Effect of forage and retail packaging types on meat quality of long-term chilled lamb loins

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ABSTRACT: The objectives of this study were to determine the effects of different forage regimes and modified atmosphere packaging (MAP) systems [high oxygen (HiOx-MAP): 80% O₂ and 20% CO₂; and CO₂–MAP: 20% CO₂ and 80% N₂] on color and lipid oxidation stability and sensory attributes of long-term chilled lamb loins during retail display. Lambs (n = 124) were randomly assigned to several pasture-feeding regimes for 12 wk before slaughter. Some had ryegrass (n = 18), lucerne (n = 19), chicory (n = 16), or red clover (Clover 12; n = 17) for all 12 wk. Some were assigned a regime of red clover for 11 wk and pasture for 1 wk (Clover 11; n = 18), with others on red clover for 9 wk and pasture for 3 wk (Clover 9; n = 18). After the lambs were slaughtered, the paired loins (M. longissimus dorsi) were excised at 24 h postmortem, vacuum-packed and stored at -1.5°C for 9 wk. Cuts were then made from each loin and randomly allocated to either HiOx-MAP or CO₂–MAP, and displayed for 7 d at 4°C under light. Chemical attributes including lipid oxidation, surface color-reversing ability, oxygen consumption, and meat quality attributes (color stability and sensory characteristics) were determined. Among the different forage types, the loins from lambs finished on ryegrass appeared to have greater color stability and less lipid oxidation than the loins from lambs finished on other forage types (P < 0.05). On the other hand, the loins from lambs finished on lucerne had the least color and lipid oxidation stabilities and least color-reversing ability (P < 0.05). The loins from lambs finished on chicory had higher aroma and flavor scores than other pasture types in general (P < 0.05). HiOx-MAP negatively influenced meat quality attributes of lamb loins during display, as substantial increases in surface discoloration and lipid oxidation were observed, along with significant decreases in aroma and flavor during retail display compared with the loins in CO₂–MAP. These results suggest that different forage types and packaging conditions could result in substantial impacts on meat quality attributes of long-term chilled lamb loins by affecting oxidation stability. Furthermore, the present study suggests that CO₂–MAP could provide beneficial effects on the eating quality of long-term chilled lamb loins by suppressing oxidation-related defects during display without compromising the ability of blooming for meat display.

Key words: forage, lamb, meat quality, modified atmosphere packaging, oxidation


INTRODUCTION

As the world’s largest lamb meat exporter, the New Zealand (NZ) sheep industry has been interested in seeking alternative forages to improve lamb performance and meat quality while maximizing the economic sustainability of the pasture-based diet system. Animal diet influences the growth and meat quality attributes by affecting antioxidant properties, fatty acid profiles, and/or the rate of protein synthesis, which subsequently impact meat color, flavor, and tenderness (Cramer et al., 1967; Devine et al., 1993; Young et al., 1994; Priolo et al., 2001; Wood et al., 2004). Besides animal diet, meat packaging type can substantially influence meat quality attributes. For exporting the NZ chilled meat products to overseas markets, it takes 6 to 10 wk to ship the products. Once arrived, the wholesale products are usually repackaged to a retail display form. High oxygen modified atmosphere packaging (HiOx-MAP) has been...
extensively used in many countries to extend the shelf life of fresh meat by suppressing microbial growth and prolonging the bright cherry-red “bloomed” (oxygenated) color during display. However, oxidation-related quality defects associated with HiOx-MAP compared to low-oxygen utilized packaging systems (e.g., vacuum, PVC, and ultra low-oxygen MAP) have also been reported in several studies (Lund et al., 2007; Grobbel et al., 2008; Aaslyng et al., 2010; Kim et al., 2010b; Kim et al., 2012).

Little information currently is available regarding the effect of forage types on chemical and meat quality characteristics of long-term chilled lamb meat. Particularly, the effects of different pasture forage treatments on myoglobin and lipid oxidation stabilities of long-term chilled meat under different retail packaging conditions have not been evaluated. Therefore, the objectives of this study were to determine effects of various forage regimes and different packaging systems on color and lipid oxidation stability and sensory attributes of long-term chilled meat.

**MATERIALS AND METHODS**

All animal care and handling procedures in this trial were approved and monitored by the AgResearch New Zealand Animal Ethics Committee.

**Raw Materials and Processing**

A total of 124 lambs (14-wk old) were randomly assigned to 7 different forage treatments for 12 wk before slaughter. Forage-feeding regimes investigated were ryegrass (Lolium perenne, cv. Commando; n = 18), lucerne (Medicago sativa L.; n = 18), chicory (Cichorium intybus, cv. Puna; n = 19), plantain (Plantago lanceolata cv. Tonic; n = 16) and red clover (Trifolium pratense cv. Colenso). For red clover, the lambs were further grouped into 3 forage regimes: grazed on red clover up to slaughter for 12 wk (Clover 12; n = 17), grazed on red clover for 11 wk and then on pasture for 1 wk before slaughter (Clover 11; n = 18), and grazed on red clover for 9 wk and then on pasture for 3 wk before slaughter (Clover 9; n = 18). Lambs were stocked onto forages in early December (early summer season in NZ). Lambs were rotationally grazed, spending 7 d in each break with a 21-d return period. Stocking rates were set to achieve an intake of 2.1 kg DM lamb⁻¹ d⁻¹.

After lambs were slaughtered, the paired loins (M. longissimus dorsi; full-size loin and the other one-half-size loin) were excised at 24 h postmortem, vacuum-packed, placed on ice in cooler boxes, and transported to the meat science laboratory at AgResearch Ltd. in Hamilton, New Zealand. The loins were stored at -1.5°C for 9 wk (simulating a typical NZ meat-export practice). Then four 4-cm thick cuts were made from each full-size loin and randomly allocated either a HiOx-MAP package (80% O₂ and 20% CO₂, certified standard within ± 5%; BOC, Hamilton, New Zealand) or CO₂-MAP (20% CO₂ and 80% N₂, certified standard within ± 5%; BOC). The loin cuts were placed in preformed trays (polypropylene, oxygen transmission rate of 0.1 cm² of oxygen per tray per 24 h at 22.7°C and 0% relative humidity; moisture vapor transfer of 2.0 g of water vapor 645.2 cm² per 24 h at 37.8°C and 100% relative humidity; Cryovac Sealed Air Corp., Hamilton, New Zealand) with soaker pads (Dri-Loc AE-50, Cryovac Sealed Air Corp.), and each tray was put in a shrinkable bag (BB7L, 30 × 39 cm, oxygen-transmission rate of 50 cc O₂/m² per 24 h at 23°C; Cryovac Sealed Air Corp.). Then, MAP packaging was accomplished by using a Securepak 10 Controlled Atmosphere Packaging Machine (Securefresh Pacific, Auckland, New Zealand) by applying vacuum, then flushing the package with the gas mixture and sealing. Within each tray, the gas:meat ratio for the MAP was approximately 2.5:1. The MAP-packaged cuts from the full-size loins (3 cuts in HiOx-MAP and 1 cut in CO₂-MAP) were displayed for 7 d at 4°C under continuous fluorescent natural white light (1350 lx, CRI = 82, color temperature = 4000 K; Osram, Auckland, New Zealand). The one-half-size loins were randomly assigned to either HiOx-MAP or CO₂-MAP and displayed for 4 d at the same display condition above. The loins were re-vacuum-packaged, frozen, and transported to Alliance Group Ltd. for trained sensory panel evaluation for meat-eating quality attributes.

**pH and Gas Composition**

The pH of the loins after 9 wk of vacuum-chilled storage was measured in duplicate by inserting a calibrated pH probe (Testo 205, Lenzkirch, Germany) directly into the meat. The gas composition of MAP trays was monitored by using a headspace oxygen–carbon dioxide analyzer (PBI Dansensor, Glen Rock, NJ) confirming that a high-oxygen (> 70% O₂) and a very low oxygen (≤ 0.05% O₂) level were maintained during the entire display period.

**Instrumental Color**

On d 1, 4, and 7 of simulated retail display, color was measured using a Minolta Color Meter (CR-300; Konica Minolta Holdings Inc., Tokyo, Japan) calibrated using a standard white tile. Lightness, a*, and b* values were measured (Illuminant D65, 1-cm-diameter aperture, 10° standard observer) at 3 random locations on each sample after opening the package. Lightness, a*, and b* values were used to calculate saturation index [(a*² + b*²)¹/²] and hue angle [(b*/a*)tan⁻¹] (AMSA, 1991). The loins in CO₂-MAP were only assessed for instrumental color at
d 7 due to sample limitation. Initial color (immediately after opening the package) and after blooming for an hour were measured for the loins under CO$_2$–MAP.

**Sensory Color**

The sensory color panelists ($n = 12$) were initially screened using the Farnsworth-Munsell 100 Hue Test before group training sessions for sensory color evaluation. The sensory color was evaluated on d 1, 4, and 7 of display for the loins in HiOx-MAP and d 1 and 7 for the loins in CO$_2$–MAP based on the American Meat Science Association (AMSA) meat color guidelines. Lean color was evaluated in 8 scale points: 1, extremely dark/brown red; 2, dark/brown red; 3, moderately dark/brown red; 4, slightly dark/brown red; 5, slightly bright red; 6, moderately bright red; 7, bright red; and 8, extremely bright red. Discoloration was determined in 7 scale points: 1, no discoloration (0% metmyoglobin); 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%). The average scores from the 12 panelists were used for the statistical analysis.

**Surface Color Reversing Ability and Oxygen Consumption**

The surface color reversing ability (CRA; change in $a^*$ values) and oxygen consumption (OC) of the loins were assayed after the start of the display period (d 1; HiOx-MAP only) and the end (d 7; both HiOx-MAP and CO$_2$–MAP) by modifying the protocols described by Sammel et al. (2002) and King et al. (2011). In brief, the top half of the loin cut ($3 \times 2 \times 1.27$ cm) was submerged in 0.3% sodium nitrite solution for 30 min to oxidize the meat surface, forming nitrosylmetmyoglobin (McClure et al., 2011) and then incubated at 30°C for 2 h under vacuum to induce the reduction. The surface meat color ($a^*$) of the cut at the start of and after incubation was evaluated using a HunterLab MiniScan XE Plus Color Meter (Illuminant D65, 2.5-cm-diameter aperture, 10° standard observer; Hunter Associates Laboratory Inc., Reston, VA). The difference in $a^*$ values of each cut was calculated to evaluate the percent CRA (indirect indication of nitric oxide metmyoglobin reducing activity). The remaining bottom half of the cut was used for OC by scanning initial bloomed (30 min at 4°C) meat surface color (oxymyoglobin formation) and after vacuum storage (30 min at 30°C; decreased oxymyoglobin formation due to oxygen consumption within the meat). The color change of the loin based on the difference in $a^*$ values of each cut before and after incubation was estimated to calculate OC (%).

**Lipid Oxidation**

After the start of display (d 1; HiOx-MAP only) and the end (d 7; both HiOx-MAP and CO$_2$–MAP), the extent of lipid oxidation of the loin cuts was determined using the 2-thiobarbituric acid method described by Buege and Aust (1978) with a few modifications. In brief, muscle tissues (5 g) were homogenized in 3 volumes of distilled water (w/v) and centrifuged at 2000 × g for 10 min at 4°C. The supernatant (2 mL) was mixed with trichloroacetic acid (15%)/thiobarbituric acid (20 mM) solution with butylated hydroxytoluene (BHT; 10%), incubated for 15 min in a boiling water bath (around 90°C), and cooled for 10 min in cold water. The absorbance of filtered supernatant was measured at 520 nm using a Shimadzu UV-2450 UV-VIS spectrophotometer (Shimadzu Corp., Tokyo, Japan). The absorption found was converted to mg malonaldehyde/kg meat and reported as thiobarbituric acid-reactive substances (TBARS). Thiobarbituric acid-reactive substances level was predetermined using known concentrations of malonaldehyde (MDA) as standard curves.

**Sensory Analysis for Eating Quality**

A trained sensory panel ($n = 8$) at Alliance Group Ltd. evaluated sensory attributes including aroma, flavor, texture, and succulence of the loins packaged in 2 different MAP systems (HiOx-MAP and CO$_2$–MAP) and displayed for 4 d. Panelists were asked to evaluate the meat samples using a 3-point scale with a quarter interval (total 9 subpoints) by following the Alliance sensory evaluation protocol (MKT-DVS-029), which is based on a New Zealand Institute of Food Science and Technology (NZIFST) sensory guideline (NZIFST, 1987): 1.0 to 1.5, any off taints/stale odors (aroma), any off/rancid flavors or taint (flavor), tough or excessively firm texture/chewy (texture), and consistently dry/absence of juices (succulence); 1.75 to 2.25, slight aroma, slight/weakness of flavors, slight resistance to the bite, slightly juicy; 2.5 to 3.0, good clean fresh aroma, good strong flavor, low resistance to the bite, succulent and adequately juicy on chewing.

**Data Analysis**

The experimental design was a split plot where the whole plot was the animals used to determine the feeding regimes, and the subplots were the loins for the packaging systems (HiOx-MAP and CO$_2$–MAP) and the display days with a random assignment. The data were analyzed using the ANOVA directive of GenStat (12th ed. 2010; GenStat for Windows, ver. 12.2.0.03717., VSN International, Oxford, UK). Least squares means for all traits of interest were separated (F test, $P < 0.05$) by using least significant differences. The sensory data
Forage and packaging effects on meat quality

were analyzed using the REML directive of GenStat, with animals and loins being the random effects and the treatments and locations being the fixed effects. The lipid oxidation data were log transformed for analysis.

RESULTS AND DISCUSSION

Package Gas Composition and pH

High oxygen modified atmosphere packaging trays maintained the high-oxygen atmosphere throughout the display period (d 1: 79.5 ± 1.5% O₂ and 18.8 ± 0.1% CO₂; d 4: 77 ± 1.3% O₂ and 19.3 ± 0.3% CO₂; d 7: 75.9 ± 1.4% O₂ and 20.2 ± 0.3% CO₂). CO₂–MAP trays also maintained the designated initial CO₂ level (19.9 ± 0.2% CO₂) and very low oxygen level (0.04 ± 0.1% O₂) through the entire display period.

The different forage types influenced pHₕwk of the long-term chilled lamb loins (Table 1 and Fig. 1). The loins from the lambs grazed on ryegrass, Clover 9, and Clover 11 had slightly higher pH than the loins from the lamb grazed on lucerne, chicory, and plantain (P < 0.05). Clover 12 was in between. It is worth noting that the loins exhibiting slightly higher pH from the lambs grazed on ryegrass, Clover 9, and Clover 11 also appeared to have more variation (range from 5.6 to 6.1) within each forage treatment compared with the forage treatments that resulted in lower pH loins (Fig. 1). The tendency of having high pH (> 5.8) could be attributed to lower energy intake due to undernutrition and/or preslaughter stress (Apple et al., 1995; Sañudo et al., 1998). Priolo et al. (2002) reported that lambs raised on pasture resulted in lighter carcasses and slightly higher pH compared to the lambs raised on concentrate-based diets. The carcasses from the lamb grazed on ryegrass and Clover 9 had significantly lower HCW (18.6 and 19.3 kg, respectively) with higher pH and more variation within each forage treatment compared to the carcasses from the lamb grazed on chicory and lucerne (25.4 and 23.4 kg, respectively). However, although there were significant differences in pH among forage treatments after 9 wk of storage, the differences were less than (or almost equal to) 0.1 pH unit, which was not considered likely to be a major factor influencing physical and/or chemical attributes of lamb meat.

Instrumental and Sensory Color

The L* values of the loins were influenced by different forage treatments and packaging types (Table 1). Initially the lightness values of the loins from different feeding types were quite similar to each other, although some significant differences were observed (e.g., plantain and ryegrass were darker than Clover 12). However, at the end of display, loins from the lambs grazed on ryegrass or Clover 11 had the lowest L* values (darkest) compared with others under HiOx-MAP (P < 0.05). The higher L* values of the loin in HiOx-MAP could be associated with the elevated oxygenation of myoglobin under the oxygen-rich condition (Kim et al., 2011b). Further, it might be attributed to the greater activities of oxygen-utilizing enzymes in the loin in CO₂–MAP resulting in less oxygen available for myoglobin to form brighter bloomed color (Kim and Hunt, 2011). Particularly, among the loins packaged under CO₂–MAP, the loins from lambs finished on Clover 11 and Clover 9 had lower L* values than other forage treatments at the end of display (P < 0.05; Table 1).

The a* values of the loins were significantly influenced by different forage types and retail packaging conditions during display (Table 1). The loins in HiOx-MAP from lambs finished on clover had higher initial a* values than those of the loins from lambs finished on chicory, plantain, and ryegrass (P < 0.05), while lucerne was the lowest at d 1. As display time increased, the a* of all the loins decreased, while ryegrass and plantain showed a superior color stability followed by
Table 1. Effects of feeding forages for 12 wk and retail packaging types on pH, HCW, color stability, and lipid oxidation (TBARS) of long-term chilled loins (for 9 wk at –1.5°C) displayed for 7 d at 4°C

<table>
<thead>
<tr>
<th>Trait</th>
<th>Package</th>
<th>Day</th>
<th>Forage</th>
<th>pH</th>
<th>HCW, kg</th>
<th>L*</th>
<th>CO₂</th>
<th>a*</th>
<th>Hue Angle</th>
<th>Chroma</th>
<th>Lean color</th>
<th>Discoloration</th>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Clover 12</td>
<td>5.74ab</td>
<td>22b</td>
<td>41.4b</td>
<td>18.7ax</td>
<td>27.0b</td>
<td>29.9b</td>
<td>6.5b</td>
<td>1.0</td>
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<td></td>
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<td></td>
<td>Clover 11</td>
<td>5.79b</td>
<td>21.2b</td>
<td>40.2ab</td>
<td>33.1b</td>
<td>27.1b</td>
<td>29.9b</td>
<td>6.5b</td>
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<td></td>
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<td>Clover 9</td>
<td>5.8b</td>
<td>19.3a</td>
<td>40.8ab</td>
<td>32.2b</td>
<td>27.5b</td>
<td>30.4b</td>
<td>6.4ab</td>
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<td></td>
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<td></td>
<td>Chicory</td>
<td>5.68a</td>
<td>25.4a</td>
<td>39.6a</td>
<td>28.6a</td>
<td>25.4a</td>
<td>28.0a</td>
<td>6.3ab</td>
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<td></td>
<td>Lucerne</td>
<td>5.73a</td>
<td>23.4b</td>
<td>39.8a</td>
<td>28.4a</td>
<td>25.8a</td>
<td>28.1a</td>
<td>6.5b</td>
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<td>Plantain</td>
<td>5.71a</td>
<td>19.5a</td>
<td>39.5a</td>
<td>28.2a</td>
<td>25.7a</td>
<td>28.2a</td>
<td>6.5b</td>
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<td></td>
<td></td>
<td></td>
<td>Ryegrass</td>
<td>5.8b</td>
<td>18.6a</td>
<td>39.2a</td>
<td>28.2a</td>
<td>25.7a</td>
<td>28.2a</td>
<td>6.5b</td>
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<td>&lt;0.001</td>
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<sup>a–eValues that differ (<i>P</i> < 0.05) within a row.</sup>  
<sup>x,yValues that differ (<i>P</i> < 0.05) within a column.</sup>  
1Lamb were randomly assigned to seven forage regimes for 12 wk before slaughter; ryegrass, Lucerne, Chicory, Plantain, red clover (Clover 12), red clover 11 wk and pasture for 1 wk (Clover 11), or red clover for 9 wk and pasture for 3 wk (Clover 9).  
2Standard errors of differences of means.  
3High-oxygen modified atmosphere package (80% O₂ and 20% CO₂).  
4<i>P</i>-value for an interaction of forage by packaging effects.  
5SED to compare the means between forage types within each package/display treatment (in a row).  
6SED to compare the means between each package/display treatment within each forage type (in a column).  
7CO₂-modified atmosphere package (20% CO₂ and 80% N₂); Traits for loins packaged this way were only determined at d 7.  
8Hue angle = [(<i>b</i>/*<i>a</i>)*tan<sup>-1</sup>].  
9Chroma = [(<i>a</i>² + <i>b</i>²)<sup>1/2</sup>].  
10<sup>8</sup>Scale points: 1, extremely dark/brown red; 4, slightly dark/brown red; and 8, extremely bright red.  
11<sup>7</sup>Scale points: 1, no discoloration; 4, modest discoloration; and 7, total discoloration.
The loins packaged in CO₂–MAP maintained significantly higher \( a^* \) values compared with the loins in HiOx-MAP at the end of display (Table 1). After opening the package and allowing the loins to bloom for 1 hr, the initial purplish-red color of the meat surface was converted to relatively bright red color (average 24% increase in \( a^* \); Fig. 2), which indicates that myoglobin of the long-term chilled loins was still capable of oxygenating after 7 d of display under the CO₂–MAP condition. Within the CO₂–MAP treatment, the loins from the lamb finished on chicory had the highest \( a^* \) values, whereas the loins from Clover 12 showed the lowest at d 7 (\( P < 0.05; \) Fig. 2).

Hue angle and chroma values also revealed that the loins from lambs finished on lucerne resulted in the most rapid surface discoloration and least color intensity closely followed by chicory throughout the display period under HiOx-MAP (\( P < 0.05 \); Table 1). In contrast, the loins from lambs finished on ryegrass had the lowest hue angle value indicating the least discoloration and thus superior color stability.

The sensory color data agreed with the instrumental color results in that the loins from lambs finished on lucerne had the sharpest decline in lean color scores after 4 d of display (6.5 to 2.1) followed by chicory, while plantain had the lowest decline in lean color scores followed by ryegrass (Table 1). The loins from lambs finished on lucerne and chicory had the most rapid accumulation rate of brown discoloration followed by Clover 12, Clover 11, Clover 9, ryegrass, and plantain. Ryegrass and plantain resulted in the lowest discoloration score (3) at d 4, which can be corresponded to 20 to 30% metmyoglobin accumulation based on the AMSA color guidelines. Interestingly, under CO₂–MAP, the loins from lambs finished on chicory (and plantain) showed the least discoloration, indicating that the forage effect on meat display color would be dependent on the retail packaging types being used. However, overall the loins packaged in CO₂–MAP had significantly lower hue angle values and sensory discoloration scores and higher chroma and sensory lean color scores compared with the loins packaged in HiOx-MAP at d 7, which confirms the overriding packaging effect on color stability as discussed above.

**Surface Color Reversing Ability and Oxygen Consumption**

The surface CRA was measured based on the difference in \( a^* \) values of the cut at the start of and after vacuum-incubation immediately after being oxidized in 0.3% sodium nitrite solution (forming nitrosylmetmyoglobin; McClure et al., 2011). A previous study found a strong negative correlation \((r = -0.81; \ P < 0.001)\) between CRA and sensory discoloration, where the higher the CRA, the lower the discoloration observed on the surface of meat during display (Y.H.B. Kim, unpublished data). Thus, this simplified assay (modified version of nitric oxide metmyoglobin reducing activity) could be used as an indirect measurement for the redox potential of myoglobin. In the current study, CRA of the loins decreased (\( P < 0.001 \)) after 7 d of retail display, but there was no packaging effect on CRA at d 7 (\( P = 0.1 \); Fig. 3A). Decreased myoglobin redox stability with increasing display time periods has been well understood (Sammel et al., 2002; Kim et al., 2009; King et al., 2011), and it is generally agreed that the decreased reducing ability negatively influences meat color stability (Ledward, 1985; Mancini and Hunt, 2005). However, the observation in the current study is interesting, because the loins in CO₂–MAP had superior color stability compared with the loins in HiOx-MAP (based on instrumental and sensory color evaluation as described in the above section), which indicates less metmyoglobin formation occurred under CO₂–MAP. However, CRA of the loins for both packaging systems was similar at d 7 (\( P > 0.05 \)). Thus, it can be speculated that the maintained \( a^* \) of the loin in CO₂–MAP at d 7 would be primarily due to the nonoxidative condition in the CO₂–MAP system rather than the remaining extent of redox potential of myoglobin (CRA per se) at d 7. Furthermore, the distinct differences in the color of the loins as affected by the forage types were only observed at d 4, whereas CRA was determined at d 1 and 7 (not d 4) due to sample limitation. Therefore, the role of CRA in color stability of long-term chilled lamb loins could not be fully determined from the present study. Overall, the loins from lambs finished on chicory had the lowest CRA compared with the ones from other feeding types (\( P < 0.05 \); Fig. 3B), which could partially explain the
inferior color stability of the loins from lambs grazed on chicory. However, in general, the CRA values of the loins from different forage types did not seem to fully explain the different color stability of the loins as discussed above.

The assay results of oxygen consumption (OC) found that the packaging type significantly affected OC of the loins (P < 0.05), whereas the display time did not (P > 0.05; Fig. 4A). The extent of OC by respiratory enzymes in long-term chilled meat (9 wk) did not seem to be substantially changed after the additional display period (7 d), while meat color stability decreased over display time. Thus, this result suggests that OC might not play a substantial role in meat color stability but may possibly be more involved in initial display color as previously discussed by King et al. (2011). Further, the higher OC level of the loins in CO₂–MAP at d 7 was likely due to the ultra-low level of oxygen in CO₂–MAP compared with HiOx-MAP, where mitochondrial respiratory enzymes of the loins had not been exposed to the oxygen-consuming environment during the retail display period. A significant forage type effect on OC was found regardless of the packaging types (Fig. 4B). The loins from lambs finished on plantain had the lowest OC, followed by ryegrass, lucerne, chicory, plantain, red clover (Clover 12), red clover 11 wk and pasture for 1 wk (Clover 11), or red clover for 9 wk and pasture for 3 wk (Clover 9).
present study were not clearly associated with \( a^* \) evaluated by both the instrument and sensory panel. Similarly, King et al. (2011) reported that OC was not significantly related to surface beef color change during 6 d of retail display, suggesting that OC would influence the initial lean color variation rather than color stability.

**Lipid Oxidation**

There was a significant increase in lipid oxidation of the loins under HiOx-MAP after 7 d of retail display (Fig. 5). However, the loins from lambs finished on ryegrass had the least accumulation of lipid oxidation [still less than 1 mg MDA/kg meat, the threshold for consumers to detect off-flavors (Jayasingh et al., 2002)] at d 7, followed by Clover 9. The loins from lambs finished on lucerne had the highest lipid oxidation accumulation (more than 2 mg MDA/kg meat). These findings can be exactly aligned with the color stability data, in that the loins from lambs finished on ryegrass had the least surface discoloration (indicating least myoglobin oxidation), whereas the loins from lambs finished on lucerne developed the most rapid discoloration during the display period. The corresponding results can be explained from the coupling reactions of lipid and myoglobin oxidation, where free radicals generated from lipid oxidation can directly induce myoglobin oxidation, forming metmyoglobin for brown discoloration (O’Grady et al., 2001; Kim et al., 2010a). Further, it is suggested that the loin from lambs grazed on ryegrass had superior lipid and color stability, which also was the finding of Fraser et al. (2004). They found that meat from lambs finished on lucerne was oxidatively less stable than that from lambs finished on ryegrass. They further discussed that the lower lipid and myoglobin oxidation stability of the loins from the lucerne forage group could be also attributed to their higher concentration of unsaturated fatty acids that are known to be more susceptible to oxidation, compared with that of the loins from the ryegrass-fed group (Fraser et al., 2004). In fact, our previous trial (Y.H.B. Kim, unpublished data) also found that the loins from the lamb grazed on lucerne had more unsaturated fatty acids \( (P < 0.05) \), such as linoleic acid \((C18:2n-6)\) and linolenic acid \((C18:3n-3)\), than the loins from the lamb grazed on ryegrass.

The packaging condition substantially affected the lipid oxidation values of the loins at the end of display. The loins in CO\(_2\)-MAP had significantly lower lipid oxidation than the loins in HiOx-MAP at d 7 (average TBARS values of 0.2 and 1.8 mg MDA/kg meat, respectively) confirming that the ultra-low level of oxygen in the CO\(_2\)-MAP maintained the least oxidative condition during display of the long-term chilled lamb loins. That could also contribute to minimized discol-

![Figure 5. Effects of forage types\(^1\) on lipid oxidation of long-term chilled loins (for 9 wk at -1.5°C) during 7 d of retail display at 4°C under HiOx-MAP (80% O\(_2\) and 20% CO\(_2\)). Absorption was converted to mg malonaldehyde/kg meat and reported as thiobarbituric acid reactive substances (TBARS). Error bars indicate the standard errors of difference. See online version for figure in color.](image)

\(^1\)Lambs were randomly assigned to seven forage regimes for 12 wk before slaughter; ryegrass, Lucerne, chicory, plantain, red clover (Clover 12), red clover 11 wk and pasture for 1 wk (Clover 11), or red clover for 9 wk and pasture for 3 wk (Clover 9).

**Table 2. Effects of feeding forages for 12 wk on sensory attributes\(^1\) of long-term chilled loins (for 9 wk at –1.5°C) displayed for 4 d at 4°C**

<table>
<thead>
<tr>
<th>Trait</th>
<th>Clover 12</th>
<th>Clover 11</th>
<th>Clover 9</th>
<th>Chicory</th>
<th>Lucerne</th>
<th>Plantain</th>
<th>Ryegrass</th>
<th>P-value</th>
<th>SED</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aroma</td>
<td>2.6(^b)</td>
<td>2.6(^c)</td>
<td>2.4(^a)</td>
<td>2.6(^c)</td>
<td>2.5(^b)</td>
<td>2.5(^b)</td>
<td>2.4(^a)</td>
<td>&lt;0.01</td>
<td>0.04</td>
</tr>
<tr>
<td>Flavor</td>
<td>2.4(^b)</td>
<td>2.4(^b)</td>
<td>2.3(^a)</td>
<td>2.5(^c)</td>
<td>2.4(^b)</td>
<td>2.4(^b)</td>
<td>2.3(^a)</td>
<td>&lt;0.01</td>
<td>0.04</td>
</tr>
<tr>
<td>Texture</td>
<td>2.5</td>
<td>2.5</td>
<td>2.5</td>
<td>2.5</td>
<td>2.5</td>
<td>2.5</td>
<td>2.5</td>
<td>0.38</td>
<td>0.03</td>
</tr>
<tr>
<td>Succulence</td>
<td>2.5(^b)</td>
<td>2.5(^b)</td>
<td>2.4(^a)</td>
<td>2.5(^b)</td>
<td>2.5(^b)</td>
<td>2.5(^b)</td>
<td>2.5(^b)</td>
<td>0.01</td>
<td>0.04</td>
</tr>
</tbody>
</table>

\(^a\)^\(^b\)\(^c\)Values that differ \((P < 0.05)\) within a row.

\(^1\)Trained sensory panel \((n = 8)\) evaluated cooked meat samples using a 3-point scale with a quarter interval (total 9 subpoints): 1.0 to 1.5, any off/taints/stale odors (aroma), any off/rancid flavors or taint (flavor), tough or excessively firm texture/chewy (texture), and consistently dry/absence of juices (succulence); 1.75 to 2.25, slight aroma, slight/weakness of flavors, slight resistance to the bite, slightly juicy; 2.5 to 3.0, good clean fresh aroma, good strong flavor, low resistance to the bite, and succulent and adequately juicy on chewing.

\(^2\)Lambs were randomly assigned to seven forage regimes for 12 wk before slaughter; ryegrass, Lucerne, chicory, plantain, red clover (Clover 12), red clover 11 wk and pasture for 1 wk (Clover 11), or red clover for 9 wk and pasture for 3 wk (Clover 9).

\(^3\)Standard errors of difference.
oration of the loins (by suppressing myoglobin oxidation) under this packaging condition during display.

**Sensory Evaluation**

Significant main effects (forage treatments and packaging types) were found for some of the sensory attributes. The trained sensory panel found that loins from lambs finished on Clover 12, Clover 11, and chicory had the highest scores in aroma, followed by lucerne and plantain. Clover 9 and ryegrass had the lowest (Table 2). The loins from lambs finished on chicory had the highest flavor scores, whereas Clover 9 and ryegrass had the lowest. Similarly, Cramer et al. (1967) reported that loin chops of clover-fed lambs had a significantly greater flavor intensity compared with those from lambs finished on ryegrass. They also found significant increases in shorter-chain saturated and C15 branched-chain acids, which are known to be responsible for the specific flavor of lamb meat (Young et al., 2003), in loin chops of the ryegrass-fed group (Cramer et al., 1967). Conversely, a few studies reported no significant effect of forage types on the eating quality of lamb loins (Young et al., 1994; Vipond et al., 1995; Fraser et al., 2004). The texture attribute was not influenced by the forage treatment ($P > 0.05$). The loins from lambs finished on Clover 9 had lower succulence scores ($P < 0.05$) than the loins from other forage treatments.

The packaging type significantly influenced sensory attributes of the loins after 4 d of retail display (Table 3). The loins packaged in HiOx-MAP had lower aroma and flavor scores than the loins in CO$_2$-MAP ($P < 0.05$). Further, there is a trend of having lower texture values of the loins in HiOx-MAP compared with the loins in CO$_2$-MAP ($P = 0.07$). These observations agree with other studies in that HiOx-MAP negatively influenced sensory attributes (decreased tenderness and juiciness, plus increased off-flavor) of beef and pork at the end-point of display (Lund et al., 2007; Kim et al., 2010b). Further, a recent study found HiOx-MAP can negatively influence even the tenderness of fully tenderized lamb loins by inducing a protein polymerization of high-molecular weight proteins during retail display (Kim et al., 2011a). In the present study, the sensory attributes of the loins were determined at the midpoint (d 4) of the 7-d display period, and thus it would likely induce more negative influences on sensory attributes while progressing toward the end of the display period.

**Conclusions**

The data from the current study found that different forage and retail packaging types substantially impacted chemical characteristics and quality attributes of the long-term chilled lamb loins. Particularly, among the forage types, the loins from lambs finished on ryegrass had superior color stability (least discoloration) and less lipid oxidation than the loins from lambs finished on the other forage types. The loins from lambs finished on plantain also had the low discoloration, similar to ryegrass, throughout the entire display. Contrarily, the loins from lucerne had the least CRA, lipid oxidation, and color stabilities. The loins from chicory were higher in aroma and flavor scores than loins from lambs finished on the other pasture types; however, rapid discoloration similar to the loins from lucerne was also observed.

HiOx-MAP negatively influenced meat quality attributes of lamb loins during display; substantial increases in myoglobin and lipid oxidation were observed in the HiOx-MAP loins, along with significant decreases in aroma and flavor during retail display, compared with the loins in CO$_2$-MAP. These results indicate that different forage types could result in profound impacts on lamb meat quality attributes by affecting the oxidation stability (myoglobin and lipid oxidation per se) during retail display. Therefore a more in-depth study of identifying the mechanism for improved antioxidation properties of lamb meat in accordance with dietary compounds, particularly using ryegrass (and possibly plantain) with other known antioxidant-diet supplementations (for a synergistic effect), would be warranted. In addition, the results from the present study suggest that low-oxygen MAP (containing CO$_2$ and N$_2$) with a dual-layer film (easy-peeling, oxygen-impermeable surface film of the pack before retail display, and the oxygen-permeable second film for meat blooming) or the mother bag system could provide beneficial effects on the eating quality of long-term chilled lamb loins.
chilled lamb meat products by suppressing oxidation-related defects during display while not compromising the ability of blooming before retail display.

LITERATURE CITED


