Effect of Transportation at High Ambient Temperatures on Physiological Responses, Carcass and Meat Quality Characteristics in Two Age Groups of Omani Sheep

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ABSTRACT : The aim of this study was to determine the effects of short road transportation in an open truck during hot season on live weight shrink, physiological responses, and carcass and meat quality of Omani sheep at 6 and 12 months of age. Thirty-six male sheep, 18 of each age group, were used. Age groups were assigned randomly to transported and not-transported groups. The transported group was transported to the slaughterhouse the day of slaughter in an open truck covering a distance of approximately 100 km. The average temperature during transportation was 37°C. The not-transported group was kept in a lairage of a commercial slaughterhouse with *ad libitum* feed and water for 48 h prior to slaughter. Blood samples were collected from sheep before loading and prior to slaughter via jugular venipuncture to assess their physiological response to transport in relation to hormonal levels. Animals were weighed just before loading onto a truck and after transport to assess shrinkage. Muscle ultimate pH, expressed juice, cooking loss percentage, WB-shear force value, sarcomere length and colour L*, a*, b* were measured on samples from longissimus dorsi, biceps femoris and semitendinosus muscles collected at 24 h postmortem at 1-3°C. Live weight shrinkage losses were 1.09 and 1.52 kg for 6 and 12 month transported sheep, respectively. The transported sheep had significantly (p<0.05) higher cortisol, adrenaline, noradrenaline, and dopamine concentration levels prior to slaughter at both ages than the not-transported sheep. Transportation significantly influenced meat quality characteristics of three muscles. Muscle ultimate pH and shear force values were significantly higher, while CIE L*, a*, b*, expressed juice and cooking loss were lower in transported than not-transported sheep. Age had a significant effect on meat quality characteristics of Omani sheep. These results indicated that short-term pre-slaughter transport at high ambient temperatures can cause noticeable changes in physiological and muscle metabolism responses in sheep. (**Key Words :** Sheep, Age, Meat Quality, Transport, Blood Metabolite)

INTRODUCTION

Transportation of livestock in open trucks between farms and slaughterhouse is a routine practice in the Sultanate of Oman. Transport of live animals has been recognized to cause significant economical and welfare implication on animals. Transportation of animals is

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generally recognized as a stressful event (Scharma et al., 1994). Vibrations and movement of the vehicle are unfamiliar to the animals, and therefore likely to elicit a stress response (Dantzer and Mormede, 1983). Adverse climatic conditions such as high or low temperatures and high relative humidity are also additional stressors to animals during transport. This may cause metabolic changes that can in turn adversely affect meat quality (Ashmore et al., 1972; Scharma, et al., 1994; Apple et al., 1995; Kannan et al., 2003; Bond et al., 2004: Jin et al., 2006). Animals are inevitably exposed to handling, loading and transportation. This may increase blood catecholamine concentrations, which may compromise cellular and humoral immune functions, reproduction, digestion, growth and other metabolic processes (Dantzer and Mormede, 1983; Nelson and Drazen, 2000).

The most important metabolic change due to preslaughter stress on meat quality is the depletion of glycogen and consequent inability of muscles to develop postmortem adequate acidity levels (Gregory and Grandin, 1998). Dark muscle colour is a common condition encountered when animals are exposed to conditions that deplete muscle glycogen levels prior to slaughter (Lawrie, 1998). Characterized by an elevated postmortem pH, dark muscle incidences produce a negative impact on meat quality. It is now a general belief that there is a negative relationship between meat quality and transport stress (Guise and Penny, 1989).

While there is substantial work (Rollin, 1995) on the effects of handling and transportation of cattle, pigs and poultry, little work has been carried out to assess the effects of stress in transported sheep. The objective of this study was to determine the effects of road transportation on physiological responses carcass and meat quality characteristics of Omani sheep of different ages.

MATERIALS AND METHODS

Animals

Thirty-six male sheep were randomly selected for slaughter at either 6 months old (18 animals with an average weight of 27.8 kg) or at 12 months old (18 animals with an average weight of 35.1 kg). Sheep were obtained from a flock raised intensively on Rhodesgrass hay and commercial ruminant concentrates at the Agricultural Experiment Station, Sultan Qaboos University. One month prior to the commencement of study, the animals were dipped in a solution of Gematox to eliminate ectoparasites. All animals were injected every two months prior to the experiment with 0.5 ml Ivomec for control of internal and external parasites.

Treatment

The sheep from each age group were assigned randomly into transported and not-transported groups. Three days prior to slaughter, the not-transported sheep were transported in the morning at 07:00 in an open truck (3×2 m) at ambient temperatures of 33-35°C to the slaughterhouse and kept in a pen under shade in a lairage (10×10 m) with feed and water available *ad libitum*. The transported sheep were subjected to two-hours of transportation conditions on the day of slaughter. Blood samples were collected and animals slaughtered between 10:30-11:00 a.m. The ambient temperature was 37.5°C.

Blood sampling and analysis

Blood samples were collected from each sheep before loading and prior to slaughter via jugular venipuncture to assess their physiological response to transport in relation to hormonal levels. Blood samples were collected using disposable vacutainer tubes containing 81 µl of 15% EDTA anticoagulant. Blood was collected from each animal with minimum disturbance to avoid excessive stress. Samples were kept in ice until plasma was separated within 2 h of collection by centrifugation at 5°C for 10 minutes at 3,000 rpm, then dispensed into 1.5 ml Eppendorf tubes and stored at -80°C. Chemiluminescence immunoassay was used for the determination of plasma hormonal levels using a Beckman Coulter Access 2 immunoassay system and reagents. (Beckman Coulter, Inc.). For the extraction of plasma catecholamines (all reagents Chromsystems GmbH), 75 mg of acid washed alumina was placed into a 2.0 ml Eppendorf tube and then 750 µl of extraction buffer, 750 µl of plasma, and 100 µl of dihydroxybenzoic acid (DHBA) standard 12 ng/ml were added. This mixture was shaken for 20 minutes using an autovortex and then centrifuged at 5,500 rpm (ALC International microcentrifuge model # 4214) for 3 minutes and then the supernatant aspirated. The resulting pellet was washed with 1 ml washing buffer. The mixture was then shaken as before, centrifuged for 3 minutes, and the wash buffer carefully aspirated. The washing process was repeated three times. To retrieve the catecholamines from the alumina, the pellet was eluted using 240 µl elution buffer and shaken for 7 minutes, using the autovortex, centrifuged at 11,500 rpm for 5 minutes and the supernatant containing the catecholamines and internal standard was pipetted carefully to a clean vial without disturbing the alumina layer. This supernatant was immediately analyzed using HPLC with electrochemical detection (Waters 600S, 464 ECD and 717 Autosampler). Results were acquired and processed using Millenium[32] software (Waters).

Meat quality evaluation

Sheep were slaughtered at the Muscat Municipality Central Slaughterhouse according to the Muslim (Halal) way by severing the throat and major blood vessels in the neck. Live body weight before and after transportation was recorded and the weight loss during transportation was calculated. Dressed carcasses were weighed within 1 h (hot carcass weight), chilled for 24 h at 1-3°C and weighed gain (cold carcass weight). The difference between hot and cold carcass weights was used to determine carcass shrinkage.

The carcasses were chilled for 24 h at 1-3°C before the Mn longissimus dorsi (LD), semitendinosus (ST) and biceps femoris (BF) were removed from the left side of each carcass. Meat quality measurements including ultimate muscle pH, expressed juice, cooking loss, Warner-Bratzler shear force, and colour (L^*, a^*, b^*) were determined. The ultimate pH was assessed in homogenates at 20-22°C (using an Ultra Turrax T25 homogenizer) of duplicate 1.5-2 g of muscle tissue in 10 ml of neutralized 5-mM sodium

Table 1. Least square means (±standard error) of cortisol, dopamine, adrenaline and noradrenaline in 6 and 12 month Omani sheep subjected to transportation stress and non-stressed before slaughter

Parameter		6-month		12-month		SEM	Significant[1]	
		NT	T	NT	T		Treat	Age
Cortisol (nmol/L)	Initial	25.3	24.5	19.6	21.2	2.31	NS	NS
	Final	23.0^a	46.0^b	20.0^a	·40^b	2.00	*	NS
	Sign.[2]	NS	**	NS	**			
Dopamine (ng/ml)	Initial	0.29	0.33	0.69	0.74	0.19	NS	*
	Final	0.32^a	0.90^c	0.71^b	0.93^c	0.15	*	*
	Sign.	NS	*	NS	*			
Adrenaline (ng/ml)	Initial							
	Final	0.26^a	0.40^b	1.58^c	1.92^d	0.34	*	*
	Sign.							
Noradrenaline (ng/ml)	Initial							
	Final	0.08^a	0.20^b	0.18^b	0.23^c	0.037	*	NS
	Sign.							
Cholesterol (nmol/L)	Initial							
	Final	1.54	1.40	1.57	1.49	0.106	NS	NS
	Sign.							
BUN$_2$ (nmol/L)	Initial							
	Final	0.13	0.25	0.10	0.21	0.084	NS	NS
	Sign.							
Lactate (nmol/L)	Initial							
	Final	0.78	2.90	0.85	2.51	0.85	*	NS
	Sign.							
CO$_2$ (nmol/L)	Initial							
	Final	0.13	0.35	0.10	0.21	0.085	NS	NS
	Sign.							
Mg (nmol/L)	Initial	0.90	0.84	0.96	1.04	0.024	NS	NS
	Final							
	Sign.							
PO$_4$ (nmol/L)	Initial							
	Final	3.17	2.53	2.14	2.40	0.125	NS	NS
	Sign.							
Ca (nmol/L)	Initial							
	Final	2.36	2.29	2.82	2.68	0.059	NS	NS
	Sign.							
Uric acid (nmol/L)	Initial							
	Final	0.02^a	0.42^b	0.03^a	0.52^b	0.001	*	NS
	Sign.							
Total protein (nmol/L)	Initial							
	Final	62.6^b	47.1^a	80.0^c	64.57^b	1.245	*	NS
	Sign.							

NT: Unstressed group, T: Transported group. SEM: Standard error of mean.
[a, b, c] Means within the same row within different superscripts were significantly different (p<0.05).
[1] Major effects (treatment and breed). [2] Effects of time of bleeding between initial and final. NS: Not significant, * p<0.05, ** p<0.01, ** p<0.001.

iodoacetate and the pH of the slurry measured using a Metrohm pH meter (Model No. 744) with a glass electrode. Chilled muscle samples (13 mm×13 mm cross section) for assessment of shear force by a digital Dillon Warner-Bratzler (WB) shear device were prepared from muscle samples cooked in a water bath at 70°C for 90 min (Purchas, 1990). Sarcomere length was determined by laser diffraction according to procedure (Cross et al., 1980; 1981). Expressed juice was assessed by a filter paper method, as the total wetted area less the meat area (cm^2) relative to the weight of the sample (g). Approximately 60 min after exposing the fresh surface, CIE L^*, a^*, b^* light reflectance coordinates of the muscle surface were measured at room temperature (25±2°C) using a Minolta Chroma Meter CR-300 (Minolta Co., Ltd., Japan), with a colour measuring area 1.1 cm diameter. It was calibrated using a Minolta calibration plate (L^* = 97.59, a^* = -5.00, b^* = +6.76). The L^* value relates to Lightness; the a^* value to Red-Green hue where a positive value relates to the red intensity; and the b^* value to the Yellow-Blue where a positive value relates to yellow. The average of two measurements from each sample was recorded as the colour coordinate value of the sample.

Table 2. Least-square means of final body weight, empty body weight, carcass weight, dressing-out %, carcass linear dimensions and major cut weights for two age groups of Omani sheep from transportation stress and control groups

Parameter	6-month		12-month		SEM	Transport	Age
	NT	T	NT	T			
Body weight before transport (kg)	28.4	28.3	35.3	36.0	1.32	NS	***
Body weight after transport (kg)	28.4[a]	27.3[a]	35.3[b]	34.8[b]	1.55	NS	***
Live weight loss (g)		1,094		-1,524	200	*	NS
Gut content (kg)	5.82[ab]	4.82[a]	6.57[b]	6.12[b]	0.589	*	**
Hot carcass weigh (kg)	12.1[a]	12.7[a]	16.5[b]	15.8[b]	0.79	NS	***
Cold carcass weight (kg)	11.8[a]	12.4[a]	16.1[b]	15.4[b]	0.78	NS	***
Shrinkage (g)	309	291	426	337	39	*	*
Carcass cuts							
Shoulder weight (kg)	5.19[a]	5.36[a]	7.79[b]	7.23[b]	0.393	NS	***
Rack weight (kg)	1.07[a]	1.21[a]	1.54[b]	1.48[b]	0.090	NS	***
Loin weight (kg)	1.16[a]	1.23[a]	1.52[b]	1.50[b]	0.077	NS	***
Leg weight (kg)	4.06[a]	4.15[a]	5.72[b]	5.16[b]	0.270	NS	***

NT: Unstressed group, T: Transported group. SEM: Standard error of mean.
[a, b] Means within the same row within different superscripts were significantly different ($p<0.05$). NS: Not significant, * $p<0.05$, ** $p<0.01$, ** $p<0.001$.

Statistical analysis

The effect of transportation and age on the carcass, meat quality and blood serum parameters and their interaction were analysed using the analysis of variance procedures (SAS, 1993). Time of bleeding was used as class initial and final as repeats (repeated measurements). Significances between individual means were assessed using the least-significant-difference procedure. Interactions between transport and age group were excluded from the model when not significant ($p>0.05$).

RESULTS AND DISCUSSION

Blood serum

Physiological parameters such as cortisol, dopamine, adrenaline and noradrenaline have been proposed as sensitive indices of physiological stress in animals that have been exposed to procedures such as transport (Broom and Johnson, 1993; Parrott et al., 1994; Apple, et al., 1995). Blood parameters values were compared between the transported and not-transported sheep at the two age groups to investigate the effects of short duration transport on sheep at high ambient temperatures on physiological parameters (Table 1).

There was a significant effect ($p<0.05$) of age on initial plasma cortisol, adrenaline, noradrenaline and dopamine concentrations (Table 1). Initial blood samples showed that the 12-month group of sheep had significantly higher hormone concentrations than the 6-month group of sheep.

Both the 6 and 12 months transported group had significantly higher ($p<0.05$) plasma cortisol levels over their counterpart not-transported group. Omani sheep transported the same day of slaughtering appear to experience some degree of stress based on the higher values of cortisol compared to not-transported animals. This indicates that two hours of transportation in an open track under Omani condition (high ambient temperature) appears to produce stress in sheep. Broom et al. (1996) examined a range of plasma stress indicators in transported sheep and found that plasma cortisol levels were higher in transported sheep during three hrs of the transportation in comparison with the control animals. Broom et al. (1996) reported cortisol levels comparable to those of Omani sheep in the present study. Ruiz-De-La-Torre et al. (2001) found that the level of cortisol was higher after four hrs on a rough journey.

Although, there were no significant differences in the plasma cortisol levels between 6 and 12 months of age groups, adrenaline, dopamine and noradrenaline were significantly higher in the 12-month sheep over the 6 months sheep. However, within each age group, the adrenaline, dopamine and noradrenaline concentrations were significantly higher in the transported 6-month sheep than in the not-transported group only.

Parrott et al. (1994) reported that adrenaline was released 10 min after sheep were subjected to transport stress with little change in noradrenaline within the first 10 min. The present findings indicated that levels of these hormones stay elevated for at least two hrs or as long as transportation continues. The release of adrenaline enables animals to mobilize body resources quickly for metabolic requirements in response to stress (Dantzer and Mormede, 1983). Typically, the sheep in the present study responded to transport stress by increasing cortisol levels, adrenaline, noradrenaline and dopamine (Axelrod and Reisine, 1984). These hormones serve to adapt the body to stressors by affecting cardiovascular, energy-producing and immune systems.

Live weight and carcass characteristics

After the two-h transportation, live body weight was significantly ($p<0.05$) decreased in the two age groups (Table 2). Loss of live weight during transportation is most

Table 3. Least-square means for a range of quality characteristics for the longissimus dorsi Omani sheep at 6 or 12 month of age from transportation stress or control groups

Parameter	6-month		12-month		SEM	Treat.	Age
	NT	T	NT	T			
Ultimate pH	5.61[a]	5.85[c]	5.71[b]	5.84[c]	0.069	**	NS
Expressed juice[b]	42.38[b]	35.93[a]	42.88[b]	36.59[a]	2.492	*	NS
Cooking loss %	22.02[b]	18.56[a]	30.32[c]	26.52[b]	3.082	*	**
WB values (kg)[c]	3.31[a]	4.60[b]	4.67[b]	5.99[c]	0.336	*	**
Sarcomere length μm	1.89[b]	1.69[a]	1.79[b]	1.65[a]	0.027	*	**
$L*$ (lightness)	67.03[c]	50.58[b]	47.64[b]	40.31[a]	1.278	*	*
$a*$ (redness)	15.28[b]	12.18[a]	18.88[c]	15.01[b]	1.510	*	*
$b*$ (yellowness)	4.60[b]	2.43[a]	10.51[d]	7.02[c]	0.728	*	**

NT: Unstressed group, T: Transported group. SEM: Standard error of mean.
[a, b, c] Means within the same row within different superscripts were significantly different (p<0.05). NS: Not significant, * p<0.05, ** p<0.01, ** p<0.001.

Table 4. Least-square means for a range of quality characteristics for the biceps femoris of Omani sheep at 6 or 12 month of age from transportation stress or control groups

Parameter	6-month		12-month		SEM	Treat	Age
	NT	T	NT	T			
Ultimate pH	5.71[a]	5.91[b]	5.63[a]	5.85[b]	0.074	**	NS
Expressed juice[b]	38.18[b]	32.43[a]	43.25[b]	35.99[a]	1.734	*	***
Cooking loss %	21.71[b]	18.18[a]	25.82[c]	22.36[b]	1.804	*	NS
BF WB values (kg)[c]	4.00[a]	5.29[bc]	5.66[b]	7.98[c]	0.230	*	*
Sarcomere length μm	1.79[b]	1.65[a]	1.74[bc]	1.61[a]	0.015	*	*
$L*$ (lightness)	69.09[c]	58.77[b]	54.13[b]	41.15[a]	1.132	*	*
BF $a*$ (redness)	14.09[b]	10.11[a]	19.38[c]	15.13[b]	1.106	*	*
$b*$ (yellowness)	5.83[b]	2.24[a]	10.82[d]	6.03[c]	0.657	**	**

NT: Unstressed group, T: Transported group. SEM: Standard error of mean.
[a, b, c] Means within the same row within different superscripts were significantly different (p<0.05). NS: Not significant, * p<0.05, ** p<0.01, ** p<0.001.

probably due to loss of water (dehydration) and deprivation of feed. High temperatures (37.5°C) during transportation may most likely cause weight loss through loss of moisture from the respiratory tract. Warriss (1993) reported that animals can lose weight when they are subjected to greater energy demands, such as those needed to maintain balance or to thermoregulate in transport. Thermoregulation may involve greater loss of body water through sweating or panting. According to Knowles, et al. (1995), during transport, live weight declines and plasma free fatty acids, β-hydroxybutyrate and urea rise, which shows that reserves of glucose are limiting and instead body fat and protein reserves are mobilized to provide energy. In the present study, transported animals had significantly higher uric acid and lower total plasma protein than not-transported animals (Table 1). Average live weight losses in sheep ranged between 0.09 to 0.34% per hour, and rate of carcass loss ranged between 0.08 to 0.15% per hour, with the onset of carcass loss occurring between 12 and 24 h after deprivation from feed (Thompson et al., 1987; Warriss et al., 1987).

Although more loss was recorded between transported than not-transported groups in 12-month animals, there were no differences in the effects of transport on carcass weight from the two age groups. However, there were significant differences in carcass shrinkage during chilling between transported and not-transported groups (Table 2). Carcasses from not-transported animals had significantly higher shrinkage values than for transported animals (368 vs. 314 g in average).

Meat quality

The ultimate pH of muscle is a major determinant of meat quality (Watanabe et al., 1996) and is related to the depletion of glycogen and liberation of lactic acid pre- and post-slaughter. In both age groups and across the three muscles, transported sheep had significantly higher ultimate pH values than those sheep that were not-transported (Tables 3, 4 and 5). Transportation significantly increased ultimate pH muscle. The muscles from the TS group in both ages had significantly higher ultimate pH than NS animals. Ruiz-De-La-Torre et al. (2001) found that the ultimate pH of sheep meat transported in a rough journey for four hours was significantly higher than that in animals transported smoothly. Apple et al. (1995) found that muscle from stressed sheep had significantly higher ultimate pH values than unstressed animals and concluded that a higher pH than 6.0 was associated with dark meat. The effort needed by the sheep to keep their balance while the vehicle moves is demanding in terms of energy requirements leading to depletion of glycogen and consequently decreasing muscle

Table 5. Least-square means for a range of quality characteristics for the semitendinosus} of Omani sheep at 6 or 12 month of age from transportation stress or control groups

Parameter	6-month		12-month		SEM	Treat	Age
	NT	T	NT	T			
Ultimate pH	5.65[ab]	5.80[b]	5.53[a]	5.75[b]	0.087	***	NS
Expressed juice[b]	39.03[b]	36.20[a]	43.25[c]	41.99[bc]	1.240	*	***
Cooking loss%	22.15[b]	14.32[a]	21.36[b]	16.82[a]	2.265	**	NS
WB values (kg)[c]	4.08[a]	5.23[ab]	4.66[b]	5.78[c]	0.213	*	*
Sarcomere length μm	1.82[b]	1.70[a]	1.78[ab]	1.64[a]	0.020	*	*
L* (lightness)	65.46[c]	55.37[b]	52.13[b]	41.15[a]	1.216	*	*
a* (redness)	15.30[b]	12.12[a]	19.18[c]	15.03[b]	1.352	*	*
b* (yellowness)	4.63[b]	2.91[a]	10.82[d]	6.03[c]	0.550	*	**

NT: Unstressed group, T: Transported group. SEM: Standard error of mean. [a, b, c] Means within the same row within different superscripts were significantly different ($p<0.05$). NS: Not significant, * $p<0.05$, ** $p<0.01$, ** $p<0.001$.

pH (Tarrant and Grandin, 1993; Apple et al., 1995). Glycogenolysis in skeletal muscle is regulated by the activity of glycogen phosphorylase (Apple et al., 1995). The activation of this enzyme is triggered by either increasing catecholamines, muscle contraction or both (Tarrant, 1989). Increased metabolism of muscle glycogen during stress may be a direct result of the calcium release into the myofibril associated with muscle contraction (Rosell and Saltin, 1973). On the other hand, increasing catecholamines levels can also activate glycolysis (Drummond et al., 1969). Therefore, in the present study, both of these factors may have played a role in the activation of glycolysis.

Variation in ultimate pH among the three muscles might be attributed to differences in proportions of red and white fiber types in muscles and, consequently to differences in patterns of energy metabolism during both ante- and post-mortem (Swatland, 1982).

Water retention of meat is primarily caused by immobilization of tissue water within the myofibrillar system (Hamm, 1981). Applying pressure can cause a shift of water from the intercellar into the extracellular space and then onto the meat surface as a result of structural alterations at the level of the sarcomeres or of the myofilaments structure. The influence of transportation on expressed juice is of particular interest, where transportation did decrease level of expressed juice in all three muscles. The three muscle samples from transportation stressor sheep in both ages had significantly lower cooking loss percentage than muscles from unstressed sheep (Tables 3, 4 and 5). Decreased cooking loss percentage is a reflection of the increased water-holding capacity (decrease expressed juice) associated with meat of high ultimate pH (Bouton et al., 1971). Similarly, Apple et al. (1995) found that muscles from stressed lambs had lower ($p<0.01$) cooking loss percentage than chops from control animals. In contrast, Bond et al. (2004) found that muscles from exercise stress sheep were significantly higher than those from no exercise animals and concluded that the mechanism causing greater water loss in the muscle of exercise stressed lambs is not unknown.

Shear force values were within the range of 3.31-7.98 kg for the three selected muscles with significant transportation and age effects (Tables 3, 4 and 5). Muscles from transported sheep had a significantly higher shear force value compared to not-transported sheep for 6 and 12 month. In contrast, muscles from stressed lambs had lower shear values, indicating that muscles from stressed lambs were more tender than those from non-stressed ones (Apple et al., 1995). Similarly, Chrystall et al. (1982) found that the muscle from lambs chased to exhaustion by dogs was more tender than those from their unstressed counterparts. The differences in shear force values between the present study and Apple et al's study may probably be due to differences in ultimate pH values. In the present study, the ultimate pH from transportation stressor animal muscles was below 5.9, while Apple et al.'s study it was above 6.4. Marsh et al. (1980-1981) reported that meat tenderness was improved in muscles with a high ultimate pH (in excess of 6.0). This is possibly a result of the higher favorable pH for activation of calpain proteases (Koohmaraie, 1988). A similar pattern of differences was found for sarcomere length.

Colour of meat is influenced by several individual factors and their interaction. The muscle from transportation stressor sheep had significantly lower ($p<0.05$) CIE *L**, *a** and *b** values (Tables 3, 4 and 5). This indicates that muscles from transported sheep were darker, less red and less yellow, respectively than muscle from not-transported sheep. Meat from stressed lambs was darker than that from non-stressed lambs (Forrest et al., 1964; Apple et al., 1995). The lower *L**, *a** and *b** values of muscles from TS sheep in the present study are similar to those reported by Apple, et al. (1995) who found lower values of *L**, *a** and *b** for muscle from lambs subjected to stress. The type and intensity of transportation also had an effect on meat color. Ruiz-De-La-Torre et al. (2001) found that *a** of sheep meat which was transported roughly for four hours was significantly higher than those transported smoothly. Bond et al. (2004) found that the color of meat from stressed

sheep was darker and further towards the red-blue end of the spectrum (a*) and less yellow (b*) than those from unstressed animals. When muscle pH increased above 6.0, CIE a* values decreased below 16.0 (Purchas, 1988; Apple et al., 1995). In the present study, mean a* values of the three muscles from TS sheep were below 16.0, indicating that the dark colour was effectively produced by the less intensive two hrs of transportation. Transportation stress has been associated with the excess depletion of muscle glycogen reserves before slaughter and the resultant formation of the dark muscle (Warriss et al., 1990). Antemortem glycogenolysis in skeletal muscle is regulated by the activity of glycogen phosphorylase, which may be triggered by either an adrenergic mechanism or a contractile mechanism or by both mechanisms acting in concert (Tarrant, 1989). Decrease in colour values is highly related to pH change and occurs at a pH of approximately 6.0 (MacDougall and Jones, 1981). Lawrie (1958) found that mitochondrial oxidase, a principal enzyme responsible for oxygen uptake by mitochondria, is more active at pH values greater than 6.0. This led Egbert and Cornforth (1986) to conclude that insufficient acid formation during postmortem glycolysis, typical of the dark color, fails to inactive mitochondrial respiration, thus allowing myoglobin to be deoxygenated and causing the muscle to remain dark. The colour of a meat surface depends not only on the quantity of myoglobin, but also on the relative proportions of the three main states of myoglobin on the surface. Ultimate pH can influence colour independently of meat Mb content (Ledward, 1985), which explained the differences in the treatments.

Transportation of sheep for two hours in an open truck at high ambient temperature caused significant effects on meat quality characteristics of various muscles of sheep. These included high ultimate pH, water-holding capacity and shear force values as well as darker meat surfaces. This is probably not solely due to transportation alone but may be also be due to high temperature.

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