | -0.35* | -- | -- | -- |
| RIMF | 0.64*** | -- | -- | -- | -- |

MRA = metmyoglobin reductase activity; RIMF = resistance to induced metmyoglobin formation; NORA = nitric oxide reducing ability; OCR = oxygen consumption rate; OPD = oxygen penetration depth; MetMb = $(K/S)_{572}/(K/S)_{525}$; OxyMb = $(K/S)_{610}/(K/S)_{525}$.

*$P < 0.05$.

**$P < 0.01$.

***$P < 0.001$.

Appendix A - 17
Correlation coefficients of biochemical, physical, and objective color measurements for *M. triceps brachii* – long head

| | MRA | RIMF | NORA | OCR | OPD |
|---|---|---|---|---|---|
| MetMb | 0.24 | -0.76*** | 0.76*** | 0.60*** | -0.24 |
| OxyMb | -0.21 | 0.45*** | -0.64*** | -0.28* | -0.05 |
| L* | -0.27* | -0.29* | 0.08 | 0.16 | -0.03 |
| a* | 0.23 | -0.62*** | 0.71*** | 0.46*** | -0.07 |
| b* | 0.01 | -0.19 | 0.31* | 0.04 | 0.30* |
| OPD | -0.49*** | 0.48*** | -0.40** | -0.61*** | -- |
| OCR | 0.32* | -0.83*** | 0.50*** | -- | -- |
| NORA | 0.38** | -0.59*** | -- | -- | -- |
| RIMF | -0.23 | -- | -- | -- | -- |

MRA = metmyoglobin reductase activity; RIMF = resistance to induced metmyoglobin formation; NORA = nitric oxide reducing ability; OCR = oxygen consumption rate; OPD = oxygen penetration depth; MetMb = $(K/S)_{572}/(K/S)_{525}$; OxyMb = $(K/S)_{610}/(K/S)_{525}$.

*$P < 0.05$.

**$P < 0.01$.

***$P < 0.001$.

Appendix A - 18
Correlation coefficients of biochemical, physical, and objective color measurements for *M. triceps brachii* – lateral head

| | MRA | RIMF | NORA | OCR | OPD |
|---|---|---|---|---|---|
| MetMb | 0.55*** | -0.73*** | 0.71*** | 0.61*** | -0.44*** |
| OxyMb | -0.39** | 0.36** | -0.56*** | -0.30* | 0.22 |
| L* | -0.06 | -0.21 | 0.28* | 0.07 | -0.03 |
| a* | 0.47*** | -0.57*** | 0.63*** | 0.49*** | -0.36** |
| b* | 0.05 | -0.13 | 0.21 | 0.11 | -0.10 |
| OPD | -0.45*** | 0.60*** | -0.52*** | -0.62*** | -- |
| OCR | 0.48*** | -0.86*** | 0.48*** | -- | -- |
| NORA | 0.51*** | -0.58*** | -- | -- | -- |
| RIMF | -0.53*** | -- | -- | -- | -- |

MRA = metmyoglobin reductase activity; RIMF = resistance to induced metmyoglobin formation; NORA = nitric oxide reducing ability; OCR = oxygen consumption rate; OPD = oxygen penetration depth; MetMb = $(K/S)_{572}/(K/S)_{525}$; OxyMb = $(K/S)_{610}/(K/S)_{525}$.

*$P < 0.05$.

**$P < 0.01$.

***$P < 0.001$.

Appendix A - 19
Correlation coefficients of biochemical, physical, and objective color measurements for *M. vastus lateralis*

| | MRA | RIMF | NORA | OCR | OPD |
|---|---|---|---|---|---|
| MetMb | 0.34$^{*}$ | -0.55$^{***}$ | 0.65$^{***}$ | 0.47$^{***}$ | -0.23 |
| OxyMb | -0.10 | 0.16 | -0.42$^{**}$ | -0.09 | -0.07 |
| L* | -0.27 | -0.17 | 0.34$^{*}$ | -0.03 | 0.16 |
| a* | 0.19 | -0.32$^{*}$ | 0.52$^{***}$ | 0.25 | -0.03 |
| b* | -0.15 | 0.13 | 0.18 | -0.10 | 0.25 |
| OPD | -0.63$^{***}$ | 0.55$^{***}$ | -0.24 | -0.68$^{***}$ | -- |
| OCR | 0.54$^{***}$ | -0.75$^{***}$ | 0.40$^{**}$ | -- | -- |
| NORA | 0.29$^{*}$ | -0.50$^{***}$ | -- | -- | -- |
| RIMF | -0.55$^{***}$ | -- | -- | -- | -- |

MRA = metmyoglobin reductase activity; RIMF = resistance to induced metmyoglobin formation; NORA = nitric oxide reducing ability; OCR = oxygen consumption rate; OPD = oxygen penetration depth; MetMb = $(K/S)_{572}/(K/S)_{525}$; OxyMb = $(K/S)_{610}/(K/S)_{525}$.

$^{*}P < 0.05$.

$^{**}P < 0.01$.

$^{***}P < 0.001$.

# APPENDIX B

## LEAST SQUARES MEANS OF OBJECTIVE COLOR AND COLOR STABILITY MEASURES IN ASCENDING OR DESCENDING ORDER FOR 19 BOVINE MUSCLES

The following tables (B – 1 through B – 13) contain least squares means of objective color and color stability measures in ascending or descending order.

Appendix B – 1
Least squares means for $(K/S)_{572}/(K/S)_{525}$ values of 19 bovine muscles in descending order

| Muscle | $(K/S)_{572}/(K/S)_{525}$ |
|---|---|
| *M. longissimus thoracis* | 1.35[a] |
| *M. longissimus lumborum* | 1.33[a] |
| *M. semitendinosus* | 1.32[a] |
| *M. tensor fasciae latae* | 1.28[b] |
| *M. semimembranosus* | 1.26[bc] |
| *M. vastus lateralis* | 1.26[bc] |
| *M. rectus femoris* | 1.26[b] |
| *M. trapezius* | 1.23[cd] |
| *M. gluteus medius* | 1.22[d] |
| *M. latissimus dorsi* | 1.21[de] |
| *M. pectoralis profundus* | 1.18[f] |
| *M. triceps brachii* – long head | 1.18[f] |
| *M. biceps femoris* | 1.18[ef] |
| *M. adductor* | 1.17[f] |
| *M. triceps brachii* – lateral head | 1.17[f] |
| *M. serratus ventralis* | 1.16[f] |
| *M. supraspinatus* | 1.12[g] |
| *M. infraspinatus* | 1.10[gh] |
| *M. psoas major* | 1.08[h] |
| SEM[*] | 0.012 |

[a-h]Means lacking a common superscript letter differ ($P < 0.05$).
[*]SEM is the standard error of the least squares means.

Appendix B – 2
Least squares means for $(K/S)_{610}/(K/S)_{525}$ values of 19 bovine muscles in ascending order

| Muscle | $(K/S)_{610}/(K/S)_{525}$ |
|---|---|
| *M. semitendinosus* | $0.22^{m}$ |
| *M. longissimus lumborum* | $0.24^{kl}$ |
| *M. longissimus thoracis* | $0.24^{lm}$ |
| *M. semimembranosus* | $0.24^{lm}$ |
| *M. rectus femoris* | $0.25^{jkl}$ |
| *M. tensor fasciae latae* | $0.26^{hij}$ |
| *M. vastus lateralis* | $0.26^{ijk}$ |
| *M. triceps brachii* – long head | $0.27^{ghi}$ |
| *M. biceps femoris* | $0.28^{fg}$ |
| *M. serratus ventralis* | $0.28^{fg}$ |
| *M. gluteus medius* | $0.28^{fgh}$ |
| *M. adductor* | $0.28^{fgh}$ |
| *M. pectoralis profundus* | $0.29^{ef}$ |
| *M. triceps brachii* – lateral head | $0.30^{cde}$ |
| *M. trapezius* | $0.30^{de}$ |
| *M. infraspinatus* | $0.32^{ab}$ |
| *M. latissimus dorsi* | $0.32^{bc}$ |
| *M. supraspinatus* | $0.32^{bcd}$ |
| *M. psoas major* | $0.34^{a}$ |
| SEM* | 0.006 |

[a-m]Means lacking a common superscript letter differ ($P < 0.05$).
*SEM is the standard error of the least squares means.

Appendix B – 3
Least squares means for L*-values of 19 bovine muscles in descending order

| Muscle | L* |
|---|---|
| *M. semitendinosus* | 49.17[a] |
| *M. tensor fasciae latae* | 47.75[b] |
| *M. latissimus dorsi* | 46.84[c] |
| *M. trapezius* | 46.76[c] |
| *M. psoas major* | 45.81[d] |
| *M. adductor* | 45.06[de] |
| *M. pectoralis profundus* | 44.98[ef] |
| *M. infraspinatus* | 44.87[ef] |
| *M. rectus femoris* | 44.24[fg] |
| *M. supraspinatus* | 44.07[gh] |
| *M. biceps femoris* | 44.02[gh] |
| *M. triceps brachii* – lateral head | 43.50[ghi] |
| *M. serratus ventralis* | 43.45[hi] |
| *M. semimembranosus* | 43.17[ji] |
| *M. gluteus medius* | 43.17[ji] |
| *M. vastus lateralis* | 42.53[jk] |
| *M. longissimus lumborum* | 42.20[kl] |
| *M. longissimus thoracis* | 41.87[kl] |
| *M. triceps brachii* – long head | 41.50[l] |
| SEM[*] | 0.28 |

[a-l]Means lacking a common superscript letter differ ($P < 0.05$).
[*]SEM is the standard error of the least squares means.

Appendix B – 4
Least squares means for a*-values of 19 bovine muscles in descending order

| Muscle | a* |
|---|---|
| *M. semitendinosus* | 27.62[a] |
| *M. longissimus thoracis* | 27.24[a] |
| *M. longissimus lumborum* | 27.13[a] |
| *M. semimembranosus* | 26.93[a] |
| *M. rectus femoris* | 25.76[b] |
| *M. vastus lateralis* | 25.69[b] |
| *M. tensor fasciae latae* | 25.10[bc] |
| *M. triceps brachii* – long head | 24.50[cd] |
| *M. gluteus medius* | 24.45[cde] |
| *M. adductor* | 24.27[cde] |
| *M. biceps femoris* | 23.97[de] |
| *M. serratus ventralis* | 23.62[ef] |
| *M. pectoralis profundus* | 23.41[ef] |
| *M. triceps brachii* – lateral head | 22.76[fg] |
| *M. trapezius* | 22.72[fg] |
| *M. latissimus dorsi* | 21.77[gh] |
| *M. supraspinatus* | 21.62[h] |
| *M. infraspinatus* | 21.14[hi] |
| *M. psoas major* | 20.53[i] |
| SEM[*] | 0.387 |

[a-i]Means lacking a common superscript letter differ ($P < 0.05$).
[*]SEM is the standard error of the least squares means.

Appendix B – 5
Least squares means for b*-values of 19 bovine muscles in descending order

| Muscle | b* |
|---|---|
| *M. semitendinosus* | 21.18[a] |
| *M. semimembranosus* | 20.19[b] |
| *M. rectus femoris* | 19.98[bc] |
| *M. longissimus thoracis* | 19.62[bcd] |
| *M. triceps brachii* – long head | 19.53[bcd] |
| *M. longissimus lumborum* | 19.48[bcd] |
| *M. adductor* | 19.43[cd] |
| *M. vastus lateralis* | 19.15[de] |
| *M. serratus ventralis* | 18.50[ef] |
| *M. biceps femoris* | 18.19[f] |
| *M. tensor fasciae latae* | 18.10[f] |
| *M. pectoralis profundus* | 18.08[f] |
| *M. gluteus medius* | 17.97[fg] |
| *M. infraspinatus* | 17.35[gh] |
| *M. supraspinatus* | 17.10[h] |
| *M. triceps brachii* – lateral head | 17.09[h] |
| *M. psoas major* | 16.87[h] |
| *M. trapezius* | 16.12[i] |
| *M. latissimus dorsi* | 15.22[j] |
| SEM[*] | 0.256 |

[a-j]Means lacking a common superscript letter differ ($P < 0.05$).
[*]SEM is the standard error of the least squares means.

Appendix B – 6
Least squares means for metmyoglobin reductase activity (nmoles/min/g) of 19 bovine muscles in descending order

| Muscle | MRA |
|---|---|
| *M. infraspinatus* | 256.9[a] |
| *M. serratus ventralis* | 252.4[a] |
| *M. supraspinatus* | 243.2[a] |
| *M. longissimus lumborum* | 227.2[b] |
| *M. gluteus medius* | 226.5[b] |
| *M. biceps femoris* | 222.6[bc] |
| *M. trapezius* | 221.7[bcd] |
| *M. adductor* | 221.1[bcde] |
| *M. triceps brachii* – long head | 220.0[bcdef] |
| *M. longissimus thoracis* | 219.5[bcdef] |
| *M. triceps brachii* – lateral head | 218.3[bcdef] |
| *M. latissimus dorsi* | 212.8[bcdefg] |
| *M. psoas major* | 210.8[cdefg] |
| *M. pectoralis profundus* | 207.8[defg] |
| *M. vastus lateralis* | 206.5[efg] |
| *M. tensor fasciae latae* | 205.4[fg] |
| *M. semimembranosus* | 202.2[g] |
| *M. rectus femoris* | 187.0[h] |
| *M. semitendinosus* | 181.5[h] |
| SEM[*] | 5.32 |

[a-h]Means lacking a common superscript letter differ ($P < 0.05$).
[*]SEM is the standard error of the least squares means.

Appendix B – 7
Least squares means for resistance to induced metmyoglobin formation (% metmyoglobin) of 19 bovine muscles in ascending order

| Muscle | RIMF |
|---|---|
| *M. longissimus lumborum* | $42.7^{h}$ |
| *M. longissimus thoracis* | $42.7^{h}$ |
| *M. semitendinosus* | $48.6^{gh}$ |
| *M. tensor fasciae latae* | $52.0^{fg}$ |
| *M. rectus femoris* | $57.0^{efg}$ |
| *M. trapezius* | $57.4^{ef}$ |
| *M. semimembranosus* | $60.6^{def}$ |
| *M. latissimus dorsi* | $61.0^{de}$ |
| *M. vastus lateralis* | $64.5^{cde}$ |
| *M. serratus ventralis* | $65.0^{bcde}$ |
| *M. gluteus medius* | $65.0^{bcde}$ |
| *M. pectoralis profundus* | $67.8^{abcd}$ |
| *M. supraspinatus* | $67.9^{abcd}$ |
| *M. triceps brachii* – long head | $69.2^{abcd}$ |
| *M. triceps brachii* – lateral head | $70.2^{abc}$ |
| *M. biceps femoris* | $71.3^{abc}$ |
| *M. infraspinatus* | $73.5^{ab}$ |
| *M. adductor* | $75.3^{a}$ |
| *M. psoas major* | $76.0^{a}$ |
| SEM* | 3.15 |

[a-h]Means lacking a common superscript letter differ ($P < 0.05$).
*SEM is the standard error of the least squares means.

Appendix B – 8
Least squares means for nitric oxide metmyoglobin reducing ability (Δ% metmyoglobin) of 19 bovine muscles in descending order

| Muscle | NORA |
|---|---|
| *M. semitendinosus* | 59.9[a] |
| *M. longissimus thoracis* | 59.6[a] |
| *M. longissimus lumborum* | 58.0[a] |
| *M. tensor fasciae latae* | 58.0[a] |
| *M. vastus lateralis* | 49.5[b] |
| *M. trapezius* | 48.2[bc] |
| *M. latissimus dorsi* | 47.2[bcd] |
| *M. triceps brachii* – long head | 47.1[bcd] |
| *M. triceps brachii* – lateral head | 47.0[bcd] |
| *M. supraspinatus* | 46.9[bcd] |
| *M. biceps femoris* | 46.4[bcde] |
| *M. gluteus medius* | 45.1[bcdef] |
| *M. pectoralis profundus* | 44.5[cdef] |
| *M. rectus femoris* | 43.1[def] |
| *M. semimembranosus* | 41.7[ef] |
| *M. infraspinatus* | 41.2[f] |
| *M. serratus ventralis* | 40.9[f] |
| *M. psoas major* | 29.4[g] |
| *M. adductor* | 29.1[g] |
| SEM[*] | 1.79 |

[a-g]Means lacking a common superscript letter differ ($P < 0.05$).
[*]SEM is the standard error of the least squares means.

Appendix B – 9
Least squares means for oxygen consumption rate ($\Delta\%$ $CO_2$) of 19 bovine muscles in ascending order

| Muscle | OCR |
|---|---|
| *M. adductor* | 1.01[e] |
| *M. tensor fasciae latae* | 1.01[e] |
| *M. latissimus dorsi* | 1.02[de] |
| *M. longissimus lumborum* | 1.05[cde] |
| *M. gluteus medius* | 1.06[cde] |
| *M. longissimus thoracis* | 1.08[cde] |
| *M. vastus lateralis* | 1.10[cde] |
| *M. semitendinosus* | 1.11[cde] |
| *M. rectus femoris* | 1.13[cde] |
| *M. semimembranosus* | 1.13[cde] |
| *M. biceps femoris* | 1.15[cde] |
| *M. pectoralis profundus* | 1.17[cde] |
| *M. triceps brachii* – long head | 1.19[cd] |
| *M. trapezius* | 1.20[c] |
| *M. psoas major* | 1.22[bc] |
| *M. triceps brachii* – lateral head | 1.22[bc] |
| *M. infraspinatus* | 1.38[ab] |
| *M. serratus ventralis* | 1.39[ab] |
| *M. supraspinatus* | 1.45[a] |
| SEM[*] | 0.063 |

[a-e]Means lacking a common superscript letter differ ($P < 0.05$).
[*]SEM is the standard error of the least squares means.

Appendix B – 10
Least squares means for oxygen penetration depth (mm) of 19 bovine muscles in descending order

| Muscle | OPD |
|---|---|
| *M. semitendinosus* | 5.61[a] |
| *M. longissimus thoracis* | 5.04[c] |
| *M. tensor fasciae latae* | 4.98[b] |
| *M. longissimus lumborum* | 4.80[bc] |
| *M. semimembranosus* | 4.73[bc] |
| *M. gluteus medius* | 4.53[cd] |
| *M. psoas major* | 4.47[cde] |
| *M. vastus lateralis* | 4.22[def] |
| *M. rectus femoris* | 4.21[defg] |
| *M. biceps femoris* | 4.12[efgh] |
| *M. adductor* | 4.11[efghi] |
| *M. latissimus dorsi* | 4.01[fghi] |
| *M. triceps brachii* – lateral head | 3.85[fghi] |
| *M. pectoralis profundus* | 3.84[ghi] |
| *M. supraspinatus* | 3.74[i] |
| *M. triceps brachii* – long head | 3.74[hi] |
| *M. trapezius* | 3.30[j] |
| *M. serratus ventralis* | 3.09[j] |
| *M. infraspinatus* | 2.94[j] |
| SEM[*] | 0.137 |

[a-j]Means lacking a common superscript letter differ ($P < 0.05$).
[*]SEM is the standard error of the least squares means.

Appendix B – 11
Least squares means for myoglobin content (mg/g) of 19 bovine muscles in descending order

| Muscle | Myoglobin |
|---|---|
| *M. gluteus medius* | 5.62[a] |
| *M. serratus ventralis* | 5.47[ab] |
| *M. triceps brachii* – long head | 5.43[ab] |
| *M. biceps femoris* | 5.41[ab] |
| *M. supraspinatus* | 5.35[ab] |
| *M. vastus lateralis* | 5.34[ab] |
| *M. infraspinatus* | 5.20[bc] |
| *M. adductor* | 5.14[bc] |
| *M. triceps brachii* – lateral head | 4.93[cd] |
| *M. semimembranosus* | 4.90[cd] |
| *M. longissimus lumborum* | 4.62[de] |
| *M. longissimus thoracis* | 4.48[e] |
| *M. rectus femoris* | 4.35[ef] |
| *M. pectoralis profundus* | 4.35[ef] |
| *M. psoas major* | 4.10[fg] |
| *M. trapezius* | 4.04[fg] |
| *M. tensor fasciae latae* | 4.01[fg] |
| *M. latissimus dorsi* | 3.97[g] |
| *M. semitendinosus* | 3.60[h] |
| SEM[*] | 0.124 |

[a-h]Means lacking a common superscript letter differ ($P < 0.05$).
[*]SEM is the standard error of the least squares means.

Appendix B – 12
Least squares means for 2-thiobarbituric acid reactive substances (mg/kg) of 19 bovine muscles in ascending order

| Muscle | TBARS |
|---|---|
| *M. longissimus thoracis* | $0.16^{h}$ |
| *M. longissimus lumborum* | $0.19^{gh}$ |
| *M. trapezius* | $0.23^{fgh}$ |
| *M. tensor fasciae latae* | $0.24^{efg}$ |
| *M. latissimus dorsi* | $0.24^{efgh}$ |
| *M. semitendinosus* | $0.24^{efgh}$ |
| *M. serratus ventralis* | $0.26^{defg}$ |
| *M. semimembranosus* | $0.26^{defg}$ |
| *M. pectoralis profundus* | $0.26^{defg}$ |
| *M. supraspinatus* | $0.28^{def}$ |
| *M. rectus femoris* | $0.28^{def}$ |
| *M. infraspinatus* | $0.29^{cdef}$ |
| *M. triceps brachii* – lateral head | $0.32^{bcde}$ |
| *M. vastus lateralis* | $0.33^{abcd}$ |
| *M. gluteus medius* | $0.33^{bcd}$ |
| *M. triceps brachii* – long head | $0.33^{bcd}$ |
| *M. adductor* | $0.37^{abc}$ |
| *M. psoas major* | $0.39^{ab}$ |
| *M. biceps femoris* | $0.42^{a}$ |
| SEM* | 0.03 |

[a-h]Means lacking a common superscript letter differ ($P < 0.05$).
*SEM is the standard error of the least squares means.

Appendix B – 13
Least squares means for pH of 19 bovine muscles in ascending order

| Muscle | pH |
|---|---|
| *M. gluteus medius* | 5.69[h] |
| *M. biceps femoris* | 5.69[h] |
| *M. semimembranosus* | 5.70[gh] |
| *M. vastus lateralis* | 5.71[gh] |
| *M. semitendinosus* | 5.73[efgh] |
| *M. adductor* | 5.73[efgh] |
| *M. pectoralis profundus* | 5.73[fgh] |
| *M. psoas major* | 5.73[fgh] |
| *M. latissimus dorsi* | 5.74[defg] |
| *M. triceps brachii* – long head | 5.75[defg] |
| *M. longissimus lumborum* | 5.77[cdef] |
| *M. triceps brachii* – lateral head | 5.77[def] |
| *M. longissimus thoracis* | 5.78[cd] |
| *M. tensor fasciae latae* | 5.78[cde] |
| *M. rectus femoris* | 5.82[bc] |
| *M. supraspinatus* | 5.84[b] |
| *M. serratus ventralis* | 5.92[a] |
| *M. trapezius* | 5.93[a] |
| *M. infraspinatus* | 5.93[a] |
| SEM[*] | 0.017 |

[a-h]Means lacking a common superscript letter differ ($P < 0.05$).
[*]SEM is the standard error of the least squares means.

# VITA

David Richard McKenna

Permanent address:

5978 17th Avenue, Garrison, IA 52229

Educational background:

B.S., Animal Science, Iowa State University, Ames, IA, December 1997

M.S., Meat Science, Iowa State University, Ames, IA, August 1999

Ph.D., Animal Science, Texas A&M University, College Station, TX, December 2003