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Effect of slaughter age and post-mortem days on meat quality of *longissimus* and *semimembranosus* muscles of Boer goats

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Abstract

This study investigated the effects of age of animal and days post-mortem (PM) on meat quality of Boer goats. Twenty-four (24) wether Boer goats of two age groups (2YO group: 2 years old and 9MO: 6-9 months, with 12 animals/group) were slaughtered in a commercial processing plant. The pH@Temp18 was estimated to be above 6 in both age groups with higher ($P < 0.01$) values in 2YO goats. The PM storage for 14 days reduced the shear force in both age groups ($P < 0.01$). 2YO goat muscles (*longissimus* and *semimembranosus*) exhibited higher ($P < 0.01$) Thiobarbituric acid reactive substance values (TBARS), indicating increased lipid oxidation. Glycogen ($P < 0.01$) and lactate content (20 min post-slaughter) in *longissimus* of 9MO were lower compared to 2YO, and total muscle glycogen concentration was lower ($P < 0.01$) in both age groups below the threshold levels. Hence, as hypothesized, age and days PM proved to play crucial roles on Boer meat quality.

Keywords: pH decline, retail meat quality, lipid oxidation, TBARS, total glycogen

1. Introduction

Australia is the largest exporter of goat meat globally (MLA, 2020). The Australian goat meat industry recorded 1.6 million head slaughtered in 2018, that was worth over AUD $182M (MLA, 2020). The majority of Australian goat meat produced is exported. Goat meat has no religious restrictions, and is one of the most widely consumed red meats in parts of Asia, the Middle East, Africa and Hispanic population across the United States of America (GICA, 2015). Although, the export market is a lucrative enterprise, domestic consumption is negligible, apart from the ethnic populations remaining true to their cultural origins (MLA, 2020). However, the Australian goat meat industry is on track to stabilize the supply base and achieve new market opportunities and expand the domestic market. However, research and development activities in Australia to reduce the inconsistent goat meat eating quality is in its early stages (MLA, 2017). Quality assurance is an innovative approach that has proven to be successful in promoting the beef and sheep meat industry (Bonny et al., 2018). When the Meat Standards Australia (MSA) beef grading system was established, inclusion of an ideal pH/temperature window was a critical concept put forward initially (Hopkins, Ponnampalam, Van de Ven, & Warner, 2014). For example for lamb carcasses, 18-35 ºC at pH = 6 was defined as the optimum pH temperature window for product to be aged for 5 days and 8-18 ºC for product aged for 10 days (Gutzke, Franks, Hopkins, & Warner, 2014). To the best of our knowledge, there is no such pH temperature window defined for goat meat. Also, little is known about goat meat quality attributes as affected by age of animals and post-mortem storage, which may be vital to develop and optimize goat meat production and processing systems. Therefore, this study was designed to document the postmortem muscle pH temperature decline, cooked meat quality and retail color stability of Boer goats as affected by animal age and days post-mortem (PM). We hypotheized that age of animal and days PM have key roles to play on the meat quality of goats.

2. Materials and methods

2.1 Animals

Twenty-four (twelve 6-9 months old goats: 9MO and twelve 2-year old: 2YO) wether Boer goats were sourced from Myrrhee farm, Victoria, Australia. The goats had been on improved pasture (rye grass) and native grasses, along with grass hay. Lucerne hay was only available 6 weeks before they were used in the study. The animals were transported (3 h) to Cedar Meats, Brooklyn, Australia and kept in lairage overnight for 14 h

before slaughter. Goats were transported using purpose-built animal transport trailer and every care was taken to minimize stress to animals as per standard practices. Goats were off feed during lairage before slaughter and had access to water only.

2.2 Slaughter procedures, Measurement and Sampling

The animals were electrically stunned (220 V) prior to slaughter, and then exsanguinated using Halal methods with no electrical stimulation of the carcasses, which was the normal practice in this plant. Halal slaughter refers to the bleeding of animals intended for meat production following the Islamic criteria of Islamic ritual slaughter (Abdullah, Borilova, & Steinhauserova, 2019). The hot carcass weights were recorded, and the Girth Rib (GR) score was measured (total tissue depth over the 12th rib, 110 mm from the midline) using a GR knife. The pH was measured in the left side of the *longissimus thoracis et. lumborum* (LTL) at the 12th/13th rib site, after calibrating the meter at chiller temperature, at 30 min, 1, 2, 3, 4, 5, 6, 8, and 24 h post-slaughter. Carcasses were chilled overnight at 4 ºC. pH of LL at 48 h post-mortem was recorded in the Meat research facility on the following day. Muscle pH was measured using meters with temperature compensation (WP-80, TPS Pty Ltd, Brisbane, Australia) and a polypropylene spear-type gel electrode (Ionode IJ 44), which was calibrated at ambient temperature. The pH meter was calibrated before use and at regular intervals using pH 4 and pH 7 buffers. Dressing percentage (DP) was calculated on the basis of live weight and hot carcass weight (HCW) using the formula HCW/LW*100. Samples for measuring glycogen and lactate content (1 g each) were taken from the LTL between the fourth and fifth lumbar vertebrae, approximately 20 min post-slaughter, trimmed of all visible connective tissue and fat using a scalpel, snap frozen in liquid nitrogen and then stored in - 80 ºC.

2.3 Meat packaging and storage

The LTL and *semimembranosus* (SM) muscles were sampled 24 h after slaughter. Vacuum packaging was performed on a Multivac C200 (Sepp Haggenmüller GmbH & Co., Wolferschwenden, Germany) using polyamide and polyetheylene vacuum pouches PA/PE 70 (Multivac) with an oxygen permeability less than 65 cc/m2 (24 h) and water transmission less than 5 g/m^2/24 h. Each age group comprised of 12 left and 12 right

LTL and SM. The 12 left and 12 right LTL and SM of each age group were then randomly assigned to 1 or 14 days PM storage (all within a carcass). After this allocation, each side was then divided into three blocks (90 g, 45 g, 90 g), which were assigned to three days of display (0, 5 and 10 days). Two of these blocks were 90 g each and one block weighed around 45 g. This was due to the limitation in muscle samples especially from the 9MO. Texture analysis was done only on 0 and 10 day (90 g each) samples due to the limited muscle samples. Each of the two 90 g blocks were used for texture analysis, color and Thiobarbituric acid reactive substances (TBARS), whereas the third block from the muscle was used for color measurement and TBARS. Hence, from one carcass, there were four 90 g blocks and two 45 g blocks.

The samples assigned to 0 day of display were first tested for color and samples for TBARS were taken from the same block. The remaining sample was then cooked for cooking loss measurement, which was then kept in chiller for overnight and used for texture analysis. Similarly, the blocks assigned to 5 day and 10 days of display were taken out from display cabinets on respective days, tested for color, cooked in a water bath, kept in a chiller overnight and tested for texture. This procedure was repeated for the 14 days PM samples.

All samples were packaged in high oxygen modified atmosphere packaging (hiOxMAP; 80% O_2, 20% CO_2) during the simulated display. The hiOxMAP packaging was conducted with a Multivac T200 (Sepp Haggenmüller GmbH & Co., Wolferschwenden, Germany) connected to a gas mixer to achieve O_2: CO_2 ratio of 80 %: 20 %. The gas ratio of the packs were checked by a gas analyser and was 80% O2, 20% $CO^2 \pm 0.1\%$. Chops (5 cm thickness, 90 g) were placed on a cello pad positioned in Cryovac black trays (170 mm × 223 mm, Sealed Air, Australia). The trays were sealed with a biaxially Oriented PolyAmide/Polyethylene / Ethylene vinyl alcohol-based film (LID-1050, OTR 10 $cm^3/m^2/24$). Trays were subsequently kept in 4-6 °C refrigerator (display cabinets) for 10 days and color was measured on the respective days of display. Retail packs were randomly distributed on the shelves of cold display cabinet with high-impact LED internal lighting on each side (maximum 18 W) with an average light intensity of 732 lux, color temperature of 4000 K, and color rendering index of 85 (GM1000LWCAS, Bromic Pty Limited). Meat color was measured using Hunterlab Miniscan EZ (model No. 45/0-L, aperture of 31.8 mm; Hunter Assoc. Labs Inc., Virginia, USA) calibrated against white and black reference tiles. Duplicate surface color measurements were taken with D65 illuminant and 10° observer angle. The CIE L* (lightness), a* (redness) and b* (yellowness) values were obtained from the average values of two readings on the surface of muscle samples.

Psychometric hue angle (h) and psychometric chroma (C∗) were calculated using the equations outlined by Hunt et al. (1991): psychometric chroma $C^* = (a^2 + b^2)^{0.5}$, psychometric hue $h = \tan^{-1}(b/a)$. Cooking loss was measured following the method of Ha, Dunshea, and Warner (2017). Muscle samples were weighed and cooked in water bath using moist cooking method (F38-ME, Julabo, 77960 Seelbach/Germany), which was pre-heated to 70 °C and samples were left in the water bath until the core temperature reached 70 ºC. The temperature of the sample was measured using a thermometer equipped with T-type thermocouples (Grant Instruments, Australia). Samples were then cooled in ice water to prevent further cooking, patted dry with paper towel and weight was recorded. The samples were stored in plastic bags (to reduce moisture loss) at 4 °C in a chiller overnight prior to Warner-Bratzler shear force (WBSF) and compression test. Hence, WBSF and compression test was done with cooked meat and color and TBARS was done on raw meat.

2.4 Warner-Bratzler shear force and compression

Samples prepared into 90 g blocks and packed in each tray were used for both WBSF and compression test (parameters measured were hardness, chewiness, and cohesiveness), which were conducted the next day after cooking, following an established method outlined by Honikel (1998) with some modifications. Briefly, six rectangular strips of 1 cm^2 were cut parallel to the direction of muscle fibers from each sample. WBSF was measured by using a shear blade (V-shaped) attached to a texture analyzer (LS5 Ametek Lloyd Instruments Ltd., Largo, FL, USA) with a 500 N load cell, and the shearing speed was set at 300 mm/min. The average of 6 sub-samples was calculated as an estimate of toughness. Compression test was conducted according to a method previously reported by Ha, Dunshea, and Warner (2017). A 0.63 cm diameter flat-ended probe was adapted to a texture analyzer (LS5 Ametek Lloyd Instruments Ltd., Largo, FL, USA). A total of 5 measurements were taken for each sample and presented as means.

2.5 TBARS assay

Samples for TBARS analysis (10 g) were collected at 0, 5 and 10 days of display and frozen. The lipid oxidation in the samples was assessed by the TBARS procedure (Sørensen & Jørgensen, 1996) and expressed as mg of malondialdehyde (MDA) per kg of muscle.

2.6 Glycogen, lactate and total glycogen content

For the determination of glycogen content, 10 mg of frozen LL sample was homogenised in 100 µl of MilliQ water and boiled for 5 minutes to inactivate enzymes. Samples were then centrifuged (Eppendorf, Centrifuge 5417C, USA) for 5 min at 13,000 x g to remove insoluble material. The supernatant from each sample was plated in duplicate and compared to glycogen standards using the colorimetric protocol detailed by the commercial glycogen assay kit (MAC016A, Sigma-Aldrich, St. Louis, MO 63103, USA). Absorbance was measured at 570 nm using a micro-plate reader (QuantStudio 1, appliedbiosystems, Thermo Fisher Scientific, USA) in order to calculate total glycogen concentration of each sample.

For lactate content, 50 mg of sample was homegenised with 4 volumes of the lactate assay buffer, and centrifuged for 10 min at 13,000 x g. Supernatant was plated in duplicate and compared to lactate standards using the colorimetric protocol detailed by the commercial lactate assay kit (MAC064, Sigma-Aldrich, St. Louis, MO 63103, USA). Absorbance was measured at 570 nm using the micro-plate reader. Total glycogen content (µmol/g) was calculated as the sum of muscle glycogen and lactate (µmol/g) (Knee, Cummins, Walker & Warner, 2004).

2.7. Statistical analysis

All statistical analyses were performed using GenStat (16th Edition, VSN International Ltd., Hemel Hempstead, UK). All instrumental parameters were analyzed by the method of restricted maximum likelihood (REML) due to multiple factors (age, days PM, display days) all with one experimental unit (carcass). This experiment was conducted as a 2×2×3 factorial design to examine the effects of age, days PM and display days on goat meat quality. The muscles were fixed; the allotment to treatments was randomized. For all instrumental measurements, animal age (9MO or 2YO), days PM (1 and 14 days PM), display days (0, 5 and 10 day) were fitted as fixed effects. The rate of pH decline with time was analyzed by regression analysis models which fit exponential curves. This firstly fits a single curve of the form $A + BR^X$, where A, B and R stand for estimates of parameters for the fitted curve. It then adds age to the model, thus producing separate values of A for 9MO and 2YO goats. The pH at temperature 18 (pH@temp18) was predicted for each carcass, rather than temperature at pH 6, as the 9MO failed to attain pH 6 at 24 h. The

standard errors were then calculated for each group. Multiple comparison was done using Tukey's test for within the group variations. When significant by ANOVA at $P < 0.05$, the means were separated by LSD test.

3. Results

3.1 Carcass characteristics

The carcass characteristics of the 9MO and 2YO goats used in this experiment are shown in Table 1, with higher live weight, hot carcass weight, DP and GR fat depth for 2YO ($P < 0.001$ for all).

3.2 Muscle pH and temperature decline

The effect of age on the animal on pH and temperature measurements is presented in Figure 1 and pH and temperature in LTL muscle at different time points is shown in Figures 2 and 3. The ultimate pH of the LL of 9MO was higher compared to 2YO goats (Table 1; $P < 0.001$). The predicted pH@Temp18 (Table 1) was higher in 9MO compared to 2YO ($P < 0.001$). However, both age group goats showed pH@Temp18 above 6. It was not possible to report Temp@pH6 as none of the goats had reached pH 6 in the optimum temperature range.

3.3 Muscle glycogen and lactate content

The glycogen content (μmol/g) in LL of both 9MO and 2YO goats is presented in Table 1. As shown in the table, glycogen content was lower in 9MO as compared to 2YO goats ($P < 0.001$). Similar trend was observed with the lactate and total glycogen content ($P < 0.01$) (μmol/g).

3.4 Meat color during retail display

Age and display day influenced the LL lightness (L*) and redness (a*) value with decreasing lightness and increasing redness with increasing animal age ($P < 0.01$; Table 2). Further, there was an interaction between age and display day such that the 9MO exhibited increase in a* value over the display days ($P < 0.01$). However, in SM all the fixed effect terms had effect ($P < 0.01$) on a* and PM and display day had effect on L*

(P < 0.001). In addition, the interaction effect between age and PM, and age and display day were also present in SM (P < 0.001). L* increased from 0 to 10 days in both muscle and in both PM days (P < 0.001). PM duration also increased the L* value in SM (P < 0.001). Also, the interaction between age and PM is evident from Figure 4, wherein brown discoloration from bright cherry red color occurred in the 14 days PM 2YO but not in 14 day PM 9MO goat meat. The influence of muscle (P < 0.01) on a* is illustrated in Figure 5 with higher value in LL muscle compared to SM. The yellowness value generally increased from 0 to 10 days on display in both muscle (P < 0.001). PM also increased the b* with increasing duration in LL (P < 0.001) and SM (P = 0.07), although age did not show much effect. Hue angle (h) showed a similar trend in both muscles with an increase on the 5 day of display and decrease on 10 day of display. This was evident in both 0 and 14 days PM meat. This trend was however not significant. Chroma (C*) showed an opposite trend with a decrease on the 5 day of display and increase on 10 day of display, which was also evident in both muscle and both PM periods. Age, PM and age x PM interactions on C* were significant in both LL and SM (P < 0.001; Table 2).

3.5 Lipid oxidation assay

Figure 6 illustrates the effect of all treatments on the amount of MDA produced per kg of muscle in LL of Boer goat during the simulated retail display. Among the fixed factors, lipid oxidation expressed as TBARS (mg MDA/ kg), was affected by age, days PM and retail display period in LL muscle of Boer goats (P < 0.01; Figure 6). Similar results were observed in SM muscle, with effect of age (P < 0.01), PM (P < 0.05) and display days (P < 0.01) on lipid oxidation. Additionally, age x PM, display day x PM, and age x PM x display day interactions were present in both the muscles (P < 0.01).

3.6 Cooking loss

Cooking loss of the 1 and 14 days PM samples are presented in Table 3. For cooking loss, there was a significant interaction between age and retail display days such that cooking loss decreased with the increasing retail display period only in the 9MO goats LL, which ranged from around 26% for 0 day display to 18% for 10 days display irrespective of PM days (Table 3). However, in SM the effects of age, days PM and display days on cooking loss were not significant. Although a similar trend of reduction in cooking loss was observed in 2YO goat meat, this was not significant.

3.7 WBSF and compression

The mean values of shear force for all treatments are presented in Table 3. Of the fixed effect terms, only PM and display days influenced ($P < 0.01$) the shear force in LL, with significant ($P < 0.001$) interaction effect between days PM and display days (Table 3). Whereas, in SM muscle, days PM ($P < 0.001$) and display day ($P < 0.001$) influenced shear force, with an interaction ($P < 0.05$) between age and display days ($P < 0.001$). The effect of PM storage on both muscles were similar, with lower values for the 14 days PM meat of both 2YO and 9MO as expected. Overall, higher shear force values were observed for the 2YO goat's SM muscle, as expected, although the variations were not significant. Moreover, the reduction in LL shear force with increased days PM (1 day PM vs. 14 days PM) was higher in 2YO as compared to 9MO. Muscle also influenced the WBSF in Boer goat meat ($P < 0.01$; Fig.7).

4. DISCUSSION

This study investigated the effect of age of animal and post-mortem storage on meat quality of Boer goats. The salient findings of the research highlight that irrespective of the age group, the ultimate pH was higher than the normal ultimate meat pH of 5.4-5.7, which was evident from the insufficient glycogen content in both age groups. Of prime importance is the finding that PM storage of goat meat for 14 days significantly tenderized the meat of both age groups. Display day and age of animal showed significant effect on the lightness, redness, yellowness, and lipid oxidation. This is similar to the findings by Warner, Kearney, Hopkins, and Jacob (2017) who showed the major effects of display period on meat color stability and Calnan, Jacob, Pethick, and Gardner (2014) who showed the role of production factors on meat color. However, these studies were with lamb meat and the present study has not established any relationship of lamb meat with goat meat quality. Nonetheless, Sheridan, Hoffman and Ferreira (2003) showed that Boer kid meat compares favorably with Mutton Merino lambs in terms of color, shear force and water-holding capacity.

4.1 Carcass characteristics

178 The live weight and carcass weight of both age groups were similar to previous studies on Boer goats of similar age groups by Yusuf, Goh,
179 Samsudin, Alimon, and Sazili (2014) and Silva et al. (2016). The significant difference in GR fat depth between 9MO and 2YO goats (3.7 *vs.* 5.5)
180 contributed mainly to the rapid and extreme chilling of 9MO (Kannan et al., 2014).

181 **4.2 Muscle pH temperature decline**

182 The postmortem muscle pH and temperature decline suggested rapid chilling of carcasses (Pophiwa, Webb, & Frylinck, 2017). The occurrence of
183 cold shortening in carcasses is generally dependent on the cooling rate of a muscle and occurs if the muscle temperature drops below 10 ºC while
184 the muscle is still in the pre-rigor state (Pophiwa, Webb & Frylinck, 2017). Higher pH@Temp18 demonstrated the severity of cold shortening
185 in 9MO, which we related to the study in goats reported by MLA (2007), wherein they used pH@Temp18 as a cut off for cold-shortening. Many
186 researchers have related the high ultimate pH solely to the pre-slaughter stress (Kadim et al., 2010; Hashem, Hossain, Rana, Islam, & Saha, 2013).

187 **4.3 Glycogen and lactate content**

188 Muscle glycogen concentration has been known to play an important role in post-mortem glycolysis and meat pH (Pethick, Rowe, & Tudor, 1995;
189 England, Scheffler, Kasten, Matarneh, & Gerrard, 2013). Glycolysis is one of the major biochemical processes that regulate the pH decline, and
190 ultimate pH (pHu) to some extent. Glycogen is the main source of energy in postmortem muscle and the skeletal muscle transforms stored glycogen
191 into ATP, lactate, and ultimately H+ ions (Chauhan & England, 2018). The formation of H+ ions results in a drop in the muscle pH from 7.2 in
192 living muscle to a pH near 5.5 in meat under normal conditions (Scheffler et al. 2011). When muscle contains low level of glycogen at slaughter,
193 it results in limited pH decline and high meat pH, called dark firm and dry meat (DFD) in pig and poultry and dark-cutting in ruminants (Chauhan
194 & England, 2018). In this study, lower glycogen content in 9MO as compared to 2YO, indicated glycogen depletion in these animals. Moreover,
195 this was in line with our results for pH_{24} as pH_{24} was higher in 9MO compared to 2YO. Of significance is the finding that in the current study,
196 glycogen content in both goat groups was relatively low, below the critical threshold of 45–55 µmol/g (Warriss, 1990). This could be the major

197 factor responsible for the high pH_{24} in the goats irrespective of the age group. Similar results of lower glycogen content were also previously
198 reported by Pophiwa, Webb, and Frylinck (2017), Kannan et al. (2014) and Kannan, Kouakou, Terrill, and Gelaye (2003) in goats.

199 Lower muscle glycogen levels in animals in this study could be explained by the non-availability of sufficient good quality feed on-farm and the
200 possible depletion of muscle glycogen due to preslaughter handling and the susceptibility of goats to inevitable ante-mortem stress associated with
201 pre-slaughter handling and transportation (Kadim et al., 2010; Archana et al., 2018). Non-availability of quality fodder and insufficient feeding of
202 animals prior to slaughter have been known to be the important contributor to antemortem glycogen depletion in ruminants (Knee, Cummins,
203 Walker, Kearney & Warner, 2007). Similarly, seasonal variation in muscle glycogen levels have been reported (Knee, Cummins, Walker, &
204 Warner, 2004) which again suggest a direct relationship between feed quality and quantity with the muscle glycogen levels. Previous research has
205 shown the reduced incidence of dark cutting in beef with high-energy supplement diets, by improving the muscle glycogen levels at slaughter
206 (Knee, Cummins, Walker, Kearney, & Warner 2007; Knee, Cummins, Walker, & Warner, 2004) and suggested that supplementary feeding with
207 high-energy diets could be executed as an 'on-farm' preslaughter strategy to reduce dark cutting in beef. Similarly, Jacob, Pethick, & Chapman
208 (2005) showed that lambs finished on grain-based feedlot rations had higher muscle glycogen content compared to lambs finished on pasture and
209 sucker lambs finished on pastures.

210 A curvilinear relation exists between muscle glycogen content and lactate content (Chauhan & England, 2018). Lower glycogen reserves at the
211 time of slaughter leads to less lactate production (Sabow et al., 2017) and less acidification of postmortem muscle. Accumulation of lactate in post-
212 mortem muscle is usually considered a good indicator of the extent and rate of glycolysis (Choe et al., 2008) (Ferguson & Gerrard, 2014) (Ferguson
213 & Gerrard, 2014) (Ferguson & Gerrard, 2014) (Ferguson & Gerrard, 2014) (Ferguson & Gerrard, 2014) (Ferguson & Gerrard, 2014). In our study,
214 higher lactate content was observed in 2YO goat meat compared to 9MO meat, which was in accordance with the glycogen content. It is usually
215 associated to the pre-slaughter stress (Kadim et al., 2010; Kannan, Kouakou, Terrill, & Gelaye, 2003; Nikbin, Panandam, & Sazili, 2016). The
216 lactate levels observed in this study are comparable to lactate content of goat meat reported by Pophiwa, Webb, & Frylinck (2017) and Nikbin,

Panandam, & Sazili, (2016) in Boer goats and Simela, Webb, and Frylinck (2004) in South African indigenous goats, though not enough to achieve normal ultimate pH.

4.4 Meat color during retail display

The visual illustration of the changes in meat color during the study (Fig. 2) illustrates the higher color stability of meat from 9MO goats, most likely due to lower myoglobin content (Warner, Kearney, Hopkins, & Jacob, 2017) and higher oxidative capacity (Calnan, Jacob, Pethick, & Gardner, 2014). Previously, the color stability of sheep meat, measured by oxymyoglobin to metmyoglobin ratio, has been shown to reduce between the ages of 8 and 22 months (Warner, Ponnampalam, Kearney, Hopkins, & Jacob, 2007). The higher color stability is likely to be associated with the higher ultimate pH of the 9MO goats in our study as Warner et al. (2007) showed in lambs that *rectus femoris* with higher ultimate pH actually had better color stability than muscles of lower pH, as measured by redness a* and also oxymyoglobin/metmyoglobin ratio. Previously, Ledward, Dickinson, Powell, and Shorthose (1986) had attributed this positive relation of high ultimate pH (> 5.8) to color stability to the rate of autoxidation of myoglobin decrease and the enzymatic reducing system being more active with increasing pH in beef. Also, increased metmyoglobin reducing activity and decreased lipid oxidation are associated with improved color stability (Mancini & Ramanathan, 2014). Our results could be also related to the finding in old Merino sheep that have a higher muscle myoglobin concentration and higher oxidative capacity (Gardner et al., 2007). Higher oxidative capacity is in turn related with higher levels of isocitrate dehydrogenase levels (Calnan, Jacob, Pethick, & Gardner, 2014) and has reduced color stability.

Lower L^* and higher a^* values for 2YO goats are similar to the findings reported by Polidori, Pucciarelli, Cammertoni, Polzonetti, & Vincenzetti (2017), who found similar results in older lambs compared to younger ones. Lightness of meat has an inverse relationship with heme iron content, which increases as slaughter age increases in lamb (Warner, Ponnampalam, Kearney, Hopkins, & Jacob, 2007; Bures & Barton, 2012; Mancini & Hunt, 2005). A recent study in two age groups of Korean native black goat (9 months and 18 months) reported a similar observation. The authors attributed the higher redness and lower lightness in the 18 months old goats to the higher number of type I muscle fibres and thicker perimysium

237 (Bakhsh, Hwang, & Joo, 2019). Conversely, and as would be expected, redness of meat increases with haem iron content and both increase with
238 age of the animal (Warner, Ponnampalam, Kearney, Hopkins, & Jacob, 2007). L* increased from 0 to 10 days in both muscles and in both 1 and
239 14 days PM meat. However, the effect of PM days on L* value was evident only in SM with higher value observed in 14 days PM meat than 1day
240 PM meat. It has been previously studied that higher L* with increasing PM period is associated with reduction of mitochondrial respiratory activity,
241 which increases oxygenation of the myoglobin molecule, resulting in greater formation of oxymyoglobin (Vitale, Pérez-Juan, Lloret, Arnau, &
242 Realini, 2014). An increase in lightness is explained as the changes in relative contents of chemical forms of myoglobin, and increased light
243 scattering due to protein denaturation (Peng et al. 2019). Peng et al. (2019) showed that the increased lightness in hiOxMAP meat during storage
244 indicates that meat loses the satisfactory color in meat.

245 The yellowness value generally increased from 0 to 10 days on display in both muscles. PM days also increased the b* with increasing duration
246 in LL and SM, although age did not show much effect. Previously, it was studied that b* values are associated to onset of brown pigmentation,
247 and unacceptable appearance in meat is related to more pronounced yellow tint, which depends on the relative balance of a* and b* (O'Sullivan
248 et al. 2003). There was no effect of any of the treatments on h value in either of the muscles. However, it is to be noted that in SM, C* showed a
249 trend of decrease from 5 to 10 days of display ($P < 0.001$), although not evident in LL. This finding was similar to the result reported by Frank et
250 al. (2017) in hiOxMAP packaged SM muscle in lamb. Noticeably, increasing L* and b* and decreasing C* marked formation of corresponding
251 brown-color indicating partial oxidation of some of the pigment to metmyoglobin, with (Mancini & Hunt, 2005). This finding could clearly be
252 related to the results of Frank et al. (2017) who did similar hiOxMAP packaging in lamb meat.

253 **4.5 Lipid oxidation assay**

254 Oxygen exposure is an essential factor contributing to lipid oxidation during storage (Amaral, Silva, & Lannes, 2018), especially in hiOxMAP
255 packaging, which was used in the present study. Lipid oxidation is the major process responsible for the quality deterioration of meat and meat
256 products by reducing shelf life and producing rancid off-flavors and taste (de Lima Júnior, do Nascimento Rangel, Urbano, & Moreno, 2013). In

our study, the peak value of MDA in LL was on the last day of display, being day 10, in both 1 and 14 days PM meat for both age groups. Although, a general trend of higher lipid oxidation with time in display as observed in the meat of 2YO goats compared to the 9MO in both 1 and 14 days PM samples, this was not uniform throughout the display days. Notably, the peak value of lipid oxidation in LL during the display days did not exceed the critical value of 2 mg/kg, defined by Campo et al. (2006) as a limit for perception of rancid taste in red meats by consumers. Similarly, in SM muscle the TBARS peak value occurred in 14 days PM meat of 2YO goats on the last day (day 10) of simulated display. However, the value exceeded the critical value as it reached 2.3 mg MDA/kg. This could be in fact related to reports of Frank et al. (2017) and Warner, Kearney, Hopkins, & Jacob (2017) in lambs who observed the reduced stability of SM muscle in hiOxMAP packed meat. Overall, regardless of the age and PM period, lipid oxidation progressed in goat meat with display time. Similar increase in TBARS with postmortem chill storage have been previously reported in LL of pork (Haak, Raes, Van Dyck, & De Smet, 2008), LL and SM of mutton (Popova & Marinova, 2013) and *gluteus medius* muscle of goat meat (Adeyemi, Shittu, Sabow, Ebrahimi, & Sazili, 2016). Lipid oxidation is highly associated with the pigment oxidation due to production of free radicals and reactive oxygen species (Faustman, Sun, Mancini, & Suman, 2010). Lipid oxidation enhance myoglobin oxidation (Lin & Hultin, 1977) and reduce surface redness. This is evident from our results of higher lipid oxidation values (Fig. 3) in the 10 day of display and the discoloration of meat during this period (Fig. 2).

4.6 Cooking loss

The lower cooking loss in the 9MO, which further reduced with display days could be associated with the higher ultimate pH (Li et al., 2014). Our result was similar to the findings in goats and lamb (Cetin, Bingol, Colak, & Hampikyan, 2012), which stated that the muscle pH affected cooking loss, but not by PM period. In addition, the increased cooking loss with increasing age in our study agreed with findings of Schönfeldt and Strydom (2011) who hypothesised that increased cross-linking of collagen with age results in decreased water-holding capacity, due to increased moisture loss upon heating or cooking.

4.7 WBSF and compression

As expected, the highest shear force values were observed in the 2YO goat meat that was 0 d aged. This could be associated with smaller extent of post-mortem proteolysis, bigger size of muscle fibers (Tornberg, Von Seth, & Göransson, 1994), presence of mature collagen cross-link (non-reducible cross-link) in advanced animal slaughter age (Mashele, 2017; McCormick, 1994). The presence of heat stable collagen cross-links limits the solubility of collagen in meat from mature sheep, even at higher temperature (Light, Champion, Voyle, & Bailey, 1985). There was a marked increase in tenderness in this study after 14 days PM in both age groups, as previously reported by Teixeira, Pereira, and Rodrigues (2011). It is well known that ageing promotes tenderization of meat (Marino, Della Malva, & Albenzio, 2015). In general, meat tenderization is mainly due to ultrastructural changes that weaken the integrity of the myofibers in the muscle tissue (Li et al., 2014). On the other hand, the toughness of meat has been attributed to low activity of proteolytic enzymes in muscle samples, especially calpains, which are considered to play a key role in the degradation of specific muscle proteins (Marino et al., 2015; Saccà, Corazzin, Bovolenta, & Piasentier, 2019). Also, lower activity of the proteolytic enzymes (calpains and caspases) and higher activity of calpastatin with age contribute to the higher toughness in older goats (Saccà, Corazzin, Bovolenta, & Piasentier, 2019). The role of myofibrillar or cytoskeletal protein degradation during refrigerated storage to meat tenderness is studied (Adeyemi et al. 2016). Proteins such as titin and nebulin, present within the I-band regions of the intact myofibril, are key structural proteins which are the major suggested reasons for the fragility of the myofibrils in the I-band region (Huff-Lonergan, Parrish, & Robson, 1995). Costamere proteins such as desmin, filamin, dystrophin, and talin (all located at the periphery of the Z-line), connects Z-disks to sarcolemma and their degradation is associated with the detachment of myofibrils from sarcolemma contributing significantly to meat tenderization (Taylor & Koohmaraie, 1998).

5. CONCLUSION

This study confirms the previous findings of higher ultimate pH and rapid chilling of carcass in commercial processing conditions in goats. Insufficient glycogen levels in Boer goats prior to slaughter which determines the post-mortem glycolysis is a critical area to be addressed by goat producers. Age influenced the ultimate pH and retail color stability with better stability observed in young goats of 6-9 months. However, days PM increased the tenderness of goat meat irrespective of age group. Noticeably, similar tenderization was observed in meat within 5 days of

display in both age groups. This emphasized the potential of post-mortem storage for a much shorter duration on tenderizing goat meat. The study reinforces the need for further research to better understand the pathway of goat meat supply chain in Australia and also ensuring adequate on-farm nutrition prior to slaughter. In particular, strategies to reduce ante-mortem stress and plant effect on pH temperature window should be pursued on account of their relevance in promoting goat meat quality in Australia.

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440

Table 1: Effect of age group [2YO (2yrs old) and 9MO (6-9 months old)] on carcass characteristics, glycogen, lactate, and total glycogen content in *longissimus thoracis et lumborum* (LTL). LW Live weight, HCW Hot carcass weight, DP dressing percentage, GR fat depth, the total tissue depth 110 mm from the spine over the 12/13th rib. Values are predicted means.

Traits	2YO	9MO	SED	*P*-value
LW (kg)	45.8	29.0	1.19	< 0.001
HCW (kg)	18.9	11.3	0.52	< 0.001
DP	41.3	38.9	0.60	< 0.001
In GR fat depth (mm)	5.5	3.7	0.40	< 0.001
pH@Temp18	6.7	7.1	0.04	< 0.001
pH_{24}	5.8	6.1	0.06	< 0.001
Glycogen (µmol/g)	27.4	11.6	3.81	< 0.001
Lactate (µmol/g)	43.5	32.8	8.86	0.25
Total glycogen content (µmol/g)	70.8	43.8	8.81	0.01

Table 2: Effect of slaughter age [Age; 2YO (2yrs old) and 9MO (6-9 months old)], days post-mortem (PM: 1 and 14 days) and display days (DD:0, 5 and 10 days) on meat color (lightness L*, redness a*, yellowness b*, hue angle h, chroma C*) for the *longissimus thoracis et lumborum* (LL) and *Semimembranosus* (SM) during retail display of Boer goat meat. No significant interactions between age, PM and display days were observed at $P = 0.05$. Means within a row bearing the same letter as superscript are not significantly different at $P=0.05$

Trait	2YO						9MO						SED	*P*-value					
	1 day			14 days			1 day			14 days				Age	PM	DD	Age X PM	Age X DD	PM X DD
	0	5	10	0	5	10	0	5	10	0	5	10							
									Longissimus thoracis et lumborum										
L*	30.6^{a}	35.14^{bc}	32.2^{ab}	32.4^{ab}	34.4^{bc}	35.3^{bc}	33.5^{abc}	36.5^{c}	34.3^{bc}	33.0^{ab}	35.1^{bc}	34.3^{bc}	0.74	0.020	0.313	<0.001	0.015	0.510	0.037
a*	17.0^{abc}	19.7^{bcd}	18.2^{abcd}	19.8^{bcd}	21.9^{d}	19.9^{bcd}	15.2^{a}	20.3^{cd}	20.8^{cd}	16.4^{ab}	21.3^{d}	20.9^{d}	0.82	0.885	<0.001	<0.001	0.123	<0.001	0.642
b*	13.8^{a}	16.9^{bc}	16.3^{abc}	17.3^{bc}	17.8^{bc}	17.14^{bc}	13.6^{a}	16.9^{bc}	18.07^{bc}	15.1^{ab}	17.6^{bc}	18.9^{c}	0.95	0.700	<0.001	<0.001	0.352	0.006	0.099
H	39.9^{a}	41.6^{a}	43.2^{a}	41.4^{a}	39.7^{a}	40.8^{a}	40.8^{a}	39.7^{a}	40.9^{a}	41.5^{a}	39.1^{a}	41.5^{a}	1.33	0.320	0.558	0.065	0.277	0.413	0.190
C*	22.2^{ab}	26.5^{bc}	24.8^{abc}	26.1^{bc}	28.3^{c}	25.9^{bc}	20.2^{a}	26.5^{bc}	27.4^{c}	22.1^{bc}	27.5^{c}	28.0^{bc}	1.38	0.003	<0.001	0.330	<0.001	0.339	0.833
									Semimembranosus										
L*	30.7^{a}	32.2^{ab}	32.4^{ab}	34.3^{bcde}	36.5^{de}	35.8^{cde}	33.5^{abc}	33.8^{bcd}	34.9^{bcde}	35.0^{bcde}	36.8^{e}	35.6^{cde}	0.60	0.072	<0.001	<0.001	0.005	0.364	0.780
a*	18.8^{bc}	17.6^{ab}	14.7^{a}	19.4^{bc}	18.9^{bc}	18.3^{bc}	14.6^{a}	19.0^{bc}	16.6^{ab}	14.6^{a}	21.0^{c}	16.5^{ab}	0.97	<0.001	0.002	<0.001	0.001	<0.001	0.240
b*	15.9^{bcde}	14.8^{abcd}	13.4^{ab}	16.0^{cde}	17.4^{e}	14.7^{abcd}	13.7^{abc}	16.6^{de}	15.1^{bcde}	12.6^{a}	17.1^{de}	15.5^{bcde}	0.53	0.121	0.070	<0.001	0.028	<0.001	0.024
H	41.6^{a}	41.9^{a}	44.1^{a}	40.4^{a}	39.7^{a}	40.4^{a}	41.8^{a}	40.8^{a}	41.4^{a}	39.4^{a}	40.4^{a}	42.6^{a}	1.71	0.726	0.048	0.175	0.198	0.995	0.882
C*	23.6^{bcde}	22.3^{abc}	19.5^{a}	24.7^{cde}	26.9^{e}	22.9^{abcd}	20.5^{ab}	25.6^{cde}	22.9^{abcd}	19.7^{a}	26.2^{de}	23.0^{abcd}	1.11	0.385	0.001	<0.001	<0.001	<0.001	0.082

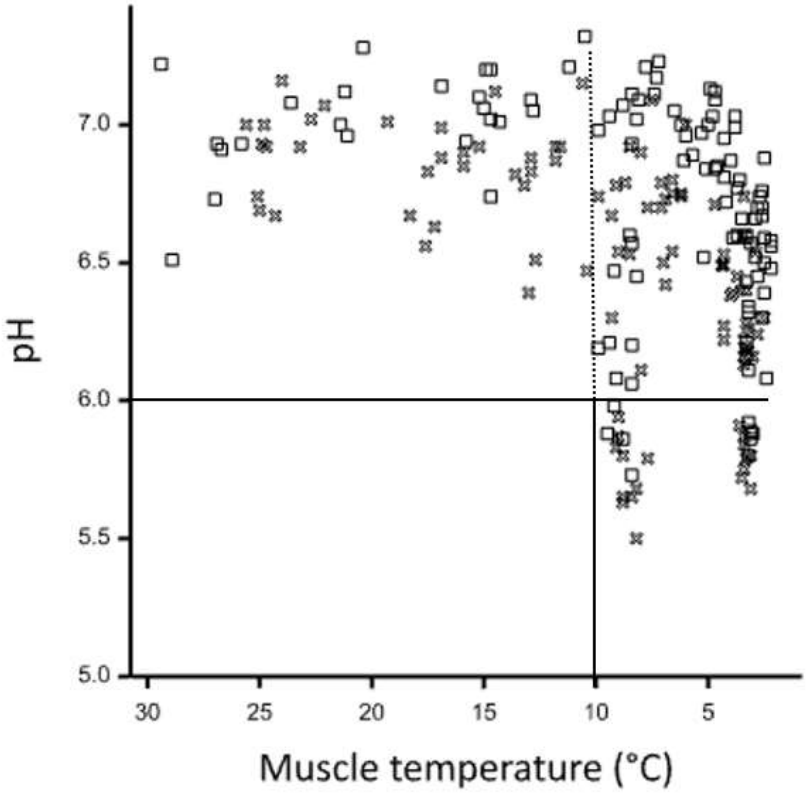
Table 3: Effect of slaughter age [Age; 2YO (2yrs old) and 9MO (6-9 months old)], days post-mortem (PM: 1 and 14 days) and display days (DD:0 and 10 days) on cook loss (% CL), Warner-Bratzler shear force (WBSF, kg) and hardness for the *longissimus thoracis et lumborum* (LL) and *M. Semimembranosus* (SM). No significant interactions between age, PM and display days were observed at $P = 0.05$. Means within a row bearing the same letter as superscript are not significantly different at $P = 0.05$

Traits	2YO				9MO				SED	*P*-value					
	1 day		14 days		1 day		14 days			Age	PM	DD	Age X PM	Age X DD	PM X DD
	0	10	0	10	0	10	0	10							
						Longissimus thoracis et lumborum									
CL (%)	29.5^{b}	24.5^{ab}	30.5^{b}	27.3^{b}	26.2^{b}	18.0^{a}	27.4^{b}	18.6^{a}	2.07	<0.001	0.160	< 0.001	0.598	0.027	0.760
WBSF (N)	69.1^{b}	39.5^{a}	35.5^{a}	35.2^{a}	61.8^{b}	41.1^{a}	36.2^{a}	34.7^{a}	3.10	0.646	< 0.001	< 0.001	0.231	0.237	< 0.001
Hardness (N)	47.8^{ce}	40.0^{abcd}	38.2^{ab}	44.8^{bcde}	39.2^{abc}	33.5^{a}	37.9^{ab}	37.9^{ab}	1.87	0.004	0.869	0.236	0.075	0.495	< 0.001
						Semimembranosus									
CL (%)	22.9^{ab}	27.8^{b}	25.9^{b}	23.8^{ab}	22.2^{ab}	23.7^{ab}	25.4^{b}	19.1^{a}	2.10	0.088	0.544	0.617	0.927	0.056	< 0.001
WBSF (N)	66.1^{b}	34.1^{a}	35.0^{a}	30.3^{a}	59.2^{b}	34.1^{a}	33.5^{a}	20.7^{a}	3.10	0.554	< 0.001	< 0.001	0.244	0.244	< 0.001
Hardness(N)	48.8^{d}	46.8^{cd}	47.1^{cd}	43.9^{bcd}	44.1^{bcd}	34.2^{a}	38.7^{abc}	37.3^{ab}	1.95	<0.001	0.183	0.002	0.671	0.237	0.163

485

486 **FIGURES**

487



488

489 **Fig.1**: pH and temperature of *M. longissimus* for 2YO (2 yrs old) (x) versus 9MO (6-9 months old) (□) goats with the speculative 'ideal'
490 pH/temperature window shown as the solid black line (pH/temperature window defined as temperature at pH 6 in the *M. longissimus* <35 ºC and
491 >18 ºC). The dotted lines represent the cold-shortening window (pH > 6 and temp < 10 ºC) and it should be noted that majority of the carcasses
492 passed through this window.

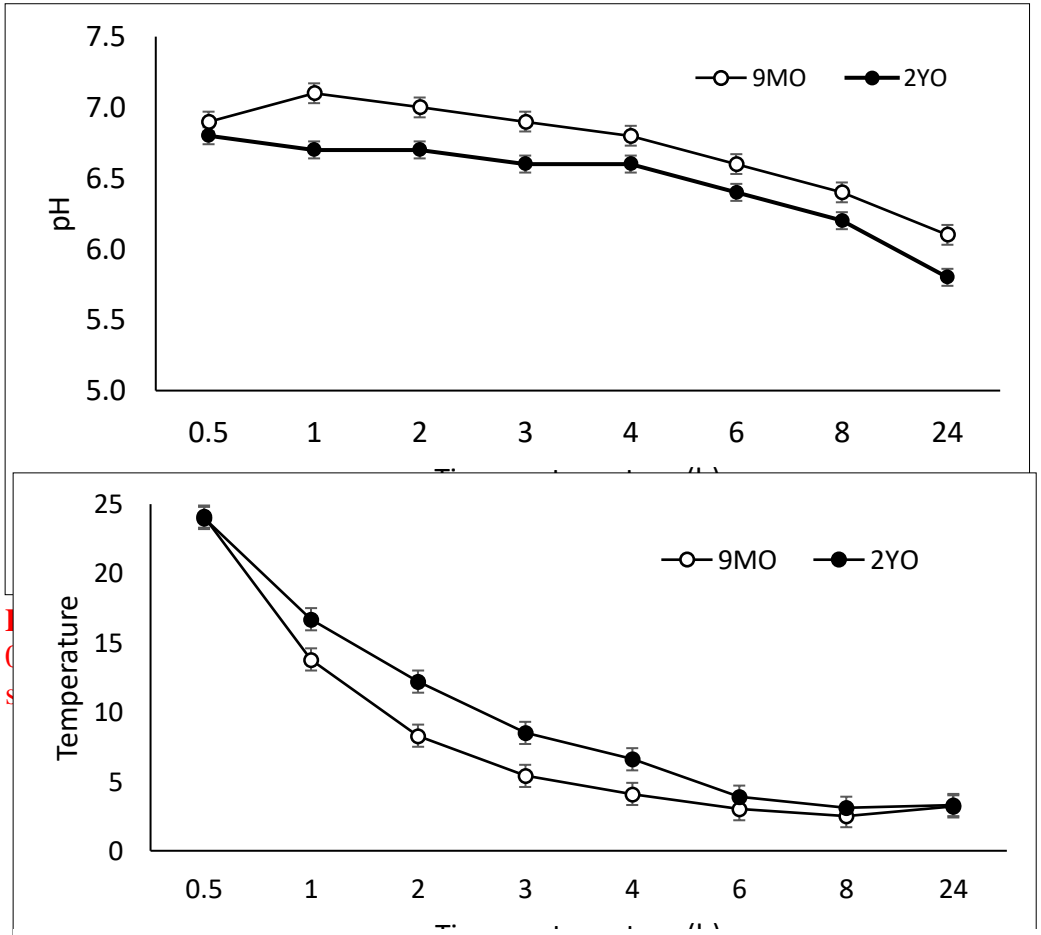


Fig. 3: Effect of slaughter age [2YO (2yrs old) and 9MO (6-9 months old)] ($P < 0.01$) on post-mortem temperature decline of M. longissimus Vertical bars represent standard errors.

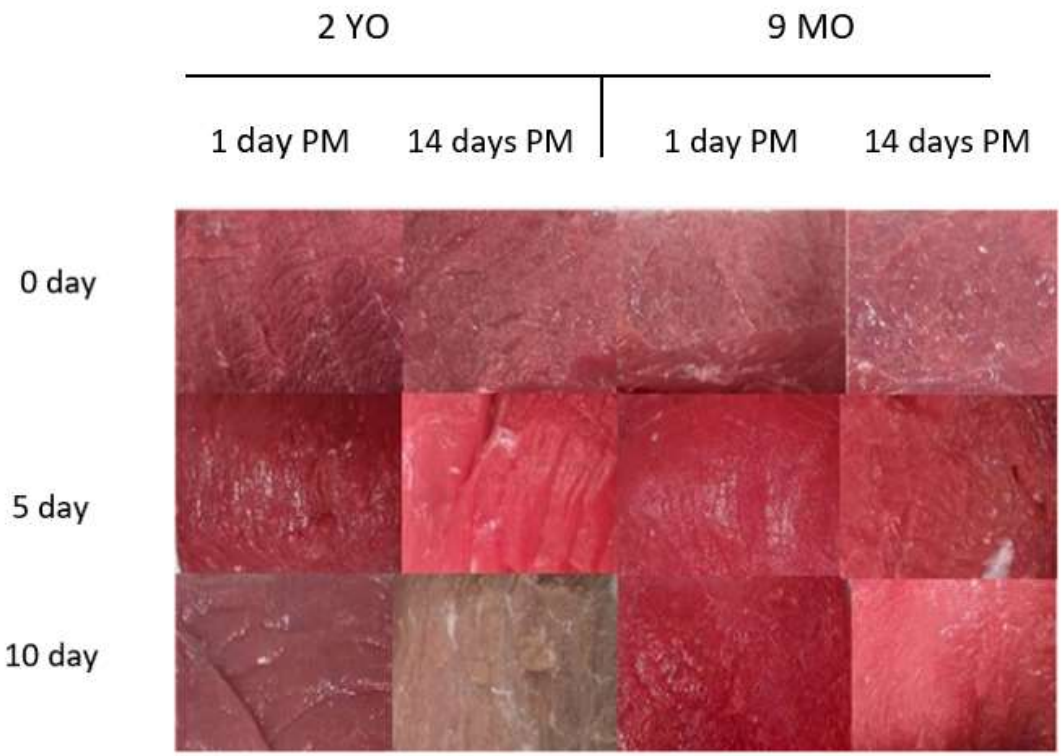


Fig. 4: Visual illustration of meat packed in in high oxygen modified atmosphere packaging (80% O2; 20% CO2) , during the study illustrating the retail color stability of 2YO (2 yrs old) versus 9MO (6-9 months old) goats during two post-mortem days (1 and 14 days) over the simulated display period, of 0 to 10 days. Note that the 0 day display samples were similar in color, the 5 day samples were bright cherry red, and the 10 day samples showed substantial variation from red to brown.

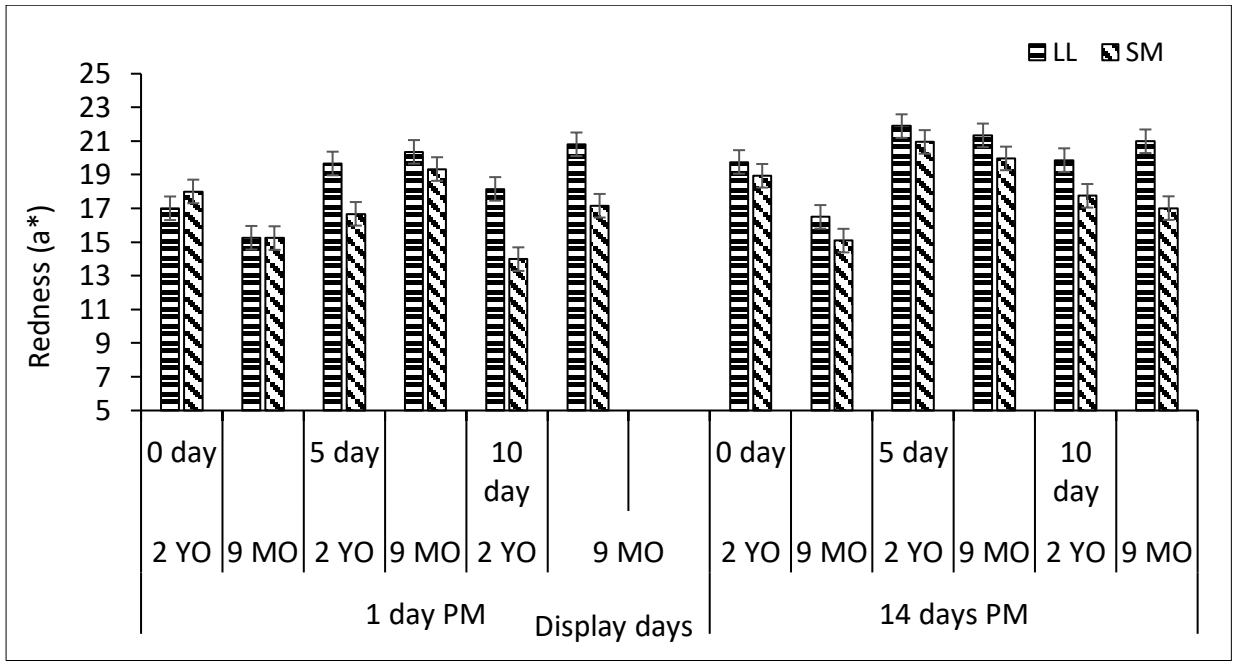


Fig. 5 Effect of muscle [SM, *semimembranosus* and LL, *longissimus lumborum*; ($P < 0.01$)], slaughter age [2YO (2yrs old) and 9MO (6-9 months old)]($P = 0.29$), and days post-mortem (PM;1 or 14 days) ($P < 0.01$) on the redness (a*) in high oxygen MAP (80%O_2; 20% CO_2) over the display period of 0 to 10 days. Interactions of age x display day and muscle x display day were $P < 0.01$. Vertical bars represent standard errors.

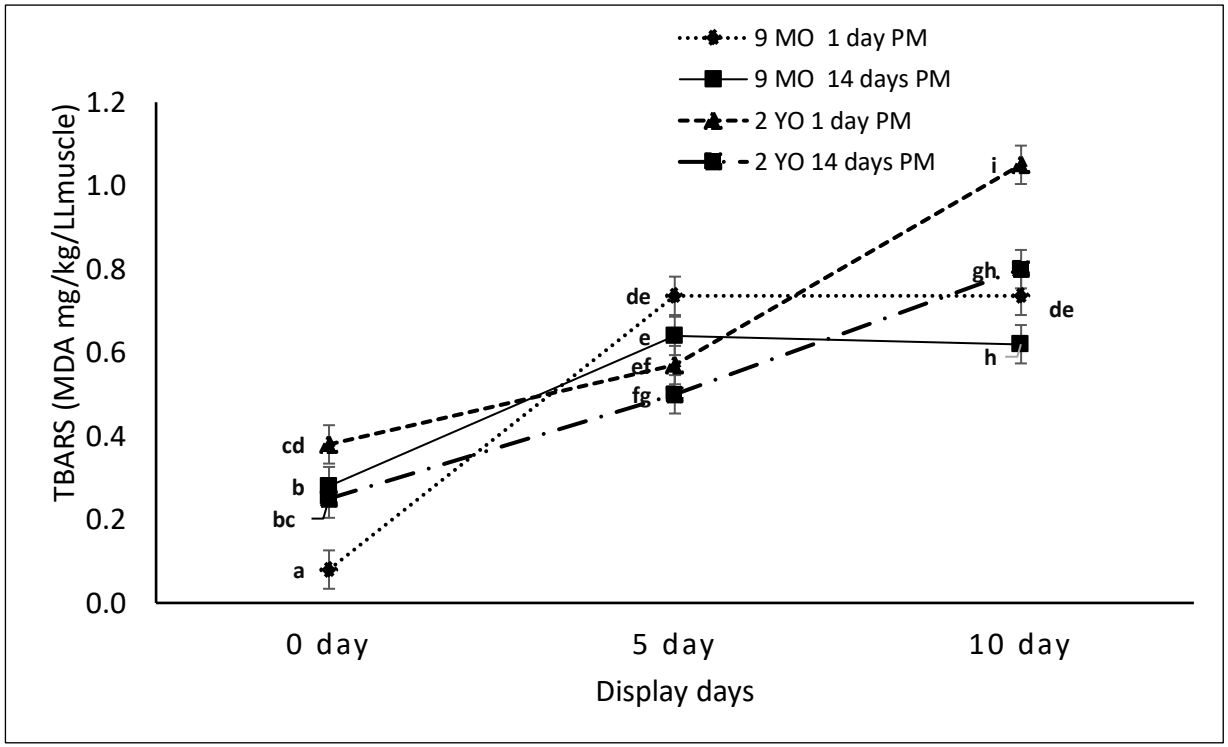
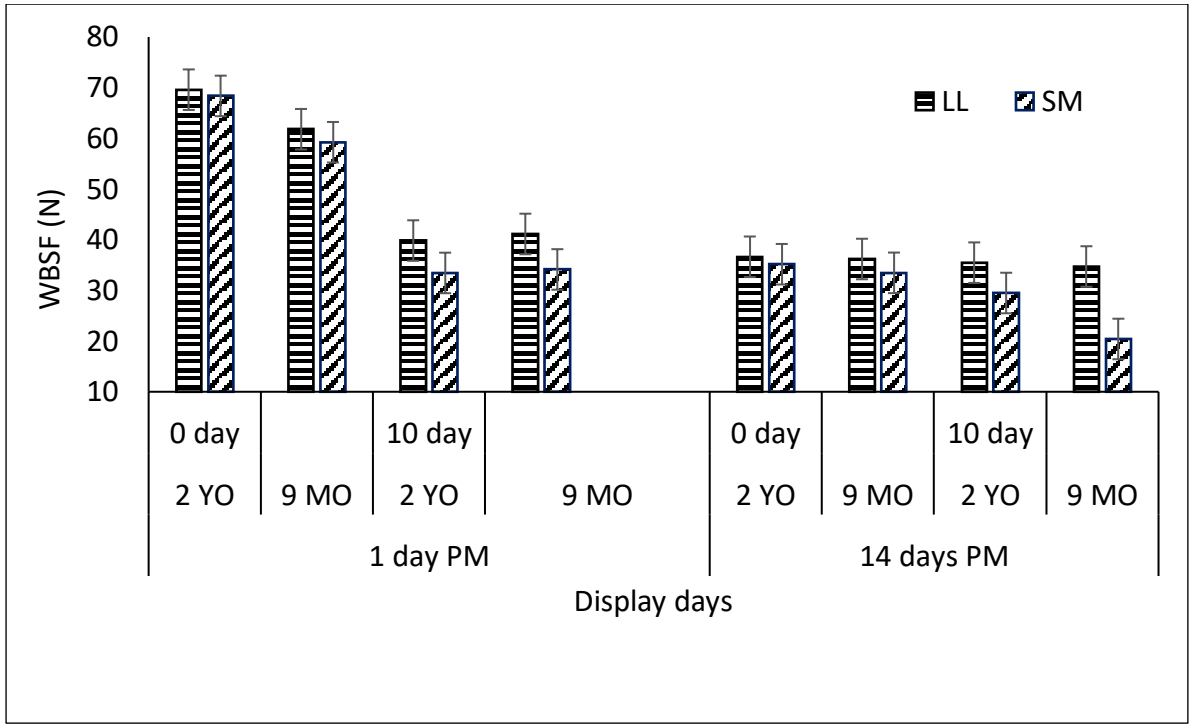


Fig. 6. Effect of slaughter age [2YO (2yrs old) and 9MO (6-9 months old)]($P < 0.01$), display time ($P < 0.01$) in high oxygen MAP (80%O2; 20% CO2 for 0, 5 or 10 days respectively) and days post-mortem PM (1 or 14 days) ($P < 0.01$) on lipid oxidation (TBARS) in *longissimus thoracis et. lumborum* muscle of Boer goats. Interactions of age x PM, PM x display day, and age x PM x display day were $P < 0.01$. Vertical bars represent standard errors.



533

534 **Fig.7:** Effect of muscle [SM, *semimembranosus* and LL, *longissimus lumborum*; (P< 0.01)], slaughter age [2YO (2yrs old) and 9MO (6-9 months
535 old)](P < 0.05), and days post-mortem (PM;1 or 14 days) (P < 0.01) on the WBSF (N) of Boer goat meat. Interactions of PM x display day was P
536 < 0.01 and age x PM x display day was P < 0.05. Vertical bars represent standard errors.

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