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Laser and thermographic infrared temperatures associated with heat tolerance in adult rams

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ABSTRACT

Heat is a major factor limiting the production of animals in the tropics. Sheep are well adapted to diverse ecosystems, however, temperature and relative humidity can influence animal husbandry. Therefore, this study was carried out to verify the thermoregulation in rams of six breeds (Bergamasca, Dorper, Ile de France, Hampshire Down, Santa Ines and Texel) through the evaluation of physiological traits, body measures, laser and thermographic infrared temperatures as well as testicle morphometry associated with heat tolerance. Animals were measured and weighed, coat and hair colour determined, as well as physiological traits and laser and thermographic infrared temperatures measured twice a day. Data were analyzed with the Statistical Analysis System®. There were differences among breeds for most of the traits linked to heat tolerance, with the Santa Ines showing better adaptation to heat stress compared to other breeds. The Dorper was not significantly better than Bergamasca or Hampshire Down breeds, while Texel and Ile de France were less well adapted. Scrotal temperatures were lowest in Hampshire Down and Dorper, while highest in Texel. Temperature gradient measured by thermography identified Hampshire Down as the least heat tolerant breed. Traits linked to heat tolerance should be taken into consideration when choosing breeds for lamb production in tropical regions.

1. Introduction

In the central-west Brazil, sheep farming is predominantly extensive, where pastures have little shade, and animals are exposed to high solar radiation and low levels of relative humidity in the dry season, which runs from late March to early October. Despite this, the climate of this region is favorable compared to other regions where sheep production is developed (McManus et al., 2009) which has led to growth of the sheep flock in this region (McManus et al., 2013).

Climate changes may lead to an increase in thermal stress due to changes in thermal energy balance between animal and environment, which is influenced by environmental characteristics (radiation, temperature, relative humidity and wind velocity) and heat exchange (conduction, radiation, convection and evaporation) (Sirohi and Michaelowa, 2007). Any changes in these factors may modify the thermoneutral zone and trigger changes in biological functions of sheep, including decrease in food consumption and use, disturbances in water, energy, protein and mineral metabolism, enzymatic reactions, hormonal secretions and metabolites in the blood (Marai et al., 2006).

Factors such as species, body condition, hair coat and skin characteristics, temperament and gender influence the response to heat stress (Scholtz et al., 2013). Physiological measures (heart, sweating and respiratory rate, and rectal temperature) as well as body measurements (cannon bone and thoracic circumference, body length and shoulder height, number of hairs per cm^2, hair length and skin and hair characteristics) have been used to investigate heat tolerance in sheep (McManus et al., 2009, 2011).

Data collection is often time consuming and expensive, especially in developing countries, where laboratory facilities and trained human resources are scarce, so there is a need to assess the usefulness of these characteristics in determining differences between breeds and individuals (McManus et al., 2011). Infrared thermography is a modern, non-invasive and safe technique that is

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used to measure the surface temperature of the body of the animals (Montanholi et al., 2008) that has been shown be related to several physiological processes associated with heat tolerance (Paim et al., 2013, 2014; Silva et al., 2014). Considering that animals react differently to the environment to which they are exposed, this technology can help to identify animals and breeds of sheep more adapted to the heat under the same management conditions.

As heat stress can greatly affect the productive and reproductive life of sheep (Veríssimo et al., 2009), this study was carried out to verify the thermoregulation in rams of six breeds, through the evaluation of the physiological traits, body measures, laser and thermographic temperatures as well as testicle morphometry associated with heat tolerance.

2. Material and methods

Animal care procedures throughout the study followed protocols approved by the Ethics Committee for Animal Use (ECAU) at the University of Brasilia, number 44568/2009.

2.1. Local and animal data

The experiment was carried out on the Sucupira Farm bellowing to Embrapa Genetic Resources and Biotechnology located southwest of the city of Brasilia-DF (15°47′S and 47°56′W), with altitudes ranging 1050–1250 m, during the dry season. The climate is Aw, according to Köppen classification system, characterized by two distinct seasons, with rainy summers and dry winters (Silva et al., 2008).

Purebred rams from six breeds (Bergamasca, Dorper, Ile de France, Hampshire Down, Santa Ines and Texel) were used. Within breed there was no genetic relationship between animals for at least three generations. All were clinically healthy, sexually mature, with an average age of six years and average body weight of 77.43 ± 1.27 kg, with good reproductive history and fertility. The number of rams per breed (3) was determined using the minimum number of replications formula in Kaps and Lamberson (2009) in accordance with ECAU regulations to detect differences between treatments at a level of 5% and 80% power of the test. All animals were reared at pasture. The animals were kept in semi-intensive system and fed with *Brachiaria decumbens*, supplementation of concentrate for sheep (22.00% crude protein, 2.30% ether extract, 4.30% crude fiber, 1.20% calcium, 0.38% phosphorus and 71.50% total digestible nutrient), mineral and water *ad libitum.*

2.2. Data collection

Samples were collected in both the morning (7:00) in the shade and the afternoon (14:00) in the sunlight. The physiological parameters included: respiratory rate (RR), heart rate (HR) and rectal temperature (RT). RR and HR were measured using a stethoscope. RT was measured with a digital thermometer introduced into the animal's rectum. Animals were also weighed. Other measures included wither height (the highest point of the interscapular region); body length (from the tip of the palette to the ischial tuberosity), posterior shin bone perimeter and thoracic circumference, using a tape measure. Skin thickness was measured at the central portion of the right scapula using digital calipers. Coat thickness was measured in centimeters at the withers (LHW), 12th thoracic vertebra (T12) and rump using a paquimeter. The thickness of the coat was the perpendicular distance between the epidermis and the surface. Number, length and diameter of coat fibers were collected according to Lee (1953). These were placed in a plastic bag and then were spread on white paper and counted with the help of needle. The coat length were measured according to Udo (1978). The diameter of the fiber was measured using an optical microscope fitted with a graduated ocular piece. Coat and epidermis colour were measured using a spectrophotometer (Byk-Gardner GMBH, Geretsried, Germany), through the CIELAB, L^*, a^* and b^* system, which determines the coordinates: L^* (brightness), a^* (red colour intensity) and b^* (yellow colour intensity). Three measurements were taken and the mean calculated for each animal.

Skin surface temperature (SST) was measured using a laser infrared thermometer Raytek MX6 PhotoTemp^{TM} (Burlington, VT, USA) at the following points: neck, rump, groin, 12th thoracic vertebra (T12) and scrotum. This thermometer uses a 635 nm laser with an accuracy of 0.75% and a resolution of 0.1 °C. The temperature of the scrotal skin was also measured by infrared FLIR thermograph ThermaCAM® (FLIR Systems Inc, Wilsonville, OR, USA) at a distance of 1 meter of the animal in five points: top, bottom, right, left and central regions.This camera has infrared resolution 320 × 240 pixels, with thermal sensitivity of <0.05 °C at 30 °C (86 °F)/50 mK. The temperature gradient (TG) was carried out in accordance with Menegassi et al. (2015) where the line tool was used to draw a one pixel wide line in Quickreport® software to create two temperature measurements—one at 1 cm from the top and the other 1 cm from the bottom of the testicle. The mean temperature on each of these lines was taken and the gradient (TG) from the top to the bottom of the temperature calculated by difference.

Other temperatures measured with ThermaCAM® were: muzzle, neck, axilla, croup, groin and average temperature of side of the body, and floor area at the side of the animal. No measures were taken on regions covered with wool.

Testicular measurements included scrotal circumference, testicular length, width and thickness, obtained with a paquimeter, and the temperature gradient variation per cm was calculated by dividing temperature gradient by testicle length.

2.3. Environment characterization and temperature-humidity index calculation

The environmental temperature (°C), relative humidity (%) and wind speed (km/h) were obtained from the National Institute of Meteorology (INMET). The minimum and maximum environment temperatures obtained in the morning and afternoon during the experiment were 15.7 °C and 23.5 °C; 25.0 and 26.9, respectively. Relative humidity ranged between 30.6–55.6% and the wind speed average was 3.8 km/h. The floor temperature average was 25.7 °C.

The temperature and humidity index (THI) was calculated according to the following Marai et al. (2002) formula: $\text{THI} = \text{ET} - \{(0.31 - 0.31\,\text{RH})\,(\text{ET} - 14.4)\}$; where ET is the environment temperature (°C) and RH is the relative humidity ((RH%)/100). The values of THI during the study period ranged between 15.40 and 23.94, which are compatible with absence of heat stress and severe heat stress, respectively (Marai et al., 2002).

2.4. Statistics analyses

The statistical design was completely randomized factorial 6 × 2 (six breeds and two periods—morning and afternoon) with six replications. The collected data were analyzed with the Statistical Analysis System® (SAS Inc, Cary, NC, USA) package, using the methods of analysis of variance (MIXED) with repeated measures and correlations. Means were compared using Duncan test with a significance level of 5%.

3. Results

Breed influenced ($P < 0.001$) the body measurements (Table 1) such as the weight, wither height, thoracic circumference, body length and shin bone perimeter. The Bergamasca breed presented

Table 1
Mean body measurements in the ram breeds.

Breed	Body weight (kg)	Wither height (cm)	Thoracic circumference (cm)	Body length (cm)	Perimeter of the posterior shin (cm)
HD	92.33a	76.16a	103.00a	95.66a	10.33a
IF	82.67b	69.66b	99.00b	85.66b	10.16a
DR	78.73b	64.33c	92.00c	82.66c	9.66b
TX	77.06bc	68.16b	98.33b	79.33d	9.06c
SI	71.33c	79.33d	94.16c	82.66c	8.76c
BE	61.76d	73.83e	88.33d	83.66bc	8.33d
CV	13.36	7.70	5.55	6.63	8.49
SD	13.27	5.78	6.94	6.34	1.20

Means with different letters in the column differ at 5% by Duncan test. HD: Hampshire Down; IF: Ile de France; DR: Dorper; TX: Texel; SI: Santa Ines; BE: Bergamasca. CV: coefficient of variation; SD: standard deviation.

Table 2
Interaction between breed and period on the respiratory rate and temperatures at the rump, muzzle, axilla and groin.

Period	Breed						Mean	CV	SD
	HD	IF	DR	TX	SI	BE			
Respiratory rate									
Morning	18.55Bb	15.22BCb	11.78Cb	23.00Ab	10.50C	12.66Cb	15.41	29.51	6.11
Afternoon	30.22Ba	32.12Ba	28.00Ba	39.77Aa	15.00C	26.88Ba	28.60	21.76	9.50
Rump temperature-infrared									
Morning	33.06Bb	34.01ABb	32.25Bb	35.44A	29.53Cb	35.38A	33.35	6.57	2.88
Afternoon	36.56a	36.45a	35.33a	36.34	35.42a	36.93	36.16	6.03	2.15
Muzzle temperature-thermography									
Morning	30.18ABCb	30.57ABCb	29.68Cb	32.58Ab	28.21Cb	31.74ABb	30.54	8.24	2.81
Afternoon	34.25Ba	35.27ABa	34.90ABa	35.18ABa	37.08Aa	34.11Ba	35.13	6.10	2.25
Axilla temperature-thermography									
Morning	24.92Cb	27.64Bb	30.40Ab	23.60Cb	31.61Ab	24.68Cb	27.06	8.97	3.78
Afternoon	31.94Ba	33.48Ba	34.73Ba	34.68Ba	38.38Aa	33.28Ba	34.43	9.29	3.63
Groin temperature-thermography									
Morning	24.10CDb	25.50BCb	30.43Ab	23.47Db	29.53Ab	26.31Bb	26.50	7.33	3.21
Afternoon	32.91Ba	33.67Ba	34.03Ba	35.12ABa	38.15Aa	34.78Ba	34.74	9.33	3.48

Different capital letters in column (A, B), different lower case letters in the line (a, b) differ statistically ($P < 0.05$) by Duncan test. Acronym of the breeds presented in Table 1. CV: coefficient of variation; SD: standard deviation.

Table 3
Means of the components of coat and coat fiber in the ram breeds.

Breed	Coat (cm)			Coat fiber			Skin thickness (mm)
	Wither	T12	Rump	Number cm^2	Diameter (mm)	Length (cm)	
HD	6.06a	3.91a	4.06a	3075a	0.21a	15.97a	5.40c
IF	3.83b	4.33a	3.01b	4450b	0.18a	17.33ab	6.11bc
DR	2.12c	1.33c	1.01c	3532c	0.21a	6.13c	7.43a
TX	9.83d	8.83b	7.83d	3448c	0.24a	19.86b	5.66c
SI	0.76e	0.81c	0.66c	276d	2.17b	2.06d	6.77ab
BE	6.83a	4.33a	4.83e	2571e	0.23a	17.47ab	7.56a
CV	67.85	72.83	74.50	49.20	147.92	55.03	14.00
SD	3.40	2.78	2.61	137.41	0.71	7.14	1.38

Means with different letters in the column differ at 5% level by Duncan test. Acronym for the breeds presented in Table 2. CV: coefficient of variation; SD: standard deviation.

the highest body weight (92.33 kg), wither height (76.16 cm), thoracic circumference (103.00 cm) and body length (95.66 cm).

There was interaction among breed and period for respiratory rate, temperature at the rump measured with an laser thermometer as well as muzzle, axilla and groin temperature measured by thermographic camera (Table 2). The animals showed lower physiological parameters and temperatures at different body sites measured with laser thermometer and thermographic camera in the morning compared to the afternoon (Table 2).

Heart rate (HR) and rectal temperature (RT) were influenced ($P < 0.001$) by breed. The Santa Ines presented the lowest HR (58.50 beats/min) and RT (38.02 °C) while the Texel breed presented the highest values (78.00 beats/min and 39.41 °C, respectively), followed by Ile de France (66.54 beats/min and 39.09 °C, respectively) with no difference among them. Hampshire Down, Bergamasca and Dorper presented intermediate values for these parameters. The coefficient of variation (CV) for heart rate was high (9.89), demonstrating that this trait was more influenced by the environment than rectal temperature (1.26).

The analysis of variance coat and skin traits studied (Table 3) showed a high degree of phenotypic variation among the breeds studied. The lowest average skin thickness was for the Hampshire Down breed (5.40 mm), followed by Texel (5.66 mm), with no difference among them. Breeds that had longer coat included Texel (19.86 cm), Bergamasca (17.47 cm) and Ile de France (17.33 cm), without significant difference among them. The coat length was lowest in Santa Ines (2.06 cm).

The greatest thickness of the coat layer at the withers (9.83 cm), T12 (8.83 193 cm) and rump (7.83 cm) were observed in the Texel. The areas that showed greater separation among the breeds were at the withers and rump.

Table 4
Means of coat and skin pigmentation levels in the ram breeds.

Breed	Coat			Epidermis		
	L	a*	b*	L	a*	b*
HD	46.38ab	−0.96d	5.37b	50.27b	1.12b	7.58b
IF	48.01ab	0.91c	9.68a	56.90a	−0.40cd	6.44cb
DR	52.11a	2.53b	11.85a	58.66a	0.29c	6.16cb
TX	50.31ab	-0.12d	5.58b	58.52a	−1.06de	4.54c
SI	29.01c	4.46a	10.11a	34.31c	3.99a	10.83a
BE	44.71b	0.97c	9.77a	59.50a	−1.27e	4.78c
CV	18.43	149.62	30.24	18.42	437.67	34.27
SD	11.42	2.21	4.12	10.64	2.09	3.95

Means with different letters in the column differ at 5% by Duncan test. Acronym for the breeds presented in Table 2. CV: coefficient of variation; SD: standard deviation.

Table 5
Body temperature (°C) measured with laser thermometer and thermographic camera in the ram breeds.

Breed	Laser thermometer			Thermographic camera		
	Neck	Groin	T12	Body side	Neck	Rump
HD	33.07	36.28a	33.76bc	32.07ab	30.67b	30.48b
IF	34.04	36.44a	33.49cd	31.21b	31.03b	30.88b
DR	33.66	34.43b	32.24d	32.47ab	32.71a	31.79ab
TX	33.88	36.72a	35.59a	33.99ab	30.81b	31.60ab
SI	33.67	34.36b	29.17e	35.01a	34.91a	36.78a
BE	34.11	36.46a	34.94ab	31.75b	31.39b	31.59ab
CV	1.11	3.02	6.90	4.43	5.13	7.16
SD	1.77	1.78	2.92	6.51	4.44	7.31

Means with different letters in the column differ at 5% by Duncan test. Acronym for the breeds presented in Table 2. CV: coefficient of variation; SD: standard deviation.

Table 6
Scrotum and testis measurements in the ram breeds.

Breed	Scrotal circumference (cm)	Testicle (cm)		
		Length	Width	Thickness
TX	29.17d	7.83c	5.67d	10.33d
IF	33.32b	9.32b	6.53ab	11.85b
HD	36.67a	10.33a	6.83a	13.17a
BE	27.00e	9.33b	6.00c	10.33d
DR	33.50b	9.33b	6.33bc	11.83b
SI	31.35c	9.26b	6.18bc	10.97c
CV	10.79	8.66	6.49	9.59
SD	3.65	1.10	0.63	1.26

Means with different letters in the column differ at 5% by Duncan test. Acronym for the breeds presented in Table 2. CV: coefficient of variation; SD: standard deviation.

The lowest average level of coat luminosity (L) was found in Santa Ines (29.01) indicating darker coats with the other breeds having values higher than 44, with the lightest being the Dorper (52.11) (Table 4). The lowest brightness of the skin pigmentation was for Santa Ines (34.31), separating it from the other breeds.

Among the three points measured with the laser thermometer, the point of the body with the highest temperature recorded was the groin (Table 5). The Santa Ines and Dorper breeds had the lowest groin temperatures (34.36 and 34.43 °C, respectively) between breeds. However, these breeds presented the highest neck temperatures (34.91 and 32.71 °C, respectively) measured by thermography.

There were differences ($P < 0.01$) in testicular biometric characteristics among breeds (Table 6). The Hampshire Down had higher values for all testicle measurements. The lowest scrotal circumferences were in the Bergamasca, and lowest testicle length and width in Texel (Table 6).

Testicular temperature was influenced by breed ($P < 0.001$). The highest average scrotal temperatures measured with the laser thermometer were in Texel and Bergamasca and lowest in the Dorper (Table 7).

No differences in testicular temperature were observed at the bottom of the scrotum using thermography among the breeds studied (Table 7). The minimal temperature gradient and the minimal temperature gradient per cm were highest for Texel, Ile de France, Bergamasca and Santa Ines breeds and lowest for Hampishire Down.

4. Discussion

All animals showed lower physiological parameters and body temperatures in the morning compared to the afternoon, as expected, due to favorable environmental conditions.

The Santa Ines breed showed lower respiratory rate compared to other breeds in the afternoon, as well as the lowest temperature at the rump measured with the laser thermometer in the morning period. However this breed showed the highest temperatures at the muzzle, axilla and groin in the afternoon, showing better adaptation to the heat compared to the other breeds through heat loss in these regions.

Commercial breeds (Hampshire Down, Ile de France, Texel and Dorper) were generally heavier, shorter and larger boned than the naturalized breeds (Santa Ines and Bergamasca) as seen by Carneiro et al. (2010). The Hampshire Down was tall while the Texel was shorter and more compact. Skeletal measurements such as body height and length, chest depth and shin measurements are less affected by nutrition and therefore indicate inherent size better than measures such as width and thoracic circumference measurements and body weights, which are thought to be more related to muscle and fat deposition (Kamalzadeh et al., 1998). Taller animals are considered to be more effective in dissipating heat than animals with a short, squat body (Mwacharo et al., 2006).

According to the heart rate ranking defined by Silanikove (2006), the Santa Ines breed showed low stress (40–60 beats/min) while other breeds showed medium-high stress (60–80 beats/min), suggesting a greater challenge in maintaining thermoregulation in the same environmental conditions.

In the present study, the breeds responded to the heat load imposed by the environment, as expected (Marai et al., 2007) with higher respiration used to dissipate body heat.

In this study, hair and skin characteristics showed a high degree of phenotypic variation among the breeds studied. Other authors also found high variation for skin traits in sheep (Jacinto et al., 2004). Coat is related to the animals' adaptation to the environment due to its boundary function, delimiting the animal and the surrounding physical environment (McManus et al., 2011). The breeds studied were of different origins (Dutch, Italian, Brazilian, French, British and South African) so the results indicate that for every breed there were distinct bioclimatic challenges in their origin which led to the development of different morphological characteristics.

Animals with thicker and denser hair have greater difficulty in eliminating latent heat by evaporation through the skin (Holmes, 1981). According to Stone et al. (1992) the thickness of the layer changes the amount of metabolizable energy required for maintenance, as difficulty in releasing latent heat causes the body to use compensatory mechanisms that lead to the transformation of energy, being detrimental to livestock production. Finch et al. (1984) also showed that hairy thick coats were associated with resistance to body heat dissipation. There is a trade off between denser hair to provide better protection from solar radiation, but this hinders heat loss. Castanheira et al. (2010) showed that hair reflectance, as well as hair length and number of hairs per unit area, were the most useful in explaining changes in physiological traits in sheep.

Table 7
Average values of temperature (°C) of the scrotum and testicles in the ram breeds using laser thermometer and thermographic camera.

Breed	Laser	Thermographic camera					Temperature gradient (°C)	Temperature gradient per cm (°C/cm)
		Top	Bottom	Left	Right	Central		
TX	32.50a	35.23a	30.84	33.34a	33.42a	34.03a	4.38ab	0.56a
IF	30.19b	34.21a	30.09	32.24ab	31.46bc	32.39b	4.18ab	0.45ab
HD	29.67cb	31.54b	30.56	31.74bc	31.79bc	31.89b	0.98c	0.09c
BE	31.63a	35.49a	30.66	31.58bc	32.68ab	33.17ab	4.83a	0.53a
DR	28.71c	32.62b	29.49	30.73c	30.90c	31.81b	3.13b	0.34b
SI	29.70bc	34.47a	30.41	32.26ab	32.66ab	32.88ab	4.13ab	0.44ab
CV	4.61	4.55	1.60	2.71	2.89	2.58	4.98	22.16
SD	2.24	2.69	2.04	1.95	2.12	2.06	2.18	0.25

Means with different letters in the column differ at 5% by Duncan test. Acronym for the breeds presented in Table 2. CV: coefficient of variation; SD: standard deviation.

McManus et al. (2009) found that brown and black Santa Ines ewes are less well adapted to high ambient temperatures compared to white ewes of the same breed as they had thicker skin, longer hair and fewer sweat glands. This was reflected in lower rectal temperatures and respiratory rates at higher ambient temperatures in white coated animals. All Santa Ines animals of the present study were black coated.

In addition to dark hair, Santa Ines rams had dark skin, similar to that observed by Veríssimo et al. (2009) and McManus et al. (2009). Although the reflection is higher in lighter coloured skin, for this to be beneficial, the epidermis must be pigmented and covered with dense hair (Paim et al., 2013). The combination of light hair with dark skin is the most desirable alternative, because of the need to block intense ultraviolet sunlight in the tropics. Sheep with dark hair have more pigmented skin unlike some tropical cattle breeds where light hair is associated with darker skin (McManus et al., 2009). Light skins have a higher radiation transmission through a surface that can cause skin lesions, but have lower absorption of thermal radiation (Silva and Pocay, 2001).

Ile de France, Bergamasca, Dorper and Santa Ines have greater ability to reflect light, which facilitates the exchange of heat when evaluating the hair component. One possible explanation may be that melanin pigment is yellowish brown. The skin of animals allocated in the positive group has greater ability to block the deleterious effects of ultraviolet rays. The influence of breed was observed in all levels of pigmentation of skin and hair.

The point of the body with the highest temperature recorded with the laser thermometer was the groin. The groin region is highly vascularized showing high temperatures (McCutcheon and Geor, 2008). In Santa Ines and Dorper breeds the temperatures of the groin were the lowest when comparing breeds. This suggests a possible influence of coat type on the heat radiation, because these breeds had no wool.

Scrotal circumference is the most common measure of scrotal size and is important at the time of selection of rams presenting a positive correlation with testicular and body weight, exhibiting high correlations with production and sperm quality (Braun et al., 1980; Langford et al., 1989).

In most breeds the thermography temperature of the top of the scrotum, near the body, was higher than at other points measured, showing that there is a temperature gradient that decreases from the body of the animal to the bottom of the testicle. This can be attributed to the cone-shaped vasculature of this organ, with greater heat dissipation near the body. Therefore, infrared thermography can adequately assess scrotal temperature gradients related to semen quality corroborating with Ramires Neto et al. (2011) who observed that the measurement of the heat radiated by the scrotum using infrared thermography in rams has been a powerful tool for characterizing scrotal surface temperature in the testicular and epididymal tail regions.

5. Conclusions

The Santa Ines breed has favorable body traits for sheep production in the tropics, losing heat through physiological mechanisms (heart and respiratory rates and rectal temperature) and offers pigmentation of hair and skin that are compatible with better thermoregulation. These traits should not be used alone to determine heat stress in sheep due to their low correlations with rectal temperature and respiratory frequency. Infrared thermography can adequately assess scrotal temperature gradients in sheep and identify breeds that are more or less heat tolerant.

Conflict of interest

The authors declare that they have no conflict of interest.

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