Effects of packaging atmospheres on beef instrumental tenderness, fresh color stability, and internal cooked color

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ABSTRACT: Fresh meat color is a major factor influencing the purchase of meat products by consumers, whereas tenderness is the primary trait determining overall eating satisfaction of consumers. The objectives of this research were to determine the effects of packaging atmosphere on beef color stability, cooked color, and tenderness. Longissimus lumborum muscles (n = 14 pairs) from USDA Select, A-maturity carcasses were assigned to either 14-d tenderness measurement or to display and then to 18-d [80% O₂, 20% CO₂ (HiO₂) modified atmosphere packaging (MAP)] or 28-d [vacuum package (VP) and ultra low (ULO₂) plus CO MAP blends] tenderness measurement. Loins were then fabricated on d 7 postmortem into 2.54-cm-thick steaks. Steaks 8 to 10 caudal to the first 7 steaks were bisected, assigned to a packaging treatment, and used for internal cooked color. One full steak was used for initial tenderness. Packaging treatments were as follows: vacuum-packaging (VP); 80% O₂, 20% CO₂ (HiO₂); 0.4% CO, 35% CO₂, 64.6%N₂ (ULO₂CO); 0.4% CO, 99.6% CO₂ (ULO₂COCO₂); 0.4% CO, 99.6% N₂ (ULO₂CON₂); or 0.4% CO, 99.6% Ar (ULO₂COAr). Steaks packaged in HiO₂ MAP were in dark storage (2°C) for 4 d, and all other steaks were in dark storage for 14 d. Steaks were displayed under fluorescent lighting (2,153 lx; 3,000 K) for 7 d, with instrumental color measured on d 0 and 7 of display. Trained color panelists (n = 10) assigned color scores. Steaks for Warner-Bratzler shear force and cooked color were cooked to 70°C. Steaks packaged in the 4 ULO₂ MAP blends with CO had no change (P > 0.05) or increased (P < 0.05) a* values for fresh color. Steaks packaged in VP or the 4 ULO₂ MAP blends with CO had little or no surface discoloration. Steaks packaged in HiO₂ MAP discolored faster (P < 0.05) and 56% more (P < 0.05) than those in any other packaging treatment. There were no differences (P > 0.05) in Warner-Bratzler shear force on d 14 postmortem. Steaks packaged in HiO₂ MAP were less tender (P < 0.05) than the other treatments at the end of display but had 10 d less aging due to a shorter dark storage period. Steaks packaged in HiO₂ had the lowest (P < 0.05) a* values for internal cooked color of all packaging treatments. Steaks packaged in ULO₂COCO₂ and VP had intermediate a* values, whereas those packaged in ULO₂COAr, ULO₂CO, and ULO₂CON₂ had the greatest (P < 0.05) a* values for internal cooked color. Ultra-low oxygen packaging treatments had longer fresh color stability than steaks packaged in HiO₂ MAP and equal or better tenderness. Packaging atmospheres altered the internal cooked color, with steaks packaged in HiO₂ MAP exhibiting premature browning.

Key words: beef, cooked color, display color, modified atmosphere packaging, tenderness

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INTRODUCTION

Several meat quality traits are involved in the overall purchase decisions and satisfaction of meat products by consumers. Color is the major factor affecting the purchasing decisions of consumers. Tenderness is the most important palatability attribute deciding the overall eating experience of consumers (Dikeman, 1987; Miller et al., 1995). Eilert (2005) reported that case-ready packaging in the meat industry was growing at a rapid rate. Case-ready packaging generally includes modified atmosphere packaging (MAP) with specific gases. There are several advantages of MAP, including use of a centralized location, improved control of sanitation, more consistent products, and increased marketing flexibility (Jeyamkóndan et al., 2000; Kropf, 2004). Packaging beef in high-oxygen (HiO₂) MAP results in a desirable bright red color (Behrends et al., 2003; Seyfert et al., 2005) but may have detrimental effects on
other quality traits, including increased off-flavors and decreased tenderness (Tørngren, 2003; Sørheim et al., 2004; Clausen, 2004; Madsen and Clausen, 2006), as well as bone discoloration (Grobbel et al., 2006). The use of CO has been approved in the United States for levels up to 0.4% in retail MAP (USFDA, 2004). Products in MAP that include CO have improved beef color stability and extended display time (Luño et al., 1998; Sørheim et al., 1999; Hunt et al., 2004).

Premature browning, originally found in ground beef, results when meat is cooked to temperatures lower than what is necessary to kill harmful pathogens but appears well done internally (Hague et al., 1994; Warren et al., 1996; Hunt et al., 1999). This phenomenon is also found in whole muscle steaks and can be attributed to packaging environments, including HiO2 MAP (Seyfert et al., 2004; John et al., 2005). Therefore, the objectives of this study were to evaluate the effects of different gas compositions in MAP and packaging type (MAP vs. vacuum-packaging) on beef tenderness, fresh color stability, and internal cooked color.

MATERIALS AND METHODS

Samples and Packaging

Animal Care and Use Committee approval was not obtained for this study because the samples were obtained from a federally inspected slaughter facility (Tyson Fresh Meat Co.).

Paired beef longissimus lumborum muscles (n = 14 pairs) from USDA Select, A-maturity carcasses were obtained from a commercial abattoir at 2 d postmortem and stored under vacuum at 2°C until 7 d postmortem. Loins from different sides were assigned to either 14-d tenderness measurement or display and then 18-d (HiO2 MAP) or 28-d (VP and ULO2 plus CO MAP blends) tenderness measurement. These times were different, because the steaks packaged in HiO2 MAP have a shorter shelf life and were held for less time in dark storage. Steaks were fabricated into 2.54-cm-thick steaks and were assigned to initial tenderness or the following 6 packaging treatments: 1) vacuum-packaging (VP; 62.2 cm Hg vac; Multivac C500, Multivac Inc., Kansas City, MO); 2) ultra-low oxygen MAP with CO (ULO2CO; 64.6% N2, 35% CO2, 0.4% CO); 3) high-oxygen MAP (HiO2; 80% O2, 20% CO2); 4) 99.6% CO2, 0.4% CO (ULO2CO2); 5) 99.6% N2, 0.4% CO (ULO2CON2; Linweld certified gas, MidSouth Inc., Tulsa, OK); or 6) 99.6% Ar, 0.4% CO (ULO2COAr; Linweld certified gas, Linweld, Manhattan, KS) and subsequent color and tenderness measurements.

Different packaging treatment gas blends were chosen to evaluate the effects of single gases (CO2 and N2) commonly used in MAP on color and tenderness, with the inclusion of 0.4% CO to allow steaks to be red in color. The use of Ar, an inert gas, is not currently approved for use with MAP in the United States but was evaluated to determine if it had any positive or negative effects on color or tenderness.

Steaks packaged in MAP (Ross Jr. S-3180, Ross, Midland, VA) were placed in 4.32-cm-deep rigid plastic trays (CS977, Cryovac Sealed Air Corp., Duncan, SC). Trays were covered with oxygen-barrier film (Lid 550; 1.0 mils; less than 20.0 oxygen transmission mL/24 h per m2 at 4.4°C with 100% relative humidity; and moisture vapor transmission less than 0.1 g/24 h per 645.2 cm2 at 4.4°C and 100% relative humidity; Cryovac Sealed Air Corp.). An additional 3 steaks from each loin were cut caudal to the first 7 steaks, bisected (dorsal to ventral), randomly assigned to a packaging treatment, stored at 2°C in dark storage until 14 d postmortem, and used for cooked internal color. High-oxygen MAP was held in dark storage (2°C) for 4 d and then put into simulated retail display and removed on d 18 postmortem. All packaging treatments without O2 were held in dark storage (2°C) for 14 d and then put into simulated retail display and removed on d 28 postmortem. Steaks in all packaging treatments used for 14-d postmortem Warner-Bratzler shear force (WBSF) were held for 7 d in the dark and then cooked for WBSF measurement. Dark storage times for HiO2 and ULO2 MAP were developed to mimic what would happen in the industry. An activated oxygen scavenger (ActiveTech, Pactiv, Chicago, IL) was included in each of the ULO2 packages to eliminate any residual O2. One steak from each loin was vacuum-packaged and used for initial WBSF on d 7 postmortem.

Cooking of Steaks

Steaks for WBSF or internal cooked color were cooked in a forced-air convection oven (model DFG-102 CH3, G. S. Blodgett Co., Burlington, VT) set at 163°C. Steaks were turned at an internal temperature of 40°C and cooked to an internal temperature of 70°C, as monitored with copper-constantan thermocouples in the approximate geometric center of each steak.

Warner-Bratzler Shear Force

On d 7 postmortem, d 14 postmortem, and at the end of each display (d 18 for HiO2 MAP or d 28 for VP and ULO2 plus CO MAP postmortem), steaks from all packaging treatments were cooked, cooled to room temperature, and stored at 2°C overnight. Eight 1.27-cm cores were removed parallel to the muscle fibers using a 1.27-cm corer (G-R Manufacturing Co., Manhattan, KS) attached to an electric drill (Craftsman 3/8″ Electric Drill, Sears, Hoffman Estates, IL). Cores were then sheared once perpendicular to the muscle fibers using a Warner-Bratzler V-shaped blunt blade (G-R Manufacturing Co.) attached to a 50-kg load cell of an Instron Universal Testing Machine (model 4201, Instron Corp., Canton, MA) with a crosshead speed of 250 mm/min. Peak shear force was recorded in kilograms, and values from the 8 cores were averaged.
The pH of the steaks was measured on d 14 postmortem by inserting the tip of a pH probe (MPI pH probe, glass electrode, Meat Probes Inc., Topeka, KS) into the longissimus lumborum muscle.

**Display Case**

Packages were displayed (unit model DMF8, Tyler Refrigeration Corp., Niles, MI) under continuous fluorescent lighting (2,153 lx, 3,000 K, and color rendering index = 85, bulb model F32T8/ADV830/Alto, Philips, Bloomfield, NJ) for 7 d at 2°C. Packages were rotated twice daily to maintain a random sample placement.

**Color Measurements**

Trained visual color panelists (n = 10) evaluated the initial color on d 0 of display and the display color and surface discoloration on d 0 to 7 of display, once each day on raw steaks. Initial color was determined using the following scale: 1 = purplish red or reddish tan of vacuum package; 2 = bleached, pale red; 3 = slightly cherry red; 4 = moderately light cherry red; 5 = cherry red; 6 = slightly dark red; 7 = moderately dark red; 8 = dark red; and 9 = very dark red. The color scale used by panelists for steaks packaged in MAP was as follows: 1 = very bright red or very bright pinkish red; 2 = bright red or bright pinkish red; 3 = dull red or dull pinkish red; 4 = slightly dark red or slightly dark pinkish red; 5 = reddish tan or pinkish tan; 6 = moderately dark red or reddish tan or moderately dark pinkish red or pinkish tan; 7 = tannish red or tannish pink; and 8 = tan to brown. Steaks packaged in VP were evaluated with the following scale: 1 = very bright purplish red or very bright purplish pink; 2 = bright purplish red or bright purplish pink; 3 = dull purplish red or dull purplish pink; 4 = slightly dark purplish red or slightly dark purplish pink; 5 = purplish tan or pinkish tan; 6 = moderately dark purplish red or moderately dark purplish pink; 7 = tannish purple red or tannish purple pink; and 8) tan to brown. For all steaks, discoloration was considered as a percentage of surface metmyoglobin, and the following scale was used to evaluate this: 1 = none (0%); 2 = slight discoloration (1 to 19%); 3 = small discoloration (20 to 39%); 4 = modest discoloration (40 to 59%); 5 = moderate discoloration (60 to 79%); 6 = extensive discoloration (80 to 99%); and 7 = total discoloration (100%). Initial color and display color scales were used to half-point increments, whereas discoloration was scored to whole-point increments.

Instrumental color (L*, a*, and b*, illuminant A) was measured using a HunterLab MiniScan XE Plus Spectrophotometer (model 45/0 LAV, 2.54-cm-diam. aperture, 10° standard observer, Hunter Associates Laboratory Inc., Reston, VA) on d 0 and 7 of display for all packaging treatments. To accomplish reading instrumental color on MAP steaks, the half-steaks from steaks 8 to 10 were packaged and stored in dark storage until d 0 of their display counterpart steaks. Steaks were scanned immediately after opening packages. Each steak was scanned in triplicate, and values were averaged.

Cooked internal color was evaluated on the half-steaks used for instrumental color on d 0 of display. Steaks were allowed to cool briefly after cooking and before being bisected, and instrumental color (L*, a*, b*, 400 to 700 nm) was measured using a HunterLab MiniScan XE Plus Spectrophotometer immediately after bisection. The internal surface was scanned in triplicate, and the values were averaged. Hue angle was calculated using \( \tan^{-1} \frac{b^*}{a^*} \) and saturation index was calculated using \( (a^*^2 + b^*^2)^{1/2} \) (Hunt et al., 1991).

**Statistical Analysis**

The experimental design was a split-plot design with the whole plot being a randomized complete block design, with block being animal. The subplot consisted of steaks from each loin. The MIXED procedure (SAS Inst. Inc., Cary, NC) was used to analyze the data. For WBSF, the fixed effects were comparison of the mean of d 7 (d 0 of packaging) to the mean of all other data, packaging treatment (comparison of the mean of d 7 to the mean of all other data), day (comparison of the mean of d 7 to the mean of all other data), and day \( \times \) packaging treatment (comparison of the mean of d 7 to the mean of all other data). Instrumental color, visual color, and discoloration fixed effects were packaging treatment, day, and packaging treatment \( \times \) day. The fixed effect for initial color and cooked color was packaging treatment. Random effects for WBSF, instrumental color, initial color, and cooked color included animal and side (animal). Random effects for visual color and discoloration were animal, side (animal), and packaging treatment \( \times \) side (animal), with day serving as a repeated measure. Means were separated using Fisher’s protected least significant differences with Prasad-Rao-Jeske-Kackar-Harville SE and the Kenward-Roger degrees of freedom (SAS). Greatest-order interactions were reported when they were significant, or main effects were reported when no interactions were significant. Significance was determined at a probability value of \( P < 0.05 \).

**RESULTS AND DISCUSSION**

**Warner-Bratzler Shear Force**

There was a packaging treatment \( \times \) day interaction (\( P < 0.004 \)) for WBSF (Table 1). Warner-Bratzler shear force values from longissimus lumborum steaks indicate that, as a system, HiO\(_2\) MAP (d 18 postmortem) resulted in steaks being less tender than those packaged in ULO\(_2\) with CO MAP or VP (d 28 postmortem). There were no differences (\( P > 0.05 \)) in WBSF on d 14 postmortem, and all treatments were more tender (\( P < 0.01 \)) on d 14 postmortem than d 7 postmortem. Conversely, steaks packaged in HiO\(_2\) MAP were less tender...
Table 1. Warner-Bratzler shear force (WBSF) packaging treatment × day means (kg) and SE for longissimus lumborum steaks packaged in different atmospheres

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Day postmortem</th>
<th>SE</th>
<th>pH (d 0 of display)</th>
<th>Initial color (d 0 of display)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ULO₂COAr</td>
<td>5.32 d</td>
<td>0.14</td>
<td>4.93 e</td>
<td>5.3 f</td>
</tr>
<tr>
<td>ULO₂COCO₂</td>
<td>5.32 d</td>
<td>0.14</td>
<td>4.77 f</td>
<td>5.34 e</td>
</tr>
<tr>
<td>HiO₂ CO</td>
<td>5.32 d</td>
<td>0.14</td>
<td>4.83 e</td>
<td>5.34 f</td>
</tr>
<tr>
<td>ULO₂CO</td>
<td>5.32 d</td>
<td>0.14</td>
<td>4.75 e</td>
<td>5.34 f</td>
</tr>
<tr>
<td>ULO₂CON₂</td>
<td>5.32 d</td>
<td>0.14</td>
<td>4.85 e</td>
<td>5.34 f</td>
</tr>
<tr>
<td>VP</td>
<td>5.32 d</td>
<td>0.14</td>
<td>4.77 e</td>
<td>5.34 f</td>
</tr>
</tbody>
</table>

Means with different superscript letters differ (P < 0.01). SE = 0.02 for pH; SE = 0.13 for initial color. ULO₂COAr = 99.6% Ar, 0.4% CO; ULO₂COCO₂ = 99.6% CO₂, 0.4% CO; HiO₂ = 80% O₂, 20% CO₂; ULO₂CO = 64.6% N₂, 35% CO₂, 0.4% CO; ULO₂CON₂ = 99.6% N₂, 0.4% CO; and VP = vacuum-packaging.

Table 2. pH and initial visual score means and SE^1 for longissimus lumborum steaks packaged in different atmospheres

<table>
<thead>
<tr>
<th>Treatment</th>
<th>pH</th>
<th>Initial color (d 0 of display)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ULO₂COAr</td>
<td>5.6</td>
<td>5.3 f</td>
</tr>
<tr>
<td>ULO₂COCO₂</td>
<td>5.5</td>
<td>5.1 f</td>
</tr>
<tr>
<td>HiO₂</td>
<td>5.5</td>
<td>4.9 e</td>
</tr>
<tr>
<td>ULO₂CO</td>
<td>5.5</td>
<td>5.2 f</td>
</tr>
<tr>
<td>ULO₂CON₂</td>
<td>5.6</td>
<td>5.4 f</td>
</tr>
<tr>
<td>VP</td>
<td>5.5</td>
<td>1.0 f</td>
</tr>
</tbody>
</table>

Means with different superscript letters differ (P < 0.05). SE = 0.02 for pH; SE = 0.13 for initial color. ULO₂COAr = 99.6% Ar, 0.4% CO; ULO₂COCO₂ = 99.6% CO₂, 0.4% CO; HiO₂ = 80% O₂, 20% CO₂; ULO₂CO = 64.6% N₂, 35% CO₂, 0.4% CO; ULO₂CON₂ = 99.6% N₂, 0.4% CO; and VP = vacuum-packaging.

(P < 0.05) than other treatments at the end of display, likely due to 10 d less aging time (d 18 vs. 28 postmortem) because of a shorter dark storage period (4 d) for HiO₂ MAP than ULO₂CO MAP and VP packaging treatments (14 d). Steaks packaged in all packaging treatments used for 14 d postmortem WBSF were held for 7 d in the dark and then cooked for WBSF measurement. Dark storage times for HiO₂ and ULO₂ atmospheres were developed to mimic what would happen in industry. There was a trend (P = 0.06) for steaks packaged in VP to be more tender than steaks packaged in ULO₂CO MAP on d 28 postmortem.

The results of other studies show more distinct differences in tenderness due to packaging environment. Steaks packaged in HiO₂ MAP have been shown to be less tender after 7 to 14 d than steaks packaged in VP or ULO₂ with or without CO MAP by instrumental, trained sensory panelists, or both, and the decrease in tenderness has been associated with O₂ in the package (Tørngren, 2003; Clausen, 2004; Sørheim et al., 2004; Madsen and Clausen, 2006). These studies used steaks from heifers, cows, or bulls and were most likely fed different types of diets than the traditional grain-fed diets most often used in cattle harvested in the United States, such as the A-maturity, USDA Select carcasses obtained in this study. The differences in cattle sex, age, and feeding regimens between this study and others may have played a role in the results we saw compared with the other studies.

**pH**

There were no (P > 0.05) differences in pH for longissimus lumborum steaks packaged in different packaging treatments (Table 2). These results agreed with expected results for pH, because packaging treatment should not alter muscle pH.

**Display Color and Discoloration**

Initial color was evaluated to characterize steak color at the time they were put into the display case on d 0 of display. There was a main effect of packaging treatment (P < 0.001) for initial color as expected. Steaks packaged in VP had the typical purplish red color, and all other treatments were classified around cherry red, with a few minor statistical differences among them (Table 2). Steaks packaged in HiO₂ and ULO₂COCO₂ MAP had the same (P > 0.05) initial color, and steaks packaged in ULO₂COAr, ULO₂COCO₂, ULO₂CO, and ULO₂CON₂ MAP were similar (P > 0.05) to each other in initial color. Including CO or O₂ in the MAP allows meat to be cherry red in color, but excluding O₂ from the package, as done in VP, results in meat being a purplish red color.

There was a packaging treatment × day interaction (P < 0.001) for display visual color (Table 3). Display color scores indicated that steaks from all treatments became darker (P < 0.05) as day of display increased, as was expected. Steaks packaged in HiO₂ MAP were slightly brighter (P < 0.05) according to display color scores than steaks packaged in ULO₂COAr or ULO₂CO MAP on d 0 of display. Vacuum-packaged steaks were the most consistent in display color throughout the 7 d of display and only changed from bright purplish red to
Table 3. Display color score packaging treatment × day means and SE\(^1\) for longissimus lumborum steaks packaged in different atmospheres and displayed

<table>
<thead>
<tr>
<th>Treatment(^2)</th>
<th>Day of display</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0 1 2 3 4 5 6 7</td>
</tr>
<tr>
<td>ULO(_2)COAr(^3)</td>
<td>3.1(\text{e}) 3.2(\text{e}), 3.4(\text{e}) 4.0(\text{e}) 4.0(\text{e}) 4.2(\text{h}) 4.4(\text{i}) 4.5(\text{i})</td>
</tr>
<tr>
<td>ULO(_2)COCO(_2)(^3)</td>
<td>2.9(\text{e}) 3.1(\text{e}) 3.2(\text{e}) 3.9(\text{e}) 3.5(\text{e}) 3.7(\text{h}) 3.8(\text{i}) 3.8(\text{i})</td>
</tr>
<tr>
<td>HiO(_2)(^3)</td>
<td>2.7(\text{e}) 2.9(\text{e}) 3.1(\text{e}) 3.4(\text{e}) 3.8(\text{i}) 4.2(\text{i}) 4.4(\text{i}) 5.0(\text{i})</td>
</tr>
<tr>
<td>ULO(_2)CO(^3)</td>
<td>3.0(\text{e}) 3.0(\text{e}) 3.2(\text{e}) 3.6(\text{e}) 3.7(\text{h}) 4.0(\text{h}) 4.2(\text{i}) 4.2(\text{i})</td>
</tr>
<tr>
<td>ULO(_2)CON(_2)(^3)</td>
<td>2.9(\text{e}) 3.3(\text{e}) 3.4(\text{e}) 3.9(\text{e}) 4.6(\text{h}) 4.3(\text{i}) 4.5(\text{i}) 4.4(\text{i})</td>
</tr>
<tr>
<td>VP(^4)</td>
<td>2.9(\text{e}) 2.7(\text{e}) 2.9(\text{e}) 3.0(\text{e}) 3.3(\text{e}) 3.7(\text{i}) 3.5(\text{i}) 3.3(\text{i})</td>
</tr>
</tbody>
</table>

\(^{e-l}\)Means within the same treatment (row) with different superscript letters differ (\(P < 0.05\)).

\(^{v-z}\)Means within the same day of display (column) with different superscript letters differ (\(P < 0.05\)).

\(^1\)SE = 0.15.

\(^2\)ULO\(_2\)COAr = 99.6% Ar, 0.4% CO; ULO\(_2\)COCO\(_2\) = 99.6% CO\(_2\), 0.4% CO; HiO\(_2\) = 80% O\(_2\), 20% CO\(_2\); ULO\(_2\)CO = 64.6% N\(_2\), 35% CO\(_2\), 0.4% CO; ULO\(_2\)CON\(_2\) = 99.6% N\(_2\), 0.4% CO; and VP = vacuum-packaging.

\(^3\)=2 = bright red or bright pinkish red; 3 = dull red or dull pinkish red; 4 = slightly dark red or slightly dark pinkish red; 5 = reddish tan or pinkish tan; 6 = moderately dark red or reddish tan or moderately dark pinkish red or pinkish tan.

\(^4\)=2 = bright purplish red or bright purplish pink; 3 = dull purplish red or dull purplish pink; 4 = slightly dark purplish red or slightly dark purplish pink; 5 = purplish tan or pinkish tan; 6 = moderately dark purplish red or moderately dark purplish pink.

or pink to dull purplish red or pink for the entire display period. Steaks in VP were expected to be stable in color and not change much throughout the 7 d of display; however, many consumers find the purplish red color of VP meat undesirable regardless of the consistent color in display. Steaks packaged in HiO\(_2\) MAP were an undesirable reddish tan by d 7 of display, whereas steaks packaged in the ULO\(_2\)CO MAP treatments were either dull red or slightly dark red by d 7 of display (Figure 1).

There was a packaging treatment × day interaction (\(P < 0.001\)) for discoloration scores (Figure 2). Steaks packaged in VP or the 4 ULO\(_2\) MAP blends with CO had little or no surface discoloration over the 7 d of display. Steaks packaged in HiO\(_2\) MAP discolored faster (\(P < 0.05\)) and to a greater extent (\(P < 0.05\)) than those packaged in any of the ULO\(_2\) MAP or VP treatments. Steaks packaged in HiO\(_2\) MAP discolored (\(P < 0.05\)) by d 4 of display and had 56% more (\(P < 0.05\)) metmyoglobin discoloration than those packaged in any other packaging treatment. On d 4 of display, steaks packaged in ULO\(_2\)COCO\(_2\) and HiO\(_2\) MAP had similar (\(P < 0.05\)) discoloration, but by d 5 of display, steaks packaged in HiO\(_2\) MAP had more (\(P < 0.05\)) discoloration than steaks in all other packaging treatments. Including O\(_2\) in the package for extended periods of time allows for oxidation of myoglobin and thus resulted in a reddish tan color by d 7 of display. Excluding O\(_2\) from the package,

Figure 1. Display color score means for longissimus lumborum steaks packaged in different atmospheres. VP = vacuum-packaging; HiO\(_2\) = 80% O\(_2\), 20% CO\(_2\); ULO\(_2\)CO = 64.6% N\(_2\), 35% CO\(_2\), 0.4% CO; CO\(_2\) = 99.6% CO\(_2\), 0.4% CO; N\(_2\) = 99.6% N, 0.4% CO; and Ar = 99.6% Ar, 0.4% CO.
as with VP or ULO2CO MAP treatments, allows myoglobin to remain in a more stable form (red) longer and delayed the onset of metmyoglobin (tan/brown) color formed through the oxidation of myoglobin.

**Instrumental Color**

There was a packaging treatment × day interaction for L*, a*, b*, and saturation index values (P < 0.001; Table 4). Steaks packaged in the 4 ULO2CO MAP treatments had greater (P < 0.05) L* values than steaks packaged in HiO2 MAP or VP. Steaks packaged in ULO2CO and ULO2CON2 MAP were redder (P < 0.05) than steaks packaged in HiO2 MAP on d 0 of display. Steaks packaged in ULO2CO and ULO2CON2 MAP had no change (P > 0.05) in a* values, whereas steaks packaged in ULO2COAr and ULO2COCO2 MAP had increased (P < 0.05) a* values from d 0 to 7 of display. Steaks packaged in HiO2 MAP had drastically lower a* values on d 7 of display compared with d 0 of display. Vacuum-packaged steaks had decreased (P < 0.05) a* values, although not nearly the extent of a reduction as found in steaks packaged in HiO2 MAP.

A greater saturation index indicates a greater saturation of red (Hunt et al., 1991). Steaks packaged in HiO2 MAP had a dramatic decrease (P < 0.05) in saturation index from d 0 to 7 of display and were much lower (P < 0.05) than the 4 ULO2CO MAP treatments by d 7 of display.

In general, instrumental color agreed with display visual color results found by trained panelists. Although panelists found that steaks packaged in HiO2 MAP (2.7) were brighter (P < 0.05) in color on d 0 of display than steaks packaged in ULO2CO MAP (3.0),

Table 4. Instrumental color packaging treatment × day means and SE1 for longissimus lumborum steaks packaged in different atmospheres

<table>
<thead>
<tr>
<th>Treatment1</th>
<th>L*</th>
<th>a*</th>
<th>b*</th>
<th>Saturation index</th>
</tr>
</thead>
<tbody>
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<td>d 7</td>
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<td>50.0f</td>
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<tr>
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<td>51.2f</td>
<td>30.4f</td>
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<tr>
<td>ULO2CO</td>
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<td>50.2f</td>
<td>32.2f</td>
<td>32.3f</td>
</tr>
<tr>
<td>ULO2CON2</td>
<td>49.2f</td>
<td>49.0f</td>
<td>31.0f</td>
<td>32.1f</td>
</tr>
<tr>
<td>VP</td>
<td>40.4f</td>
<td>42.5f</td>
<td>22.9f</td>
<td>20.6f</td>
</tr>
</tbody>
</table>

1SE = 0.7 for L*, a*, and b*; SE = 0.03 for saturation index.

Figure 2. Discoloration score (1 = 0%, 2 = 1 to 19%, and 3 = 20 to 39% metmyoglobin) means for longissimus lumborum steaks packaged in Ar (99.6% Ar, 0.4% CO), CO2 (99.6% CO2, 0.4% CO), HiO2 (80% O2, 20% CO2), ULO2CO (84.6% N2, 35% CO2, 0.4% CO), N2 (99.6% N2, 0.4% CO), or VP (vacuum-packaging) and displayed. Means with different letters differ (P < 0.05).
Figure 3. Reflectance means for steaks packaged in high-oxygen (HiO₂) and ultra-low oxygen with CO (ULO₂CO) modified atmosphere packaging and vacuum-packaging (VP) on d 0 and 7 of display.

the difference found in display color score was minor. Instrumental a* values indicated that steaks packaged in ULO₂CO MAP (32.2) were brighter (P < 0.05) on d 0 of display than steaks packaged in HiO₂ MAP (30.4), the exact opposite from what panelists found, indicating the difference is not of practical significance. Steaks packaged in HiO₂ and all ULO₂ with CO MAP treatments had an initial desirable red color. Argon, CO₂, and N₂ were compared at the 99.6% level with 0.4% CO (included to have meat in the red, carboxymyoglobin state and not in deoxymyoglobin) to determine if a single gas in the blends associated with MAP had an effect on beef color. The small differences found in display color and instrumental color among the 4 blends of ULO₂ with CO MAP were of no practical significance.

Steaks packaged in VP, HiO₂, and ULO₂CO MAP had similar spectral reflectance means from 400 to 700 nm (Figure 3). At a specific wavelength (i.e., 525, 572, and 610), when 2 or more forms of myoglobin pigment are equal, they are considered to be isobestic (Hunt et al., 1991). Figure 3 indicates that VP, HiO₂, and ULO₂CO MAP are similar at isobestic wavelengths 525 and 572 nm on d 0 of display, whereas HiO₂ and ULO₂CO MAP are similar at 610 nm. The data suggest that oxymyoglobin found in HiO₂ MAP and carboxymyoglobin found in ULO₂CO MAP are similar to each other. After 7 d of display, steaks packaged in HiO₂ MAP do not appear to share isobestic wavelengths with steaks in other packaging treatments, indicating discoloration of steaks packaged in HiO₂ MAP.

Beef stored in ULO₂CO MAP maintained its red color, whereas steaks packaged in HiO₂ MAP discolored more rapidly. Behrends et al. (2003) reported acceptable color stability of steaks packaged in HiO₂ MAP through d 5 of display. Other researchers showed increased times of storage beyond the 5 d. Behrends et al. (2003) reported in HiO₂ MAP for steaks being red in color; however, some of these steaks were stored in dark storage and not displayed under lights as in the current study. John et al. (2005) reported that steaks in HiO₂ MAP were red in color through 14 d of storage, and steaks in ULO₂CO MAP were red through 21 d of storage. They also found that the majority of steaks stored in VP remained purple in color through d 21 of storage; however, some of their VP steaks must have had residual oxygen in the package, because they turned brown in color. In addition, Sørheim et al. (1999) reported bright red color and high a* values of steaks stored in ULO₂CO MAP through their 11 d of storage, whereas steaks in HiO₂ MAP discolored from d 3 to 8 of storage, and VP steaks did not change in color throughout the 11-d storage period.

Internal Cooked Color

There was a packaging treatment main effect (P < 0.001) for internal cooked a*, b*, a*/b*, hue angle, and saturation (Table 5). The L* value main effects were not significant (P = 0.059; data not shown). Steaks packaged in HiO₂ had the lowest (P < 0.05) a* values (brownest) for internal cooked color of all packaging treatments. Steaks packaged in ULO₂COCO₂ and in vacuum had intermediate a* values, whereas those packaged in ULO₂COAr, ULO₂CO, and ULO₂CON₂ had...
Table 5. Instrumental internal cooked color means and SE for longissimus lumborum steaks packaged in different atmospheres

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Internal cooked color</th>
<th>a*</th>
<th>SE</th>
<th>b*</th>
<th>SE</th>
<th>a*/b*</th>
<th>SE</th>
<th>Hue angle</th>
<th>SE</th>
<th>Saturation index</th>
<th>SE</th>
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<tbody>
<tr>
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<td>18.63hi</td>
<td>1.10i</td>
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<tr>
<td>ULO₂COCO₂</td>
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<td>18.26hi</td>
<td>1.01h</td>
<td>45.03h</td>
<td>26.03h</td>
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<td>HiO₂</td>
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<td>13.99g</td>
<td>0.67g</td>
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<td>ULO₂CO</td>
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<td>19.3j</td>
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<td>20.91i</td>
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</tbody>
</table>

Means with different superscript letters within columns (instrumental measurements) differ (P < 0.05).

1ULO₂COAr = 99.6% Ar, 0.4% CO; ULO₂COCO₂ = 99.6% CO₂, 0.4% CO; HiO₂ = 80% O₂, 20% CO₂; ULO₂CO = 64.6% N₂, 35% CO₂, 0.4% CO; ULO₂CON₂ = 99.6% N₂, 0.4% CO; and VP = vacuum-packaging.

In conclusion, results from this study indicated that steaks packaged in HiO₂ MAP had less color stability than all other packaging treatments evaluated, because they discolored faster and to a greater extent. Ultralow oxygen + CO MAP and VP treatments had better fresh color stability than steaks packaged in HiO₂ MAP and had equal or better tenderness. Packaging atmospheres altered internal cooked color, with steaks packaged in HiO₂ MAP exhibiting premature browning. Longissimus lumborum steaks packaged in the HiO₂ MAP system were less tender at the end of display than other packaging treatments, which may have been because of the shorter aging time associated with the HiO₂ MAP system. Packaging beef in ULO₂CO MAP provides beef with a bright red color with extended color stability and provides for a longer aging time and increased tenderness while resulting in an internal cooked color that is expected for medium degree of doneness, both of which would be beneficial to the meat industry.

ACKNOWLEDGMENTS

We express appreciation to Cargill Meat Solutions (Wichita, KS) for the use of their facilities and equipment, with special thanks to April Archer with Cargill Meat Solutions for her help with this project.

LITERATURE CITED


