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Impact of heat stress on the growth performance and retail meat quality of 2nd cross (Poll Dorset × (Border Leicester × Merino)) and Dorper lambs

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ABSTRACT

The present study investigated the impact of heat stress and genetics on lamb growth performance and meat quality. Forty-eight Dorper and 2nd cross [Poll Dorset × (Border Leicester × Merino)] lambs (38-–42 kg; 4–5 months old) were allocated to either thermoneutral [TN; 18–21 °C, 45–55% relative humidity (RH)], or heat stress (HS; 28 °C–38 °C, 40–60% RH) conditions in a 2 × 2 factorial design for 2 weeks. Compared with 2nd cross, Dorper lambs had a lower respiration rate (RR) and rectal temperature (RT), and exhibited less decline in body weight under HS. 2nd cross lambs showed a higher body weight gain than Dorpers under TN conditions. HS increased *a** and chroma of the *Longissimus thoracis et lumborum* (LTL) from 2nd cross lambs over 10 days of display, but had no impact on Dorper LTL. In conclusion, Dorpers showed higher heat tolerance compared with 2nd cross lambs during the 2 weeks HS.

1. Introduction

Heat stress (HS) is one of the greatest challenges facing the global livestock industry. An increase in global temperature and relative humidity (RH) is likely to compromise animal welfare and production during hot summer months, especially in the warmer parts of the world. HS occurs when an animal is unable to maintain normal core body temperature due to increased ambient temperature which compromises the animal's ability to lose heat from the body. HS is not only detrimental for animal welfare and production, but has been implicated in higher incidence of dark cutting or pale soft and exudative (PSE) meat (Gonzalez et al., 2020; Gregory, 2010; Zhang et al., 2020).

Stress is well known to deplete muscle glycogen stores and lead to lower acidification of postmortem muscle and consequently a higher ultimate pH (pHu) (Scanga, Belk, Tatum, Grandin, & Smith, 1998) and dark cutting. However, the studies reporting the impact of HS on different meat quality traits of ruminants are equivocal, and most of these focused on effects of long-term (≥ 1 month) HS. For example, Kadim, Mahgoub, and Khalaf (2014) reported that seasonal HS (34.3 ± 1.67 °C and 48.8 ± 7.57% RH, 6 m) had a negative effect on fresh colour, tenderness and water holding capacity (WHC) of sheep and goat meat. Conversely, albeit at a much lower ambient temperature, Saha et al. (2013) and Rana et al. (2014) reported that 4 and 8 h (27.8 °C, 81.9% RH; 45 d) heat exposure had no effect on goat slaughter weight and drip loss of the meat. Recently, Archana et al. (2018) showed that seasonal HS significantly increased *Longissimus thoracis et lumborum* (LTL) pH_{24}, and shear force of meat from Osmanabadi and Salem Black goats, but had no influence on colour and WHC. The majority of researchers agree that high summer temperatures would have negative impact on animal welfare and meat quality (Gregory, 2010; Zhang et al., 2020). However, the extent to which it is affected may vary depending upon the severity of HS which in turn depends upon the daily ambient temperature, RH, and exposure duration (Tang, Yu, Zhang, & Bao, 2013; Zhang et al., 2018a, b) as animals may have variable responses to short-term and chronic HS. Ponnampalam et al. (2016) reported that one-week of HS (28–40 °C, 30–40% RH) had no effect on lamb growth performance (slaughter weight, carcass weight and fat depth) or meat quality (pHu and lipid oxidation). Thus, there is a need for further research to

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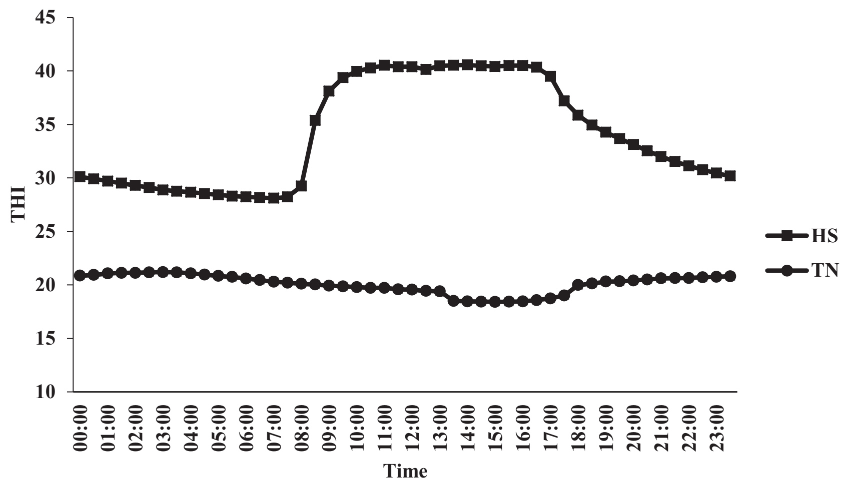

Fig. 1. Average daily Temperature Humidity Index (THI) recorded in the heat stress (HS) and thermoneutral (TN) treatments during the experimental period. The average THI of HS was 34.1 (stander error = 0.34) and the THI of TN conditions was 20.1 (standard error = 0.41). THI < 22.2 = no stress, 22.2 to 23.3 = moderate heat stress, 23.3 to 25.6 = serve heat stress, >25.6 = extreme severe heat stress (Marai et al., 2007).

elucidate the impacts of HS exposure on growth performance and meat quality of small ruminants.

Hair and wool traits are known to affect heat tolerance in sheep (McManus et al., 2011). Hair sheep breeds such as Pelibuey, Dorper, Katahdin, and their crossbreds have better adaptability to high environmental temperatures which is attributed to improved physiological and metabolic responses (lower thyroid hormone levels and metabolic heat production, and deeper breathing compared with wool sheep breeds (Correa et al., 2012; Romero, Pardo, Montaldo, Rodriguez, & Ceron, 2013; Ross, Goode, & Linnerud, 1985). In Australia, higher carcass yield was reported for Dorper and Damara (African hair sheep) compared to Merino sheep (Almeida et al., 2013). However, it is unknown whether heat tolerance would have any implications for meat quality attributes and growth performance, when heat exposure shorter than 1 month and breeds are compared. The objective of this study was therefore to compare the growth performance and meat quality attributes of hair-type sheep breeds (Dorper) and wool-type sheep breeds [2nd cross; Poll Dorset × (Border Leicester × Merino)] exposed to two weeks of HS during the finishing phase. The choice of breeds for examination was based on the hypothesis that, under HS conditions, Dorper lambs (hair breed) would exhibit a higher degree of thermotolerance, better growth rates and meat quality attributes compared to 2nd cross lambs (wool breed).

2. Materials and methods

2.1. Animals and experimental conditions

The experiment was approved by the University of Melbourne Faculty of Veterinary and Animal Sciences Animal Ethics Committee (AEC ID 1714357.1) and the protocols used for the live animal part of this study have been reported elsewhere (Joy et al., 2020). Briefly, forty-eight lambs [Poll Dorset × (Border Leicester × Merino) (n = 24) and Dorper (n = 24)] aged 4–5 months (body weight range: 38–42 kg) were purchased from 5 different breeders across North-East Victoria. All lambs were purchased following thorough examination for general health and were vaccinated and dewormed as per standard practices on farm. Using a randomized 2 × 2 factorial design with 4 consecutive experimental runs (n = 12), lambs from each breed (n = 3) were randomly allocated to either HS (28 °C–38 °C, 40–60% RH) or TN (18–21 °C, 45–55% RH) conditions, following 2 weeks acclimatization (13.9–29.1 °C) to indoor experimental facilities. The lambs were acclimatized for 1 week in group pens and then housed in individual pens for 1 week before being relocated to metabolism cages (1.0 × 0.5 m with polypropylene slat flooring that has a stable grip preventing sheep from slipping). Lambs were individually fed a mixed ration consisting of oaten (25%) and lucerne (25%) chaff and standard lamb finisher pellets (50%; 14% protein, 8% crude fibre, 2% added salt, 1% added urea) formulated as per NRC, 2007. Lambs were fed ad libitum and offered at 2 times maintenance requirements, and water was always available. Daily feed requirements of the animals were calculated using the equation; feed (kg DM/day) = W0.75 × 450/1000/ME, where ME is maintenance energy.

After acclimatization, animals were exposed to thermo-neutral (TN; 18–21 °C, 45–55% RH, n = 6 for each replication) or cyclic HS; 38 °C (between 0800 and 1600 h) and 28 °C (between 1600 and 0800 h) 40–60% RH, n = 6 for each replication) for 2 weeks while housed in metabolism cages in purpose-built climatic chambers. Briefly, heat was turned on at 8 a.m. (allowing the temperature to rise to the peak at 38 °C in 4–6 h and then maintained between 36 and 38 °C till 4 p.m.) and turned off at 4 p.m. (allowing the temperature to drop to 28 °C by 6 p.m. and then maintained between 26 and 28 °C overnight until the next morning at 8 a.m.) to simulate hot summer conditions (hot day followed by warm night). Room temperature and RH were recorded every 30 mins by temperature-humidity data loggers and the temperature–humidity index (THI) was calculated by the following equation: THI = db °C-((0.31–0.31 RH) (db °C- 14.4) (Marai, El-Darawany, Fadiel, & Abdel-Hafez, 2007 and is presented in Fig. 1 for the two treatments.

2.2. Growth performance and physiological parameters

At the beginning of the experimental period, and then on a weekly basis, lamb body weights were recorded (after overnight fasting) using walkover scales in the morning (before feeding) to calculate the average daily body weight gain (ADG). Physiological parameters, respiration rate (RR) and rectal temperature (RT) were measured at 0800, 1200, and 1600 h daily, as reported previously (Joy, Dunshea, Leury, DuGuacomo, et al., 2020). The RR was determined by counting the flank movements for 20 s and was converted to breaths per minute. A digital thermometer (DT-01; Tollot Pty. Ltd., Blacktown, AU) was used to measure RT. Daily feed intake was recorded by weighing the refusals before the morning feeding at 10:00 am.

2.3. Slaughter and carcass quality

At the end of each replication, animals were transported to a commercial abattoir with 1 h transportation and kept in lairage for 12 h. All

Table 1
The effect of temperature (thermoneutal, TN vs heat stress HS) and breed (Dorper vs 2nd cross, Poll Dorset × (Merino × Border Leicester)) on growth performance and carcass characteristics of finishing lambs ($n = 48$).

	Dorper		2nd cross			*P*-value		
	TN	HS	TN	HS	SED[5]	Breed	Temp.[1]	Breed×Temp.
Daily feed intake, kg / d	1.29	1.29	1.39	1.22	0.05	0.612	0.029	0.039
ADG[3], g / d	5.95	−50.6	101	−92.3	52.6	0.475	0.002	0.073
Hot Carcass weight, kg	21.6	21.5	23.3	22.7	0.71	0.006	0.448	0.679
GR[4] depth, mm	16.3	15.8	14.2	14.2	1.50	0.076	0.841	0.841
Loin eye area, cm[2]	14.0	13.5	13.3	14.6	0.89	0.711	0.579	0.163
pHu[2]	5.54	5.60	5.60	5.63	0.03	0.008	0.018	0.365

[1] Temp. = Temperature.

[2] pHu = ultimate pH at 24 h after slaughter.

[3] ADG = Average daily body weight gain.

[4] GR = total tissue thickness at the twelfth rib, 110 mm from the midline.

[5] SED = Standard error of the difference of means.

slaughter procedures were followed as per standard commercial operations including stunning and electrical stimulation. After slaughter, carcasses were weighed for hot carcass weight (HCW) before moving into the chiller set at 0–4 °C and the GR tissue depth was measured with a GR knife at 24 h postmortem (total tissue thickness at the 12th rib, 110 mm from the midline) (Hopkins, Anderson, Morgan, & Hall, 1995). The *Longissimus thoracis et lumborum* (LTL) was removed from both sides of the carcasses and the cross-sectional area of LTL was measured at the 12th rib by taking the length and width of the muscle and multiplying this value by 0.8. Ultimate pH (pH_u) was measured at lumbar/sacral junction of the LTL at 24 h postmortem using a combined pH and temperature meter (WP-80M, TPS, Brendale, Australia) with a spear-head IJ44C pH probe (TPS, Brendale, Australia). The pH probe was calibrated using 7.0 and 4.0 buffers at regular intervals before use.

2.4. Packaging and retail display conditions

After 48 h postmortem, each LTL was cut into 6 pieces (90 g) and randomly allocated to a display time after packaging in modified atmosphere packaging (80% O_2, 20% CO_2). The high oxygen (HiOx) modified atmosphere packaging (MAP) was conducted with a Multivac T200 (Sepp Haggenmüller GmbH & Co., Wolferschwenden, Germany) connected to a gas mixer to achieve a final O_2: CO_2 ratio of 80%: 20%. LTL chops (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 stored at 4–6 °C in display cabinets with high-impact LED internal lighting on each side (maximum 18 W) (GM1000LWCAS, Bromic Pty Limited). for 0 d, 2.5 d, 5 d, 7.5 d and 10 d retail display. Meat colour, cooking loss, purge loss, Warner-Bratzler peak shear force (WBSF) and texture profile analysis were measured at each display time point as described below.

2.5. Meat quality measurements

2.5.1. Surface colour

Meat colour (lightness, redness/greenness and yellowness/blueness (L^*, a^*, b^*) of the LTL surface was measured using a Minolta colorimeter (CR-400, Konica Minolta, Japan; 10° observer angle and D65 illumination) at 0 d, 2,5 d, 5 d, 7.5 d and 10 d, and the average of three readings were recorded. The chroma and hue angle were calculated as $(a^{*2} + b^{*2})^{1/2}$ and $\tan^{-1}(b^*/a^*)$ respectively. Muscle drip loss was measured at 0 d retail display day by EZ-drip loss equipment (Danish meat, Denmark), as specified by Otto, Roehe, Looft, Thoelking, and Kalm (2004). Samples (17 cm thickness, 10 g) were excised using a circular knife, then weighed (W_1) and placed in EZ-drip loss tube container at 4–6 °C. After 48 h, samples were weighed again (W_2), and the drip loss was calculated as: Drip loss (%) = $\{(W_1\text{-}W_2)/W_1\} \times 100$.

2.5.2. Water holding capacity

Water holding capacity (WHC) was determined by measuring drip loss, cooking loss and purge loss of the samples. Meat samples were used for purge loss and cooking loss after colour measurements. Muscle samples (90 g) were weighed (W_1) and packaged in trays. After 5 d to 10 d retail display, the samples were weighed (W_2) and cooked in plastic bags using a temperature-equilibrated water bath (F38-ME, Julabo, 77960 Seelbach/Germany) until a core temperature of 71 °C was reached, as measured with a Grant thermometer equipped with T-type thermocouples during cooking. After cooking, samples were chilled at 0–4 °C for 16 h and reweighed (W_3) (Hopkins, Ponnampalam, van de Ven, & Warner, 2014). Purge and cooking loss were calculated as: Purge loss (%) = $\{(W_1\text{-}W_2)/W_1\} \times 100$/Cooking loss (%) = $\{(W_2\text{-}W_3)/W_2\} \times 100$.

2.5.3. Texture measurements

After cooking loss measurements, the cooked samples (from cooking loss measurements) were subjected to Warner-Bratzler peak shear force (WBSF) and texture profile analysis (TPA, hardness, adhesiveness, springiness, chewiness) by the texture analyzer (TA-1, Lloyd Instruments, AMETEK, USA), which was conducted as per the previously established protocols outlined by Ha, Dunshea, and Warner (2017). Each sample was cut into 6 cuboid (1 cm × 1 cm × 4 cm) for WBSF and a separate 1 cm thickness sample was used for TPA (Hardness, Adhesiveness, Springiness and Chewiness) with 6 readings (each reading point located at the centre of 2 cm × 2 cm square pieces) and all samples were cut parallel to the direction of muscle fibers. WBSF was measured by a shear blade (V-shaped) with a 500 N load cell, and the shearing speed was set at 300 mm/min. The TPA was performed using a 0.63 cm diameter flat-ended probe with 1.5 cm height, 50 mm/min speed and 80% penetration for a 1 cm thick sample. A total of 2 penetrations were applied to meat cut parallel to the direction of muscle fibers and the force work was recoded. A total of 6 measurements were taken for each sample and presented as means.

2.6. Statistical analysis

Statistical analysis was performed using liner mixed model procedures in GenStat 16th edition. Breed and temperature were fitted as fixed factors for the lamb growth performance (RT, RR, feed intake, ADG) and carcass parameters (carcass weight, GR, loin eye area and pHu), whereas replication and sheep/carcass ID were kept as random terms. For the analysis of retail meat quality parameters (colour, WHC and texture), fixed factors were breed, temperature and retail display time, and replications and sheep ID were included as random terms in the model. Means were considered to differ statistically when $P \leq 0.05$ based on 2 times the standard error of the difference (SED).

3. Results and discussion

3.1. THI and growth performance

Temperature–humidity index (THI) is commonly used to measure heat stress which is calculated based on the ambient temperature and relative humidity. An ambient environment with a THI lower than 22.2 is classified as the absence of a heat stress condition. From 22.2 to 23.3 is recognized as moderate heat stress. When THI ranges from 23.3 to 25.6, it is referred to as a severe heat stress condition, and extreme severe heat stress condition when the THI exceeds 25.6 (Marai et al., 2007; St Pierre, 2003). In this study, the average THI in the HS room was 34.1. Hence in this study, the recorded THI clearly showed that the lambs exposed to high temperature in the climatic chambers were exposed to severe extreme heat stress conditions (Fig. 1). HS led to a significant ($P < 0.05$) decline in feed intake of the 2nd cross lambs while had no influence on Dorper lambs. Both Dorper and 2nd cross lambs lost body weight during the HS period ($P < 0.05$), and the decline in weight of the 2nd crosses was higher than in the Dorpers. However, for lambs under the TN conditions, 2nd cross lambs had higher ($P < 0.01$) average daily gain (ADG) and feed intake (Table 1).

In this study, HS reduced lambs' feed intake ($P < 0.05$) and ADG ($P < 0.01$), which has been reported previously (Marai et al., 2007).There was an effect ($P < 0.01$) of breed on carcass weight such that the 2nd cross (both HS and TN) groups had higher carcass weights compared with Dorpers ($P < 0.01$), but there was no effect of temperature ($P > 0.05$) nor was there an interaction between temperature and breed. Both temperature and breed had no influence ($P > 0.05$) on GR or loin eye area. In contrast to growth results, HS had a very limited effect on the two breeds in terms of carcass quality parameters.

The lack of reduction in feed intake and lower decline in body weight of Dorper lambs as compared to the 2nd cross lambs, suggests that the Dorper breed is better adapted to higher environmental temperatures and thus may exhibit better growth performance than the high producing breed, which has been reported previously (Archana et al., 2018; Srikandakumar, Johnson, & Mahgoub, 2003). Under the TN conditions, 2nd cross lambs had better growth performance than Dorpers, which included a higher daily feed intake, ADG and hot carcass weight ($P < 0.05$ for all). These variations of growth performance with Dorper and 2nd cross under TN conditions agreed with the results of previous studies which reported that Dorpers had lower carcass weights, ADG and higher fat thickness compared to Suffolks (Burke & Apple, 2007; Schoeman, 2000; Snowder & Duckett, 2003). However, Almeida et al. (2013) pointed out that Dorper and Damara (hair sheep) had higher feed intakes and carcass weights compared with Merino (wool-type sheep) lambs.

3.2. Respiration rate and rectal temperature

Respiration rate and rectal temperature are some of the most commonly used indicators of physiological responses to HS in sheep and cattle (Marai et al., 2007). Under high ambient temperature and humidity, respiratory heat loss contributes about 60% of the total heat loss to maintain thermal balance in sheep (Wojtas, Cwynar, & Kołacz, 2014). Similar to other homeothermic animals, sheep body temperatures are maintained within a very narrow range (38.3–39.9 °C) and are affected by higher ambient temperatures due to insufficient heat loss (Franzmann, 1971).

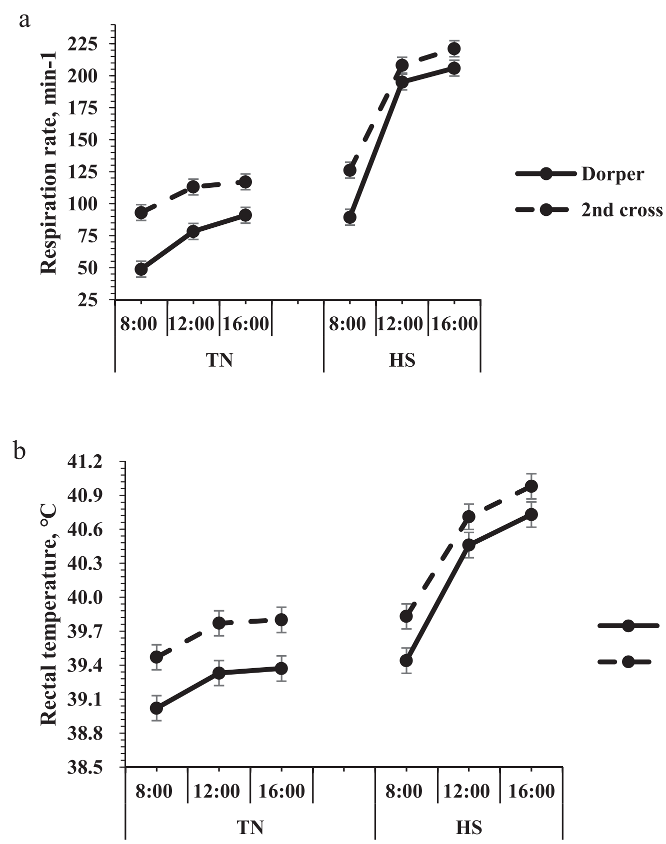

Fig. 2. The mean effect of heat stress (HS) or thermoneutral (TN) treatments, breed (2nd cross, Poll Dorset × (Merino × Border Leicester)); Dorper) and time (08:00, 12:00 and 16:00 h) on (a) respiration rate and (b) rectal temperature in finishing lambs (n = 48) (Joy, Dunshea, Leury, DuGuacomo, et al., 2020).
(a) Respiration rate; temperature, breed, time, temperature × breed, treatment × time, breed × time, all $P < 0.001$.
(b) Rectal temperature; temperature, breed, time, temperature × breed, treatment × time, all $P < 0.01$. breed×time, $P < 0.05$.
Least squares mean are shown and error bars are the pooled SED for the interaction of temperature × time × breed.

In this study, significant breed differences were observed for lamb RR and RT as reported before (Joy, Dunshea, Leury, DuGuacomo, et al., 2020). HS increased RR and RT ($P < 0.01$) of both Dorper (RR 163.8/min, RT 40.2 °C) and 2nd cross (RR 185.2/min, RT 40.5 °C) lambs (Fig. 2; $P < 0.05$), which confirms the lambs were under HS conditions and agreed with previous studies (Chauhan, Celi, Leury, Clarke, & Dunshea, 2015; Marai et al., 2007). Based on the classification of RR by Silanikove (2000), 40–60/min is classified as low stress, 60–80 is medium-high stress, 80–120/min-high stress and > 200 is a severe stress condition. A comparison of 2nd cross lambs with the Dorpers showed lower RR and RT in the latter ($P < 0.05$), under both temperature conditions throughout the day (0800, 1200 and 1600 h). This showed that Dorpers had a higher ability to regulate body heat during the heat exposure period (Horton, 1990; Srikandakumar et al., 2003). As reported by Macias-Cruz et al. (2016), hair sheep breeds appear to produce low concentrations of thyroid hormones, hence they tend to reduce their metabolic heat production, and their breathing is slower and deeper than wool breeds which helps them to lose more body heat. Compared with wool breeds, hair sheep with lower coat thickness, shorter and lower density of hair, and higher sweat glands are adapted to HS, and a lower density of hair increases the penetration of air in the sheep fleece to improve heat transfer (McManus et al., 2011).

Table 2
The effect of temperature (thermoneutal, TN vs heat stress HS) and breed (Dorper vs 2nd cross, Poll Dorset × (Merino × Border Leicester)) on colour of *Longissimus thoracis et lumborum* during 10 d high oxygen package retail display of finishing lamb meat (n = 48).

	Dorper		2nd cross			*P*-values			
Day	TN	HS	TN	HS	SED[2]	Breed	Temp.[1]	Time	Breed×Temp.
CIE-L* value									
0	34.1	34. 4	33.4	33.5	0.97	0.082	0.665	<0.001	0.832
2.5	36.4	36.6	35.2	36.6					
5	39.1	38.3	37.9	37.4					
7.5	38.3	37.7	37.7	36.1					
10	39.1	39.4	38.8	38.1					
CIE-a* value									
0	16.3	16.4	16.3	16.6	0.81	0.219	0.006	<0.001	0.120
2.5	16.8	17.3	16.4	17.8					
5	12.5	13.9	12.2	15.1					
7.5	10.3	11.2	10.7	12.7					
10	9.54	9.29	9.05	11.5					
CIE-b* value									
0	7.17	7.38	7.19	7.69	0.37	0.492	0.033	<0.001	0.914
2.5	8.99	9.55	8.98	9.86					
5	8.16	9.01	8.37	8.81					
7.5	8.43	8.40	8.50	8.19					
10	9.15	9.29	9.38	9.44					
Chroma									
0	17.9	18.0	17.8	18.3	0.62	0.203	<0.001	<0.001	0.019
2.5	19.1	19.7	18.7	20.4					
5	14.9	16.7	14.9	17.5					
7.5	13.6	14.2	13.8	15.1					
10	13.5	13.5	13.1	15.0					
Hue angle									
0	23.7	24.2	23.7	24.7	2.76	0.307.	0.226	<0.001	0.178
2.5	27.9	29.0	28.6	28.6					
5	33.6	33.6	35.0	30.1					
7.5	40.7	38.8	39.5	32.8					
10	45.0	46.3	46.2	39.7					

[1] Temp. = Temperature.

[2] SED=Standard error of the difference of means.

3.3. Retail meat quality

3.3.1. Meat colour and pHu

Overall, 2nd cross lambs had higher pHu compared with Dorpers ($P < 0.01$), and HS had an impact on the pHu of the LTL ($P < 0.05$). As shown in Table 1, the pHu of Dorper HS (5.60) was higher than Dorper TN group (5.54) but, there was no difference between 2nd cross HS (5.63) and 2nd cross TN (5.60; $P > 0.05$).

Compared with TN, the overall increase in pHu of meat under the HS condition ($P < 0.05$) was consistent with previous HS studies of ruminants. Kadim et al. (2008) reported that seasonal HS (35 °C, 47% RH) significantly increased the pHu in the *Psoas major and minor* of Omani Somali goats and Somali Merino sheep compared with cool season (21 °C, 59% RH). Compared to each treatment group, the pHu of the 2nd cross HS was greater than that of the Dorper TN ($P < 0.05$). Using 5.7 as the threshold for dark-cutting high pHu meat (McGilchrist, Alston, Gardner, Thomson, & Pethick, 2012), HS did not result in dark cutting meat for either Dorper or 2nd cross in the present experiment. The increase of pHu of HS lambs in this study is in accordance with previous studies of sheep and goats, although the magnitude of the difference in pHu between HS and TN was much lower compared with previous studies (Archana et al., 2018; Kadim et al., 2007, 2008). The different exposure times could be a reasonable explanation as a previous study by Lowe, Gregory, Fisher, and Payne (2002) that exposed sheep to 33 °C, 85–100% RH for 12 h, and a recent study (Chauhan, Dunshea, Plozza, Hopkins, & Ponnampalam, 2020) that exposed lambs to 28–40 °C, 30–40% RH for 1 week, showed that the short term HS had no influence on muscle pHu. The critical time point of the negative impact of HS exposure duration might exist between 2 weeks to 1 month, as a difference in pHu was reported with longer HS duration, as shown by Archana et al. (2018) (28 and 40 °C and 29–58% RH, 1 month), Macías Cruz (2020) (28.4 °C, 55.2%; 1 month) and Kadim et al. (2007) (35 °C and 47% RH; 6 months). As such, the influence of HS on muscle loin pH might be greater with the increased duration of HS exposure.

For meat colour during display, HS increased LTL muscle *a** ($P < 0.01$), *b** ($P < 0.05$), and chroma ($P < 0.01$) values of both breeds, but had no effect on *L** ($P > 0.05$) (Table 2). Across both TN and HS, Dorpers had higher *L** values than 2nd cross lambs, but the difference was not significant. There was an interaction between breed and temperature for chroma value such that HS increased the chroma of 2nd cross over the 10 d of retail display ($P < 0.05$) while had no effect on Dorpers ($P > 0.05$). After 10 d retail display, 2 weeks HS significantly reduced meat hue and increased chroma value of 2nd cross breed but had no impact on Dorpers.

During the display period, samples from 2nd cross HS animals had better colour performance as indicated by the highest *a** and chroma values and lowest hue values. A previous study showed that HiOx MAP increased the redness *a** values of beef steaks with higher pH values (>5.80) after 4 d of chilled storage and HiOx MAP had no effect on the redness *a** level of meat with normal pH < 5.8 (Zhang et al., 2018a, b). Neethling, Hoffman, Sigge, and Suman (2019) also reported that a higher pH of LTL had a positive correlation with springbok muscle colour stability and metmyoglobin reducing activity during 8 d of overwrapped storage. Similar to lamb physiological parameters, Dorper lamb pHu was not influenced by the HS condition again indicating that Dorper (a hair breed) had better heat tolerance when compared with

Table 3
The effect of temperature (thermoneutal, TN vs heat stress HS) and breed (Dorper vs 2nd cross, Poll Dorset × (Merino × Border Leicester)) on drip, purge and cooking loss of *Longissimus thoracis et lumborum* during 10 d high oxygen package retail display.

	Dorper		2nd cross			*P*-values			
Day	TN	HS	TN	HS	SED[2]	Breed	Temp.[1]	Time	Breed×Temp.
Drip loss (%)									
0	1.94	2.36	2.23	1.80	0.35	0.652	0.980	–	0.093
Purge loss (%)									
5	6.21	7.21	6.74	6.77	0.44	0.457	0.127	<0.001	0.117
10	8.00	8.64	8.61	8.52					
Cooking loss (%)									
0	19.4	21.9	22.1	21.3	1.39	0.041	0.206	<0.001	0.101
5	19.5	20.9	21.1	20.6					
10	17.5	18.2	18.8	19.6					

[1] Temp. = Temperature.

[2] SED=Standard error of the difference of means.

high production 2nd cross lambs (wool breed). This also supports the previous observations that the impact of HS is variable and depends on animal breed, and the extent of increases in environment temperature, humidity and solar radiation (Aggarwal & Upadhyay, 2013; Silanikove, 2000). Many HS studies have pointed out that the seasonal HS could lead to increased incidence of dark cutting meat. For example, Kadim et al. (2008) reported 6 months high temperature (35 °C and 47% RH) significantly increased the muscle psoas major and minor a* and decreased *L** and *b** values of sheep and goats. Gregory (2010) also pointed out a higher frequency of dark cutting beef during summer months. However, for a shorter duration of heat exposure, the relevant studies are very limited and the negative impact of HS on meat colour is weak. For example, Macías Cruz (2020) reported that 1 month of summer feeding (28.4 °C, 55.2% RH) had no detrimental changes in hair breed sheep (Dorper × Katahdin) meat colour compared with the winter (19.2 °C, 41.7% RH), which was in accordance with the results reported by Archana et al. (2018) (28 and 40 °C and 29–58% RH, 1 month), Chauhan et al. (2020) (28–40 °C, 30–40% RH, 1 week), and Lowe et al. (2002) (33 °C, 85–100% RH, 12 h). Combined with the results of this experiment, it appears that the impact of HS on meat colour is quite limited when the heat exposure time is shorter than 1 month.

3.3.2. Water holding capacity and texture

Overall, there was no main effect of breed and temperature on meat drip loss or purge loss (Table 3) and neither were there any interactions between breed and temperature ($P > 0.05$ for all traits covered here). However, there was an effect of breed on cooking loss such that 2nd cross lamb meat had higher cooking loss ($P < 0.05$) as compared to Dorpers. The purge loss increased ($P < 0.01$) from 5 d to 10 d display. The retail display time also had a significant impact on cooking loss such that cooking loss of both Dorper and 2nd cross lambs exposed to TN conditions was decreased from 0 d to 10 d display ($P < 0.05$), but not in 2nd cross ($P > 0.05$) lambs exposed to HS conditions. The decrease in cooking loss in MAP could have resulted from the increased content of

Table 4
The effect of temperature (thermoneutal, TN vs heat stress HS) and breed (Dorper vs 2nd cross, Poll Dorset × (Merino × Border Leicester)) on WBSF and texture profile analysis (TPA) of *Longissimus thoracis et lumborum* during 10 d high oxygen package retail display.

	Dorper		2nd cross			*P*-values			
	TN	HS	TN	HS	SED[2]	Breed	Temp.[1]	Time	Breed×Temp.
WBSF (N)									
0 d	46.3	47.2	50.9	48.6	4.00	0.482	0.897	<0.001	0.639
5 d	31.9	29.5	33.7	31. 7					
10 d	26.1	30.0	27.7	27.7					
Hardness (N)									
0 d	38.4	39.1	37.1	38.0	2.14	0.051	0.435	<0.001	0.725
5 d	38.7	38.3	36.4	37.0					
10 d	34.9	35.8	32.1	33.7					
Adhesiveness (Nmm)									
0 d	4.64	4.55	4.45	4.49	0.75	0.154	0.983	<0.001	0.363
5 d	4.34	4.28	3.97	4.50					
10 d	3.30	2.65	1.50	1.95					
Springiness (mm)									
0 d	−1.64	−1.68	−1.70	−1.55	0.09	0.831	0.207	0.059	0.872
5 d	−1.56	−1.55	−1.53	−1.62					
10 d	−1.73	−1.60	−1.69	−1.64					
Chewiness (N)									
0 d	13.3	13.5	12.8	13.5	1.10	0.155	0.150	0.073	0.637
5 d	13.6	14.2	13.0	13.3					
10 d	11.9	13.6	11.5	12.0					

[1] Temp. = Temperature.

[2] SED=Standard error of the difference of means.

exogenous enzymes (Marcinkowska-Lesiak et al., 2016), as the collagenase enzymes disintegrate the myofibrillar proteins and connective tissue thereby improving water holding capacity of proteins (Jama et al., 2008). Generally, cooking loss has a negative correlation with sheep meat pHu in the region of 5.5–5.8 (Adzitey, 2011; Bouton, Harris, & Shorthose, 1971). However, there are limited reports on the cooking loss of sheep meat from animals exposed to HS conditions and most of them investigated only fresh meat quality (within 48 h. postmortem) which did not include further ageing or display periods. Present studies of fresh meat reported that a high temperature environment (35 °C, 47% RH; 4 months) had a negative impact on expressed juice of *psoas major and minor muscle* of Merino sheep with higher pHu (5.77) compared with a cool season (21 °C, 59% RH; pHu 5.64) (Kadim et al., 2008). Archana et al. (2018) showed that HS had a negative effect on cooking loss of Salem Black goat meat while there was no effect on Osmanabadi goat meat.

For texture results, HS, breed and their interaction had no effect on the WBSF and TPA ($P > 0.05$) (Table 4). Our results for texture were in contrast to previous findings which showed HS increased meat WBSF, hence increased toughness (Archana et al., 2018; Saha et al., 2013). Kadim et al. (2007) reported HS decreased the myofibril fragmentation index, which indicates reduced proteolysis and reduced tenderness, for meat from Merino sheep, but they showed no effect in Somali sheep. It is worth mentioning that the various results of water holding capacity and texture were conducted under different heat exposure times, breeds, slaughter and chilling ways as mentioned previously (Archana et al., 2018; Saha et al., 2013;), and the magnitude of the increase in pHu with HS was also variable in these studies.

4. Conclusion

Two weeks cyclic HS had significant negative effect on both Dorper and 2nd cross lambs' physiological responses and growth performance. When exposed to 2 weeks cyclic HS, Dorpers showed higher heat tolerance (less decline of feed intake and body weight and lower RR and RT) than 2nd cross lambs. However, 2nd cross lamb's had higher growth performance compared with Dorpers under the TN conditions. Two weeks of heat exposure caused a small increase in muscle pHu of the two breeds. In terms of retail meat quality, meat from 2nd cross HS animals had higher redness a^* during 10 d of retail display. Except for colour, HS had no impact on drip loss, purge loss, cooking loss and texture in both 2nd cross and Dorper lambs. It is suggested that high meat production breeds are more likely to exhibit adverse effects of HS due to lower heat adaption capacity as compared to hardy breeds that are more adapted to heat. While the negative impacts of HS on sheep growth performance are quite evident, the impact of short-term (2 weeks) HS on meat quality are not as evident and might be variable depending upon the duration of heat exposure. Hence, further research is still warranted to evaluate the effect of HS on meat quality under different durations of temperature exposure, as there are significant variations in animal responses to acute and chronic heat exposure.

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