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Light Source Influences Color Stability and Lipid Oxidation in Steaks from Low Color Stability Beef *Triceps brachii* Muscle

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Abstract: Color of retail fresh meat is one of the most important quality attributes affecting purchasing decisions for consumers. The objective of this study was to evaluate the impact of different light sources on surface color and lipid oxidation during retail display of fresh steaks from beef *Triceps brachii* (TB), a muscle with low color and lipid oxidative stabilities. Steaks (n = 12) from 20 TB muscles were overwrapped with oxygen-permeable polyvinyl chloride, and assigned to one of three lighting treatments, i.e., high UV fluorescent (HFLO), low UV fluorescent (FLO), and light emitting diode (LED), in temperature-controlled deli cases. Steaks were removed on retail display d 1, 3, 5, and 7 for evaluating instrumental color (L^*, a^*, and b^* values), surface myoglobin redox forms, metmyoglobin reducing ability, and lipid oxidation. Surface redness (a^* values) of TB steaks decreased ($P < 0.05$) during retail display. Light source influenced a^* values, with HFLO-displayed steaks having higher ($P < 0.05$) a^* values than steaks exposed to both FLO and LED light sources. Oxymyoglobin levels were higher ($P < 0.05$) for TB steaks displayed under HFLO lights than those displayed under FLO (on d 3 and 7) or LED (on d 5 and 7) lights. Steaks displayed under HFLO lights had lower ($P < 0.05$) metmyoglobin levels than those exposed to both FLO and LED lights on d 5 and 7. Lipid oxidation increased over retail display time, and on d 7 of retail display, steaks exposed to HFLO had less ($P < 0.05$) lipid oxidation than those displayed in FLO or LED. The results of the present study indicated that color stability and lipid oxidation in TB steaks during retail display are impacted by light source. The HFLO lighting may help to minimize surface discoloration and lipid oxidation in low color stability beef muscles.

Keywords: beef color, lighting, myoglobin, oxidation, *Triceps brachii*
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Introduction

Consumer purchasing decisions are influenced by fresh beef color more than any other quality parameter in a retail setting (Mancini and Hunt, 2005; Suman et al., 2014). Fresh meat quality is impacted by length of retail display (Jeremiah and Gibson, 2001; Martin et al., 2013), temperature (Martin et al., 2013), and light source (Steele et al., 2016; Cooper et al., 2016). With multiple factors impacting meat color stability, it is imperative that we provide complete information on those factors to assist retail establishments in implementing procedures to capitalize on product freshness and overall marketability of fresh beef products to maximize profit. Therefore, evaluating the impact of light sources during retail display on beef muscles with varying color stabilities is critical to both the beef and retail industries.

A recent study conducted at the University of Missouri, on ground beef displayed under light emit-

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ting diode (LED), fluorescent, and no light, demonstrated that LED light sources promoted redness retention in high- and low-fat ground beef patties during retail display (Cooper et al., 2016). This conflicts with a report by Steele et al. (2016) who reported no differences in *a** values between ground beef displayed under LED and fluorescent, but did find differences in beef steak redness.

Beef color stability varies from muscle to muscle within a carcass (McKenna et al., 2005; Seyfert et al., 2007; Canto et al., 2016). McKenna et al. (2005) evaluated 19 beef muscles for color stability, metmyoglobin reducing activity, and other biochemical attributes governing color and reported that *Triceps brachii* (TB) is a muscle with low color stability. Practical strategies to maximize the color shelf-life of beef muscles with low color stability are relevant the meat industry. While the influence of several post-harvest strategies on the color attributes of fresh beef has been studied extensively (Suman et al., 2014; Suman and Nair, 2017), there are many questions unanswered regarding the retail color stability of whole-muscle beef cuts under various light sources. The objectives of the present study were to evaluate the impact of low-UV fluorescent (FLO), high-UV fluorescent (HFLO), and LED lighting sources on the surface color and lipid oxidation of steaks from TB, a beef muscle with low color stability, during retail display.

Materials and Methods

Beef fabrication and retail display

Twenty beef shoulder clod hearts (USDA Select grade, Institutional Meat Purchase Specification 114E; USDA, 2010) were purchased from a local purveyor and delivered to the University of Missouri meat laboratory in vacuum packaging. Muscles were aged for 20 d postpackaging date at 1.1 ± 1°C, and the TB muscles were removed. Twelve steaks (1.9 cm thick) were cut from each muscle. Steaks were then individually packaged on Styrofoam trays and overwrapped with oxygen permeable polyvinyl chloride (15,500 to 16,275 cm^3/m^2 per 24 h oxygen transmission rate at 23°C). Steaks from each clod heart were then randomly assigned to 1 of 3 lighting treatments (HFLO, FLO, and LED) × day of retail display (1, 3, 5, and 7) combination, and were placed into the deli case (TDBD-72-4, True Food Service Equipment, O'Fallon, MO) containing the appropriate lighting treatment and all external light sources blocked out. Temperature was monitored by factory-supplied thermometers within each deli case. All 3 deli cases had temperature of 2 ± 1°C. The average light intensities, measured with a GS-1150 Spectrophotometer (Gamma Scientific, San Diego, CA), for HFLO, FLO, and LED bulbs were 304.4, 184.2, and 707.6 lux, respectively.

Proximate composition

Determination of fat percentage was done in triplicate utilizing microwave drying and nuclear magnetic resonance as described in Dow et al. (2011) with a CEM SMART Trac rapid fat analysis system 5 (Matthews, NC). Briefly, 2 CEM sample pads were heated and dried before 3.75 to 4.5 g of minced sample from the remaining beef clod heart muscle after steak fabrication was smeared across 1 pad and topped with the remaining pad. Samples were dried using the CEM Moisture/Solids Analyzer, and moisture was determined on a dry weight basis. Following determination of moisture, sample pads were wrapped in TRAC paper, inserted into a CEM TRAC tube and placed into the CEM Rapid Fat Analyzer. Fat percentage of samples was then determined on a dry basis using NMR and was ultimately converted to a wet basis. Triplicate values were averaged to determine overall fat percentages for each muscle.

Meat pH

The pH was determined according to the American Meat Science Association (2012). Briefly, duplicate, 10-g sample of each remaining beef clod heart muscle after steak fabrication was homogenized with 100 mL of distilled water. After homogenization, pH of the homogenate was measured using a benchtop probe (SevenCompact ph/Ion meter S220, fitted with InLab Versatile Pro probe, Mettler-Toledo AG Analytical, Schwerzenbach, Switerland).

Instrumental color

On the assigned retail display days (1, 3, 5, or 7), the steaks were removed from their packages. *L** (lightness), *a** (redness), and *b** (yellowness) values were measured on 3 random locations on the light-exposed steak surfaces using a HunterLab MiniScan 45/0 LAV (Hunter Associates Laboratory, Reston, VA) with a D65 light source, 25 mm aperture and 10° standard observer (American Meat Science Association, 2012). Physical standards were used to calibrate the HunterLab MiniScan each day before readings were taken. Instrumental color readings were also utilized to calculate a/b ratio, saturation index (SI), and hue angle (HA) values (American Meat Science Association, 2012).

Myoglobin redox forms on the steak surface

The proportions of myoglobin (Mb) redox forms, i.e., deoxymyoglobin (DMb), oxymyoglobin (MbO_2), and metmyoglobin (MMb), on steak surfaces were determined (American Meat Science Association, 2012) after each retail display time. Reflectance was measured at wavelengths of 470, 530, 570, and 700 nm on the light-exposed steak surfaces employing a HunterLab MiniScan 45/0 LAV (Hunter Associates Laboratory), and the proportions of Mb redox forms were determined utilizing the equations according to the American Meat Science Association (2012).

Myoglobin content

Duplicate 2.5 g minced steak surface samples 0.64-cm deep were homogenized using a Polytron homogenizer (Polytron 10–35 GT, Kinematica Inc., Bohemia, NY) in 22.5 mL of ice-cold sodium phosphate buffer, pH 6.8, for 90 s. Homogenate was then filtered through filter paper with particle retention of 4 to 8 μm and a flow rate of 25 mL/min (Fisherbrand P4 Grade, Fisher Scientific, Suwanee, GA) into clean tubes. Filtrate absorbance was read at 525 nm on a Genesys 20 spectrophotometer (Thermo Fisher Scientific Inc., Waltham, MA). Myoglobin concentrations were calculated utilizing the equation provided by the American Meat Science Association (2012).

Metmyoglobin reducing ability

Duplicate cubes, 4 cm × 4 cm × 0.64 cm deep, from the center of each steaks surface were removed on each day of designated retail display for all light treatments. Upon removal, samples were submerged in 0.3% sodium nitrite solution for 20 min to induce MMb formation. After 20 min, samples were removed from the solution, blotted dry, and vacuum sealed (Multivac, Chamber Machine P200, Kansas City, MO) in individual packages. Readings of each sample were taken immediately after packaging utilizing a HunterLab MiniScan in triplicate to obtain reflectance data. Samples were incubated at room temperature for 120 min to induce MMb reduction. After incubation, samples were rescanned in triplicate with a HunterLab MiniScan. Surface MMb values were calculated using K/S ratios and formulas provided in American Meat Science Association (2012). Metmyoglobin reducing ability was calculated using the equation below.

$$\% \text{ MRA} = 100 \times \frac{(\text{Pre-incubation \% metmyolglobin} - \text{Post-incubation \% metmyoglobin})}{\text{Pre-incubation \% metmyoglobin}}$$

Lipid oxidation

Lipid oxidation was determined utilizing the distillation method to analyze thiobarbituric acid reactive substances (TBARS) as described in Tarladgis et al. (1960) with modifications found in Fernando et al. (2013). Duplicate 5 g surface steak samples were minced, and homogenized (Polytron 10–35 GT, Kinematica Inc.) with 25 mL of distilled water. Homogenate was then poured into a 250 mL Kjeldahl flask and blending tubes were rinsed with an additional 25 mL of distilled water and transferred into the same flask. Two drops of antifoam solution (Antifoam B Silicone Emulsion, Thermo Fisher Scientific Inc.) along with 2.5 mL of 4N HCl to balance sample pH between 1.5 and 1.6 were added to the flask immediately before distillation. Flasks were placed into controlled heating elements (Thermo Fisher Scientific Inc., Pittsburg, PA) and 25 mL of sample was distilled through a water-cooled distillation apparatus. After distillation, 5 mL of sample was pipetted into a glass tube containing 5 mL of thiobarbituric acid reagent (TBA) and vortexed individually. Tubes were then placed into a boiling water bath for 35 min immediately following removal from the water bath, tubes were submerged into an ice bath for 10 min. Color absorbance was measured at 538 nm using a Genesys 20 spectrophotometer (Thermo Fisher Scientific Inc.). Values for TBARS concentrations were obtained by obtaining the average absorption of the duplicate sample readings and mg/kg of malonaldehyde was determined using the K value of 7.8 (Tarladgis et al., 1960).

Statistical analyses

The experimental design was a randomized complete block design with 20 replicates. Data were analyzed with the model including fixed effects of light (HFLO, FLO, LED), length of retail display (1, 3, 5, or 7 d), and all possible interactions. Analyses of instrumental color, myoglobin redox forms, myoglobin content, metmyoglobin reducing activity, and lipid oxidation were done using the GLIMMIX function of SAS (Version 9.4, SAS Inst. Inc., Cary, NC) to obtain LS means and standard error estimates. Significance was determined at $P < 0.05$ level. The PROC CORR procedure of SAS was then used to generate correlations.

Results and Discussion

Proximate composition and meat pH

Average pH for TB steaks was 5.42 (Table 1). Von Seggern et al. (2005) also reported similar pH values for

Table 1. Proximate composition and pH of beef *Triceps brachii* steaks ($n = 20$)

Parameter	Average	Minimum	Maximum
pH	5.42	5.31	5.63
Fat, %	6.04	2.85	11.18
Moisture, %	75.10	68.87	79.21

the beef TB. The average fat content in TB was 6.04%, and this value was in agreement with the study of Von Seggern et al. (2005) in which a mean fat percentage of 5.65% was reported for TB muscles. Nonetheless, fat content varied between TB muscle samples in the present study indicating the animal-to-animal variations in fat deposition regardless of all muscle samples being the same USDA Quality Grade.

Instrumental color

Five parameters (*a*/*b*, HA, MbO_2, MMb, and TBARS) demonstrated interactions ($P < 0.05$) between light source and retail display day. No differences ($P > 0.05$) were found in lightness (L^*) values of TB steaks under different light sources (Table 2) or over the duration of retail display (Table 3). This observation disagreed with the findings King et al. (2011) who reported that TB steaks consistently decreased in L^* values from d 0 through d 6 of retail display.

The TB steaks exposed to HFLO lights had greater ($P < 0.05$) a^* values (redness) than those exposed to FLO and LED light sources (Table 2), indicating that the use of HFLO lights increased retention of redness more than FLO and LED light treatments in retail display. This observation disagrees with the findings of Steele et al. (2016), where no differences were reported for a^* values in beef longissimus lumborum and semimembranosus steaks between FLO and LED light treatments over retail display. This disagreement may be attributed to muscle-specificity in beef color (McKenna et al., 2005). An a^* value of 14.5 has been determined as a threshold for consumer acceptance of redness (Holman et al., 2017). Steaks displayed under all light sources had mean values above this threshold indicating an acceptable red color. Retail display time also impacted a^* values in TB steaks with values decreasing ($P < 0.05$) over retail display (Table 3), which could be attributed to the formation of brown MMb on the steak surface. The data on surface redness agree with the literature (Hamling et al., 2008; Steele et al., 2016; Canto et al., 2016), which showed decrease in a^* values and decline in red color retention with increasing retail display time. Data from the present study indicate that light source and retail display length impact a^* value and red color retention in steaks from beef muscles with low color stability.

Table 2. Effect of light source on color traits of beef *Triceps brachii* steaks ($n = 20$)

	Light source[1]				
Parameter	HFLO	FLO	LED	SEM	*P*-value[2]
L*	42.89	42.62	42.33	0.25	0.0848
a*	18.45[a]	16.72[b]	16.61[b]	0.25	< 0.0001
b*	16.97[a]	16.12[b]	16.30[b]	0.14	< 0.0001
SI[3]	25.13[a]	23.42[b]	23.22[b]	0.26	< 0.0001
DMb[4]	4.56	4.28	4.32	0.18	0.2483
Mb[5]	5.41	5.20	5.22	0.17	0.4681
MRA[6]	14.48[b]	18.28[a]	14.52[b]	1.70	0.0389

[a,b]Means within a row, without a common superscript, differ ($P < 0.05$).

[1]HFLO = high UV fluorescent; FLO = low UV fluorescent; LED = light emitting diode.

[2]*P*-value of LS Means.

[3]SI = Saturation Index.

[4]DMb = Deoxymyoglobin (%).

[5]Mb = Myoglobin concentration (mg/g).

[6]MRA = Metmyoglobin reducing ability.

Table 3. Effect of retail display day on color traits of beef *Triceps brachii* steaks ($n = 20$)

	Retail display day					
Parameter	1	3	5	7	SEM	*P*-value[1]
L*	42.96	42.42	42.50	42.50	0.29	0.2377
a*	22.14[a]	17.73[b]	15.72[c]	13.49[d]	0.29	< 0.0001
b*	18.61[a]	16.47[b]	15.69[c]	15.09[d]	0.16	< 0.0001
SI[2]	28.94[a]	24.21[b]	22.24[c]	20.30[d]	0.30	< 0.0001
DMb[3]	5.73[a]	4.75[b]	4.10[c]	2.96[d]	0.21	< 0.0001
Mb[4]	5.72[a]	5.03[b]	5.39[a]	5.02[b]	0.19	0.0008
MRA[5]	29.97[a]	19.27[b]	10.58[c]	3.22[d]	1.96	< 0.0001

[a–d]Means within a row, without a common superscript, differ ($P < 0.05$).

[1]*P*-value of LS Means.

[2]SI = Saturation Index.

[3]DMb = Deoxymyoglobin (%).

[4]Mb = Myoglobin concentration (mg/g).

[5]MRA = Metmyoglobin reducing ability.

Values for b^* mimicked the trends in a^* values for TB teaks and agreed with the findings in Canto et al. (2016). Yellowness was greater ($P < 0.05$) for steaks displayed under HFLO lights than for steaks displayed under FLO and LED light sources (Table 3). Steele et al. (2016) reported that LED-displayed semimembranosus steaks had greater b^* values than those displayed in fluorescent lights. The b^* values decreased as retail display time increased in TB steaks indicating a loss of yellowness over retail display.

Light source and retail display time influenced ($P < 0.05$) *a*/*b* ratios in TB steaks (Table 4). Mean *a*/*b* ratios decreased ($P < 0.05$) for steaks displayed under all light sources over each day of retail display indicating a steady loss of red color over time. Steaks displayed with HFLO light sources had greater ($P < 0.05$) a/b ratio than steaks displayed under FLO and LED light sources on retail display d 5 and 7. This finding indicated that steaks displayed under HFLO retained greater ($P < 0.05$) surface redness over retail display than steaks displayed under FLO or LED light sources.

Saturation index (SI) values were greater ($P < 0.05$) for steaks displayed in HFLO than for steaks displayed under FLO or LED (Table 2) indicating greater levels of redness retention in HFLO steaks than those displayed in FLO or LED. Greater ($P < 0.05$) SI values also indicated greater surface redness for HFLO displayed steaks as opposed to steaks displayed in FLO and LED. Saturation index decreased ($P < 0.05$) over the retail display (Table 3). Data for SI from the present study agreed with Steele et al. (2016) and Cooper et al. (2016) indicating a loss of redness on the fresh meat surface over time.

Hue angle in TB steaks displayed under all light sources increased ($P < 0.05$) over the duration of retail display, indicating a loss of redness and increased discoloration. This agreed with the findings of Steele et al. (2016). Nonetheless, the TB steaks displayed under HFLO lights had lower ($P < 0.05$) HA than steaks displayed in both FLO and LED lights (Table 4). This observation suggested that TB steaks under FLO or LED had greater discoloration and loss of redness at the end of retail display compared to those under HFLO lights. In partial agreement, Steele et al. (2016) reported that beef semimembranosus steaks exhibited greater HA during retail display under LED lights than under fluorescent light sources.

Surface myoglobin redox forms

Light source did not influence ($P > 0.05$) the proportion of DMb in TB (Table 2). Not surprisingly, retail display time affected DMb levels, with decreases ($P < 0.05$) occurring over time (Table 3). These results agree with those of Djenane et al. (2001) as increased oxygen exposure results in the oxygenation of DMb to MbO_2 and later on the oxidation of MbO_2 to MMb (Suman and Joseph, 2013).

The MbO_2 concentrations decreased ($P < 0.05$) in steaks under all light treatments over retail display (Table 4). Steaks exposed to HFLO lights had greater ($P < 0.05$) MbO_2 concentrations than FLO displayed steaks on retail display d 3. On retail display d 5, HFLO-displayed TB steaks had greater ($P < 0.05$) concentrations of MbO_2 than steaks exposed to LED lights. By retail display d 7, HFLO-displayed steaks had greater ($P < 0.05$) MbO_2 concentrations than steaks exposed to both FLO and LED. These results indicated that steaks from beef muscles with low oxidative and color stabilities retained more redness when displayed under a HFLO light source as opposed to FLO or LED light sources.

As expected with decreasing MbO_2 values, MMb increased ($P < 0.05$) in steak surfaces displayed under all light sources over retail display (Table 4). Steaks displayed under HFLO had less ($P < 0.05$) MMb concentrations on retail display d 5 and 7 than steaks exposed to both FLO and LED light sources. Similarly, McKenna et al. (2005) reported that discoloration and MMb formation occurred over retail display time for TB steaks. The find-

Table 4. Impact of light source[1] and retail display day on color and lipid oxidation of beef *Triceps brachii* steaks ($n = 20$)

	Retail display day													
	d 1			d 3			d 5			d 7				
Parameter	HFLO	FLO	LED	HFLO	FLO	LED	HFLO	FLO	LED	HFLO	FLO	LED	SEM	*P*-value[2]
a/*b*	1.20^{a}	1.19^{a}	1.18^{a}	1.10^{b}	1.07^{bc}	1.05^{c}	1.05^{c}	0.98^{d}	0.97^{d}	0.97^{d}	0.84^{e}	0.86^{e}	0.02	0.0198
HA[3]	39.79^{d}	40.17^{d}	40.39^{d}	42.24^{c}	43.06^{c}	43.68^{c}	43.69^{c}	45.89^{b}	46.16^{b}	46.10^{b}	50.43^{a}	48.59^{a}	0.75	0.0063
MbO_2[4]	57.03^{a}	56.45^{abcd}	56.64^{abc}	56.76^{ab}	56.15^{cde}	56.37^{bcd}	56.17^{bcde}	55.57^{ef}	55.36^{f}	55.93^{def}	54.18^{g}	54.40^{g}	0.31	0.0365
MMb[5]	37.38^{f}	37.62^{f}	37.68^{ef}	38.55^{de}	38.95^{cd}	38.96^{cd}	39.46^{c}	40.54^{b}	40.61^{b}	40.48^{b}	42.43^{a}	42.69^{a}	0.46	0.0008
TBARS[6]	1.16^{e}	1.30^{e}	1.25^{e}	2.20^{d}	2.25^{d}	2.32^{d}	2.82^{c}	3.10^{bc}	2.90^{bc}	3.28^{b}	4.33^{a}	3.97^{a}	0.21	0.0205

$^{a–f}$Means within a row, without a common superscript, differ ($P < 0.05$).

[1]HFLO = high UV fluorescent; FLO = low UV fluorescent; LED = light emitting diode.

[2]*P*-value of LS Means.

[3]HA = Hue Angle.

[4]MbO_2 = Oxymyoglobin (%).

[5]MMb = Metmyoglobin (%).

[6]TBARS = Thiobarbituric acid reactive substances (mg/kg).

ings of the current study suggested that in low color and oxidative stability beef muscles, the use of HFLO lights can promote redness retention throughout retail display.

Myoglobin content

Light source had no impact ($P > 0.05$) on myoglobin content in TB (Table 2). Duration of retail display led to differences ($P < 0.05$) in myoglobin contents, with d 1 and 5 having greater myoglobin concentration than d 3 and 7 (Table 3). These results may potentially be attributed to the low oxidative and color stabilities of the TB muscle (McKenna et al., 2005); increased oxidation could have led to the degradation of myoglobin, potentially leading to changes in myoglobin concentrations over retail display time (McKenna et al., 2005). Although McKenna et al. (2005) reported that myoglobin content varied with beef muscles, no relationship between myoglobin concentration and beef color stability was determined. Additionally, all steaks were randomly allotted to light treatment × day combination so steak location within the muscle could have contributed to these results.

Metmyoglobin reducing ability

Metmyoglobin reducing ability (MRA) can increase color stability by reducing MMb to DMb (McKenna et al., 2005; King et al., 2011; Garner et al., 2014). The MRA was greater ($P < 0.05$) for TB steaks displayed under FLO lights than those displayed with HFLO or LED light sources (Table 2). Data in Table 3 demonstrated that retail display time also impacted MRA ($P < 0.05$), with values decreasing over retail display. This trend indicates a loss in MRA and subsequent increase in discoloration over retail display, and agrees with the previous studies (Reddy and Carpenter, 1991; Joseph et al., 2012; Canto et al., 2016) documenting that greater MRA resulted in greater color stability. However, the findings of the present study disagree with those of McKenna et al. (2005) who found that muscles with low color stability often had higher MRA values than their color stable counterparts. Both oxidative and reductive capacities are critical to fresh meat color stability (Suman and Nair, 2017). While the oxidative capacity is measured as oxygen consumption (Bendall and Taylor, 1972), the reductive capacity is estimated by MRA (Bekhit and Faustman, 2005). A complex relationship exists between MRA and oxygen consumption and can affect the ways post-mortem beef muscles compensate for oxidative stress (Madhavi and Carpenter, 1993; Suman and Nair, 2017). In this standpoint, there is debate on the significance of MRA alone, and O'Keeffe and Hood (1982) found that MRA is of little importance in determining color stability. Similarly, Atkinson and Follett (1973) and Bekhit et al. (2001) also found no conclusive relationship between MRA and color stability in muscles of multiple meat species.

Lipid oxidation

Lipid oxidation, as indicated by TBARS values, increased ($P < 0.05$) over retail display for all light treatments (Table 4). Previous research (McKenna et al., 2005; Joseph et al., 2012; Canto et al., 2016; Steele et al., 2016; Cooper et al., 2016) reported that increased retail display time leads to increase in lipid oxidation in fresh beef products. As TB steaks have low oxidative stability, these results were anticipated and agreed with the findings of McKenna et al. (2005).

By d 3 of retail storage, TB steaks displayed under all light sources had exceeded a TBARS value of 2.0 indicating detectable rancidity (Campo et al., 2006). No differences ($P > 0.05$) occurred between light treatments on retail display d 1, 3, and 5. However, on retail display d 7 HFLO displayed steaks had lower ($P < 0.05$) TBARS values than steaks displayed with FLO or LED light displays. Steele et al. (2016) also found that beef semimembranosus steaks exposed to LED lights had greater TBARS values than those displayed with FLO light sources. Data from the present study indicated that over retail display time, the use of HFLO light sources may minimize lipid oxidation in steaks with low color and oxidative stability.

Relationship between color measurements and lipid oxidation

The correlation among various color parameters and biochemical attributes in beef TB steaks is presented in Table 5. Strong negative correlations exist between TBARS values and a^* ($P < 0.0001$) and b^* ($P < 0.0001$) values. Weak negative correlations ($P < 0.001$) occurred between TBARS and MbO_2 concentrations. Conversely, strong positive correlations ($P < 0.0001$) were observed between TBARS and percent MMb concentration. Strong relationships have been reported between lipid oxidation and MMb formation in fresh meat products (Faustman and Cassens, 1990; Martin et al., 2013). Faustman et al. (2010) reported that increased level of lipid oxidation is associated with MMb formation, resulting in brown discoloration on fresh meat surfaces. The findings of the current study reiterated that lipid oxidation and oxidation of Mb are related.

Moderate positive correlations between MRA and instrumental color measurements for a^* ($P < 0.0001$) and b^*

Table 5. Correlation among various color traits and biochemical attributes in beef *Triceps brachii* steaks ($n = 20$)

Parameter	L^*	a^*	b^*	MMb	DMb	$Mb0_2$	TBARS	Mb	MRA	pH
L^*	1.00									
a^*	0.03	1.00								
b^*	0.26***	0.91***	1.00							
MMb[1]	–0.02	–0.86***	–0.73***	1.00						
DMb[2]	0.11	0.74***	0.60***	–0.77***	1.00					
MbO_2[3]	–0.08	0.53***	0.48***	–0.71***	–0.67***	1.00				
TBARS[4]	–0.14*	–0.74***	–0.70***	0.71***	–0.67***	–0.37***	1.00			
Mb[5]	–0.17*	0.25***	0.18*	–0.18*	0.08	0.19*	–0.15*	1.00		
MRA[6]	–0.16*	0.57***	0.44***	–0.53***	0.45***	0.34***	–0.43***	0.09	1.00	
pH	–0.18*	0.10	0.04	–0.11	0.10	0.06	–0.17*	0.10	0.29***	1.00

[1]MMb = Metmyoglobin (%).

[2]DMb = Deoxymyoglobin (%).

[3]MbO_2 = Oxymyoglobin (%).

[4]TBARS = Thiobarbituric acid reactive substances (mg/kg).

[5]Mb = Myoglobin concentration (mg/g).

[6]MRA = Metmyoglobin reducing ability.

*$P < 0.05$.

***$P < 0.0001$.

($P < 0.0001$), as well as percent DMb ($P < 0.0001$) were observed. Correlations between MRA and MbO_2 concentrations were weak ($P < 0.0001$). Alternatively, MRA had moderate negative correlations between both TBARS ($P < 0.0001$) and MMb concentrations ($P < 0.0001$). MRA is an indicator of color stability in fresh meat products (McKenna et al., 2005; Bekhit and Faustman, 2005; Wu et al., 2015), and therefore negative correlations between TBARS and MMb values are to be expected.

Conclusions

Light source influenced surface discoloration, Mb oxidation, and lipid oxidation in TB steaks during retail display. Use of HFLO light source promoted retention of redness in steaks from this beef muscle with low oxidative and color stability during retail display compared to FLO or LED light sources. The meat industry may be able to use HFLO lights during retail display of steaks from other beef muscles with low color stability to improve redness retention and marketability.

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