



Efficiency of infrared pyrometer and infrared thermography for assessing body surface temperature in hair sheep

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ABSTRACT

The objectives of this study were: (i) to verify and compare the coat surface temperature (CST) of regions of interest (ROI) measured through infrared pyrometer (IRP) and thermography (IRT) under two environmental conditions, to evaluate (ii) reliability and (iii) sensitivity of the two infrared equipments to the environmental effect. Twenty hair ewes (*Ovis aries*), multiparous, non-lactating, non-pregnant, with body weight 59.38 ± 6.23 kg and body score condition ranging from 2.5 to 4.5 were evaluated. All CST, in both infrared methods, were higher ($P < 0.001$) in the afternoon (2 to 3 p.m.), with the exception of eyes surface temperature (TSEY) from IRT, which was higher ($P < 0.001$) in the morning (8 to 9 a.m.). Regarding the infrared methods at different times (twice a day, morning and afternoon), of the day, CST values for all ROIs were significantly higher ($P < 0.001$) in thermography, regardless of the time shift, except for ear pinna surface temperature (TSE) and rectum surface temperature (TSR), which showed no significant difference ($P > 0.05$) between the infrared methods during the morning shift. The thermal environment significantly influences ($P < 0.001$) the surface temperature of various anatomical regions in both infrared methods. The correlation coefficients between IRT and IRP were moderate. The IRT is more sensitive to the thermal environment, as it presented higher canonical coefficients in the environmental variables. Among surface temperatures, eye surface temperature is the most influenced by variables in the thermal environment, especially THI. All three methods (digital thermometer-DT, IRT and IRP) showed $>80\%$ of the data variation in the first two components. Using the DT, we observed an association between vaginal temperature (VT) and RT with air temperature (AT) and temperature humidity index (THI), which was similar to the infrared thermography pattern, in which all ROIs were highly correlated with AT and THI. The opposite was observed in the pyrometer, in which an association between eye temperature and RH and lower factor loadings of the other ROIs with AT and THI in the first component was observed. In conclusion, while IRP and IRT showed similar performance in the morning, IRT proved to be more accurate in the afternoon, demonstrating a higher success rate in classifying the group of origin. Therefore, it is concluded that IRT is more reliable than IRP in detecting surface temperature changes under high temperatures.

1. Introduction

Innovative technologies contribute to the advancement in animal

research, allowing the development of equipment, processes and services for the application of the precision livestock farming concept (Chacur et al., 2016). Due to its rapid advance in the last decade, the

Abbreviations: A_T , Air temperature; CST, Coat surface temperature; ICC, Intra correlations coefficients; IR, Redundancy index; IRP, Infrared thermometric pyrometric; IRT, Infrared thermometric; KMO, Kaiser-Meyer-Olkin; R^2c , Square canonical correlation; R_{RH} , Relative humidity; ROI, regions of interest; RT, Rectal temperature; SD, standard deviation; ST, Surface temperature; T_{DB} , Dry bulb temperature; T_{RH} , Temperature Humidity Index; T_{WB} , Wet bulb temperature; T_{SR} , Rectum surface temperature; T_{SV} , Vulva surface temperature; T_{SM} , Muzzle surface temperature; T_{SEY} , Eyes surface temperature; T_{SE} , Ear pinna surface temperature; V_T , Vaginal temperature.

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development of healthy livestock and animal welfare have been vigorously pursued, since the computerization of livestock requires a precise and real-time understanding of the animals' physiological status (Wathes et al., 2008).

Among the thermoregulatory responses and the health status of the animals, internal body temperature is the most reliable physiological indicator (de Castro Júnior and da Silva, 2021; Silveira et al., 2021a), as it directly demonstrates situations of pyrexia and the instant condition of homeostatic regulation (Giro et al., 2019). Endothermic animals regulate their body temperature through a process of heat inter-change between the amount produced by metabolism and the environment. The control of heat exchange between body surface and external environment plays a very important role in regulation of body temperature during different physiological phases and/or activities throughout the life cycles of homeotherms. The variations in environmental temperature and humidity, alongside with a variety of physiological situations including age, fasting and food intake, stress circumstances and inflammation status induce changes in internal temperature which are followed by changes in body surface temperature in production and companion animals (Arfuso et al., 2022; Giannetto et al., 2022; Giannetto et al., 2020; Sousa et al., 2013).

Traditionally, the main method of measuring internal body temperature is through digital thermometers, but this practice requires relocating animals to specific facilities, which can result in increased body temperature (Lees et al., 2018). Recently, infrared radiation has been adopted as an efficient and non-invasive method to measure the animals' body temperature, and has been used in identifying the estrous cycle phase (de Freitas et al., 2018a, 2018b), phenotypic plasticity (Castro et al., 2020), mammary gland health (Zaninelli et al., 2018), response to transport in horses (Aragona et al., 2024), stress response in sheep (Arfuso et al., 2022) and mineral supplementation (Silveira et al., 2021b).

Infrared pyrometer (I_{RP}) and thermography (I_{RT}) are the two main commercial equipment's which detect infrared radiation emitted or reflected by materials, and convert the energy factor into a temperature reading (McManus et al., 2016). However, I_{RT} has several advantages over I_{RP} : 1) the pyrometer provides only one number \times the thermographic cameras generate an image and 2) the pyrometer reads the temperature from a single point \times a thermographic camera provides temperature readings for each pixel of the entire thermographic image.

Therefore, the evaluation of surface temperature through I_{RT} , a non-invasive technique which allows to obtain images of a specific body region at a distance, represents a valuable tool to monitor the physiologic status, welfare and the stress responses of animals. (Aragona et al., 2024; Arfuso et al., 2016; McManus et al., 2016). The use of I_{RT} and I_{RP} in animal production is innovative, low cost, quick measuring, non-destructive, and measures the temperature with no need for physical contact with animals (McManus et al., 2016). Some studies reveal that I_{RT} even allows detection of minor changes in temperature with precision (Salles et al., 2016; Lees et al., 2018) with a positive and significant correlation with rectal temperature (George et al., 2014); however, this technology is very sensitive to environmental fluctuations. For de Freitas et al. (2018a, 2018b), the environmental effects can be minimized by inserting the temperature and humidity of the environment in the camera before the images are obtained or considering these environmental factors in the statistical model of the study.

There are several investigations evaluating the use of I_{RT} (Giro et al., 2019; Peng et al., 2019; Maley et al., 2020), but no studies have evaluated the effectiveness of I_{RP} in detecting the body temperature of animals. Although they operate with the same physical principle, do both equipments show similarities regarding the animals' body temperature? Which equipment is more sensitive to environmental effects?

The objectives of this study were (i) to verify and compare the coat surface temperature (C_{ST}) of regions of interest (ROI) measured through I_{RP} and I_{RT} under two environmental conditions, to evaluate (ii) reliability and (iii) sensitivity of the two infrared equipments to the

environmental effect.

2. Material and methods

2.1. Study site and animals

The study was carried out in February and March 2016 at the Animal Reproduction and Genetic Improvement Laboratory of the Norte Fluminense State University- UENF located in Campos dos Goytacazes city, Rio de Janeiro, Brazil (22° 54' 13" N, 43° 12' 35" E, 20 m sea.). In this region, February and March correspond to the summer season and the average of air temperature, relative humidity and rainfall from 2011 to 2016 were 28.2 °C, 73.2 % and 98.8 mm. months⁻¹, respectively (Alvares et al., 2013).

Twenty (20) Santa Inês hair ewes, multiparous, non-lactating, non-pregnant, body weight (B_w) 59.38 ± 6.23 kg and body score condition ranging from 2.5 to 4.5 (Russel, 1984) were assessed. Genetic variability in these animals is naturally low because it is a small herd and new animals are seldom added; however, we believe that this does not influence the interpretation of the data. Animals did not lose or gain weight during the experimental period.

2.2. Management and facilities

The ewes were reared in a semi-extensive system, in which during the morning they were kept in natural pasture (*Cynodon* spp.), and in the afternoon they were housed in a covered rectangular facility (6 m length \times 2 m width \times 3 m high). Mineral supplementation and water were available ad libitum.

2.3. Data collection

The C_{ST} (°C) were measured during 10 consecutive days (D -14 to D -5) as shown in the experimental design by de Freitas et al. (2018b). These days were selected because the animals were in the same physiological condition (uniformity of the estrous cycle provided by the presence of a progesterone implant), thus limiting the interference of the reproductive cycle on body temperature. Before data collection, the ewes were placed individually inside the facility 30 min prior to the temperature measurements in order to avoid exposure to the sun and subsequent changes in temperature. Response measurements were carried out in the morning (8 to 9 a.m.) and in the afternoon (2 to 3 p.m.) shifts (based on the semi-intensive herd management system), alongside with environmental variables measurements. The animals in this study were used to daily handling from birth, so this was not a stressing factor for the animals.

2.3.1. Environmental variables and thermal comfort index

Air temperature (A_T ; °C) or dry bulb temperature (T_{DB} , °C), wet bulb globe temperature (T_{WB} , °C) and relative humidity (R_H , %) were recorded daily with the use of a Heat Stress WBGT Meter (HT30, Exttech®, Nashua, New Hampshire, USA). The instrument was always used inside the facility where the ewes were evaluated, with no direct exposure to the sun. Based on these data, the Temperature Humidity Index (T_{HI}) was calculated using the following eq. 1 (NRC, 1972).

$$THI = (DBT + WBT) \times 0.76 + 40.6 \quad (1)$$

In which:

DBT- dry bulb temperature (°C) and WBT- wet bulb temperature (°C).

2.3.2. Thermoregulatory responses

Rectal (R_T ; °C) and vaginal (V_T ; °C) temperatures were measured with a Med® digital thermometer (D_T) (accuracy of ± 0.1 °C; Cotronic Technology Ltd., Shatin, Hong Kong, Chinese) inserted in the rectum and vagina, respectively, at a depth of three centimeters until the

thermometer stabilized.

2.3.3. Coat surface temperature

2.3.3.1. Infrared pyrometer. The C_{ST} of the eyes was measured with a distance of 5 cm, while for the rest of the regions (rectum, vulva, muzzle and ear pinna) a distance of at least 30 cm was adopted. The measurements were performed with an I_{RP} (accuracy of ± 1 °C, minimum of -60 °C and maximum of 760 °C, TD 965, *ICEL, Manaus, Amazonas, Brazil*). Thermal emissivity is 0.95, sampling of 140 μ m, spectral responses of 8–14, distance factor of 1:12 according to the instruction manual (<http://www.icel-manaus.com.br>).

2.3.3.2. Infrared thermographic. The C_{ST} of the vulva, rectum, eyes, ear pinna and muzzle were measured with an IRT (FLIR®series i50; FLIR Systems Co. Ltd., Shatin, Hong Kong, Chinese). The images were captured at a distance of 1 m from the animal, with emissivity of 0.98 (Talukder et al., 2015) and rainbow palette. The camera was inclined so the image could be best visualized on the monitor. The perineal region was gently wiped with dry paper towels in order to remove fecal matter and moisture. The images were transferred to a computer and analyzed with the Flir Quickreport® version 1.2 SP2 (1.0.1.217) 2009 software. In the program, we selected the assessment regions (around the rectum and in the central part of the vulva, muzzle, eye, and ear pinna) with the area tool, represented by the smallest square. This tool identifies maximum, minimum and mean temperature for the selected thermogram area. The mean temperature was analyzed in each anatomical region, in each captured image. During the evaluation of the images with the software, it was necessary to change the color palette (initially the rainbow palette), to sharpen the definition of each structure. For evaluation of the rectum and vulva, the “rain hi” palette was used; for evaluation of the muzzle, “inverted gray” was used, for evaluation of the eye, “gray” was used, and for the ear, “inverted gray” was used. The saturation of the images was changed several times in order to make some areas more evident. The changes in the color palettes did not alter the temperature readings.

2.4. Statistical methods

The statistical methods used in this study were divided into six steps. The collected data were processed and analyzed using SPSS® (SPSS, 2012) and SAS® OnDemand (SAS Documentation, 2015).

Step 1 [Data curation] Exploratory analyzes were performed with all the variables under study. The univariate outliers were identified in the two databases using boxplots (\pm three standard deviations from the mean) and then imputed by the median of each variable. Univariate normality was verified using a distribution histogram. Furthermore, data normality and homoscedasticity were assessed using the Shapiro Wilk and Levenne tests, respectively.

Step 2 [Correction] The C_{ST} s of the two infrared methods were corrected (y_{corr}) according to the expression:

$$y_{corr} = y - \sum_{i=1}^4 \hat{\beta}(x_i - \bar{x}) \quad (2)$$

Step 3 [Statistical design] The environmental variables and ST s of the ROI of both infrared methods were subjected to ANOVA repeated measurements, using a general linear model, and the means were compared using the Tukey test ($P < 0.05$). The effect of the day shift (morning and afternoon) and infrared methods (I_{RP} e I_{RT}) were considered as fixed effects.

Step 4 [Methods Validation] The paired t -test was used to compare the differences between temperatures in the two infrared methods in both shifts of the day. The limits of agreement between the I_{RP} and I_{RT} surface temperature value pairs were determined according to the method suggested by Bland and Altman (1986). The intraclass

correlation coefficient (ICC) was used as a measurement of reliability between pairs of C_{ST} s values of the two methods (I_{RP} and I_{RT}). The following classification of the ICC values was used (Weir, 2005): values from 1.00 to 0.81 (excellent reproducibility), 0.80 to 0.61 (very good), 0.60 to 0.41 (good), 0.40 to 0.21 (reasonable), and 0.20 to 0.00 (poor).

Step 5 [Association between variables] Canonical correlation analysis (C_{CA}) was performed to determine the magnitude of the relationships between the variables of the thermal environment and the ST of ROI the two infrared methods. The ST of the ROI with no environmental correction (Step 2) was considered a dependent variable, whereas A_T , R_H , T_{HI} were considered independent variables. Standardized canonical loads were used to define which variables are most important in canonical correlations. We calculated square canonical correlation (R^2c) in order to determine the influence of the thermal environment on the special temperatures according to the infrared method. Finally, principal component analysis (P_{CA}) was performed to analyze relationships between the thermoregulatory responses, thermal environment and C_{ST} of the ROI of both methods in order to explain the relationship between these variables. The adequacy of the KMO sample was $PCA_{DT} = 0.681$; $PCA_{IRT} = 0.87$, and $PCA_{IRP} = 0.76$ and Bartlett’s sphericity test was significant ($P < 0.001$) in both PCA. The first two principal components (PC) were considered, and the PC matrix was developed using orthogonal rotation, varimax method.

Step 6 [Differentiation of the methods/ day shifts] The canonical discriminant analysis (CDA) was used to differentiate the dynamics of ST according to the infrared methods and the day shifts. The discriminating power of the variables was assessed by the value of Wilks’ Lambda statistic, eigenvalues of the discriminating functions, P -value, canonical correlations and the standardized canonical discriminating coefficients. The CDA was performed by the simultaneous procedure considering the inclusion of all variables that are explanatory together in the model.

3. Results

The variables which characterize the thermal environment according to the day shifts are shown in Table 1. A_T and T_{HI} were higher ($P < 0.001$) in the afternoon, while R_H was higher ($P < 0.001$) in the morning. It is inferred, therefore, that we can test our hypotheses, since the thermal environment was different in both day shifts.

The shift effect and infrared method for the C_{ST} of ROI s is shown in the Fig. 1. All C_{ST} , in both infrared methods, were higher ($P < 0.001$) in the afternoon, with the exception of TSEYES from I_{RT} which was higher ($P < 0.001$) in the morning. In relation to the infrared methods according to the shifts of the day, all C_{ST} of the ROI s were higher ($P < 0.001$) in thermography regardless of the shift, with the exception of TSE and TSR which were equal ($P > 0.05$) between the infrared methods during the morning shift.

The Bland – Altman plots (Fig. 2) show the limits of 95 % agreement between the two infrared methods in both shifts: rectum (morning = -1.92 ± 0.84 °C and afternoon = -0.092 ± 1.00 °C); vulva (morning = -1.41 ± 1.00 °C and afternoon = -1.37 ± 1.05 °C); snout (morning = -2.18 ± 1.43 °C and afternoon = -1.98 ± 1.25 °C); eye (morning = -1.42 ± 0.84 °C and afternoon = -1.21 ± 0.94 °C) and ear (morning = -4.47 ± 2.50 °C and afternoon = -3.56 ± 2.19 °C).

The intraclass correlation analysis (ICC; Fig. 3) between I_{RT} and I_{RP} , in both shifts of the day, for measuring TSV, SST and TSEY revealed very

Table 1
Meteorological variables and thermal comfort index recorded during the experimental period.

Variables	Morning	Afternoon	\pm Standard deviation	P-value
Air temperature (°C)	27.47	30.33	1.85	$P < 0.001$
Relative humidity (%)	79.82	67.63	8.44	$P < 0.001$
Temperature Humidity Index	78.90	81.92	2.07	$P < 0.001$

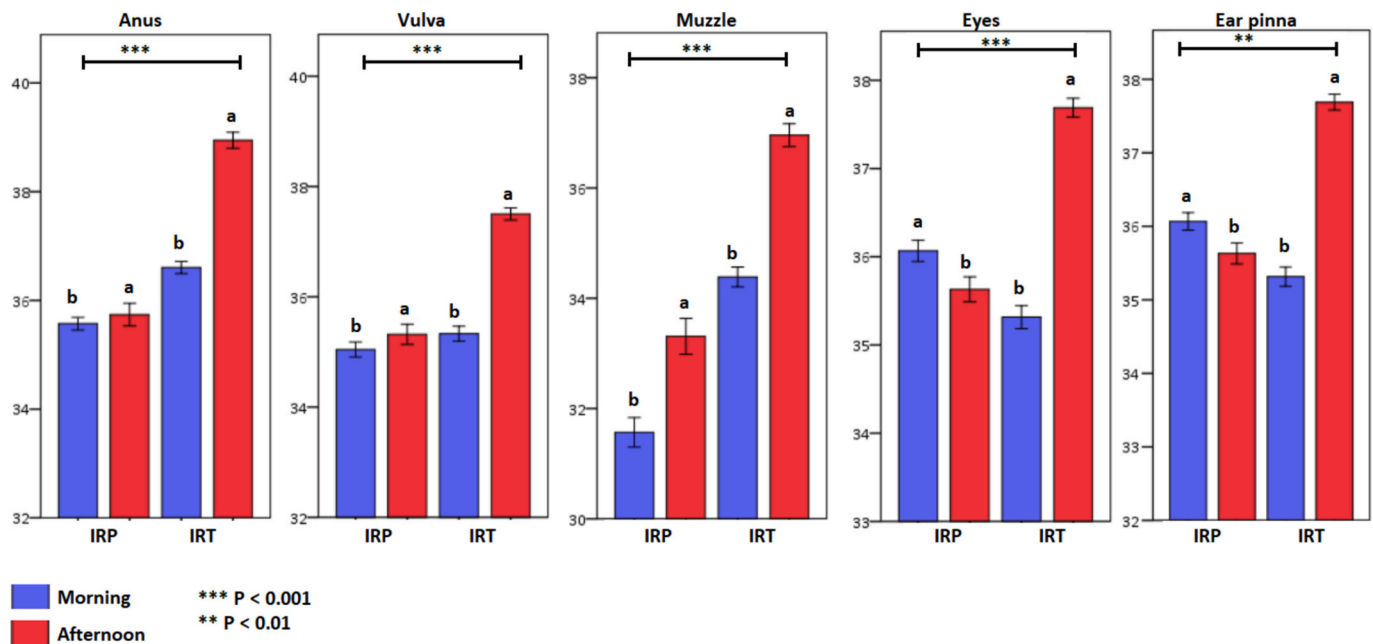


Fig. 1. Mean and standard deviation (\pm SD) of the surface temperatures of different body regions of two methods of infrared temperature in ewes in tropical region. Variations between shifts and within shifts for equipment were assessed using the Tukey Test ($P < 0.05$).

good reproducibility (> 0.60 ICC < 0.80) and good for TSE; whereas for TSR it was very good in the morning, but acceptable in the afternoon. The ICC coefficients between the three methods, without considering the shift effect, are presented in Fig. 4. The reproducibility between IRT and IRP is excellent; however, when comparing the digital thermometer with both infrared methods, it showed good reproducibility ($\geq 0.4 \leq 0.6$).

The thermal environment influences ($P < 0.001$) the surface temperature of different anatomical regions in both infrared methods (Fig. 5). The correlation coefficients were moderate (IRT = 0.51 and IRP = 0.63). The IRT is more sensitive to the thermal environment, as it presented higher r_c coefficients in the environmental variables. Among surface temperatures, the temperature of the eye is the one most influenced by variables in the thermal environment, especially THI.

The association of thermoregulatory responses and environmental variables according to the measurement method is shown in Fig. 6. All three methods presented $>80\%$ of the data variation in the first two components. Using the digital thermometer, we observed an association between VT and RT with AT and THI, which was similar to the infrared thermography pattern, in which all ROIs were highly correlated with AT and THI. The opposite was observed in the pyrometer, in which an association between eye temperature and RH and lower factor loadings of the other ROIs with AT and THI in the first component was observed.

The first two discriminatory functions were significant ($P < 0.01$) and explained 86.88 % of the differences between infrared/dayshift methods with a high canonical correlation ($0.71 \leq r_c \leq 0.79$) (Fig. 7). TSR discriminates 52.4 % and eye surface temperature 31.88 %. Vulvar temperature did not show discriminating power. We observed, through the centroid, a similarity between the IRP and IRT in the morning shift; however, in the afternoon this response was different, in which the IRT distanced itself from the IRP with a higher percentage of success in classifying the group of origin, that is, the IRT is more accurate at high temperatures.

4. Discussion

Given the importance of thermoregulation in livestock, particularly in the context of climate change, and the increasing use of precision livestock measurement technologies, this study is one of the first to compare surface temperature measurement methods using an infrared

pyrometer and a thermographic camera in production animals. While both methods operate on the same physical principle, the pyrometer measures temperature at a single point, while infrared thermography captures temperature across multiple pixels, creating a thermal image that allows for detailed body mapping and a better understanding of temperature dynamic.

Clear differences in meteorological parameters and thermal comfort indices were observed between shifts throughout the day across different ROIs. Interestingly, however, measurements taken from the anus, vulva, and snout using IRP showed lower variation during the hottest period of the day compared to IRT. This observation leads to practical conclusions that there are dynamics of body heat flow in animals in different anatomical regions, and that equipments, even based on the same physical principles, operate differently in capturing temperature. Of all the ROIs, only the eyes and ear (measurements which were equal between methods depending on the shifts) followed the same response pattern with higher temperatures in the afternoon when compared to the morning shift, while the other parts presented opposite results between methods, which may be justified because the IRP is not efficient in cartilage regions (ear - no blood circulation) and in the eyes; this can be explained because it measures only a single point, so the infrared radiation from IRP in the eyes can cause nictation in the animal, compromising collection efficiency. The higher temperature values for the ROIs compared to the IRT methods are explained by the better precision of their measurement of the animal's body temperature, while the highest values in the afternoon for ROI temperatures are associated with the highest values in the THI in tropical climates (Castro et al., 2020).

Although rectal temperature values are higher in summer, they are close to the variation range for sheep (38.5°C to 39.9°C), confirming the efficiency of IRT (Robinson, 2008). Unlike a Pyrometer target point, which only provides a single number, the camera image allows for more detailed analysis depending on the observed region, providing temperature readings for each pixel and facilitating rapid inspection of large areas. Infrared thermography is increasingly relevant as a safe method, as it has a greater range of distance from the target. The difference in distance from the target is notable, given that a pyrometer is capable of measuring a 1 cm target at a distance between 10 and 50 cm. The thermal camera can accurately measure the temperature of a target of

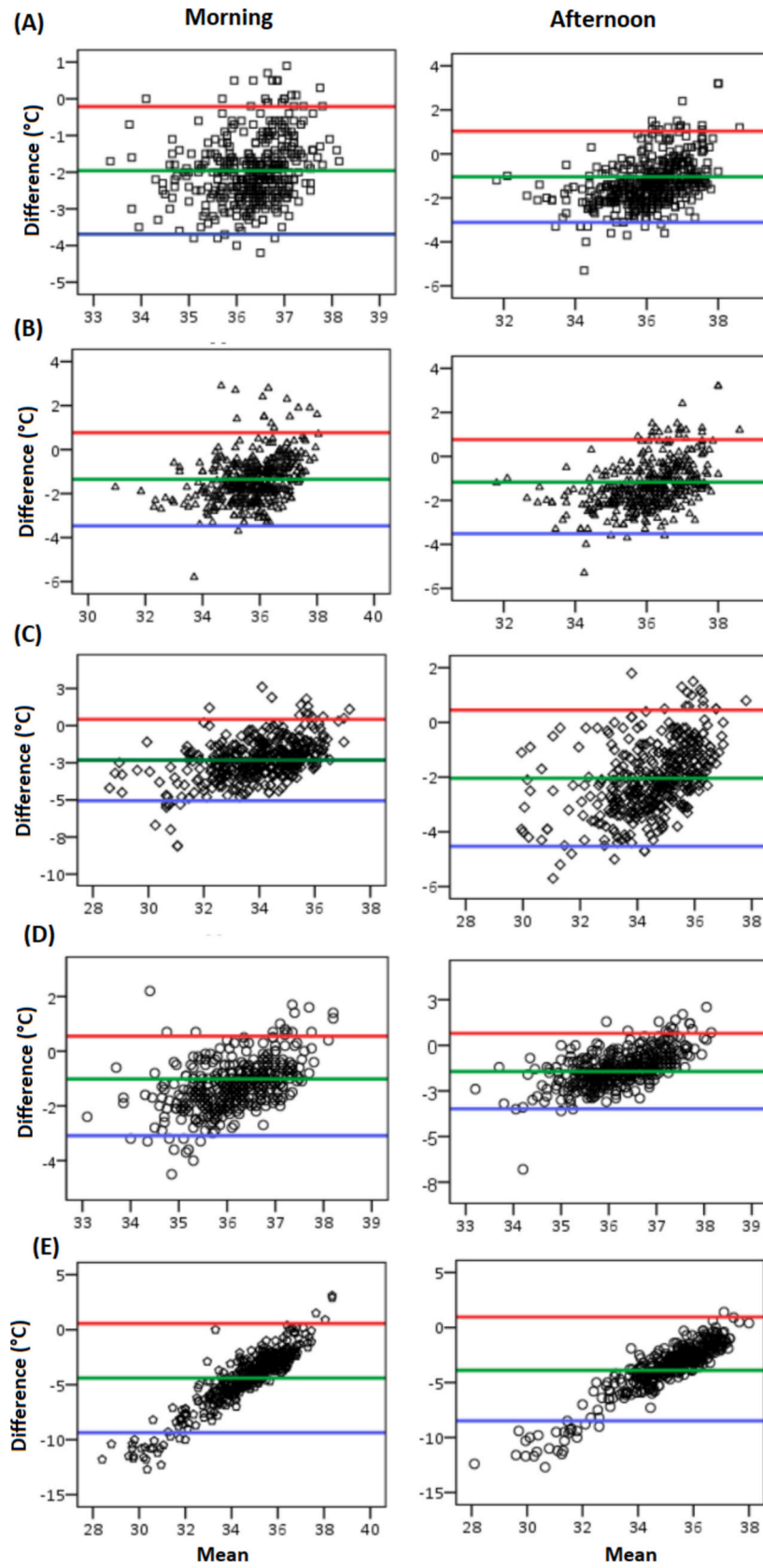


Fig. 2. The Bland - Altman graph with 95 % concordance limits illustrates the difference in the surface temperature measurements of the different anatomical regions for the two infrared methods. (A = Anus; B = Vulva; C = Muzzle, D = Eyes and E = Ear pinna).

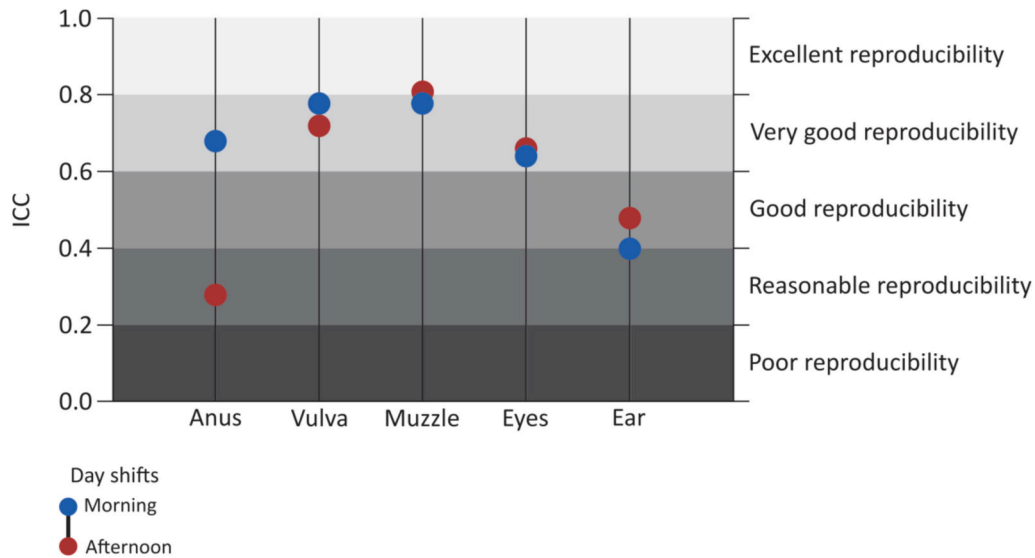


Fig. 3. Intra-class correlation coefficients (ICC) between infrared pyrometer (IRP) and infrared thermographic (IRT) in the morning and afternoon shifts.

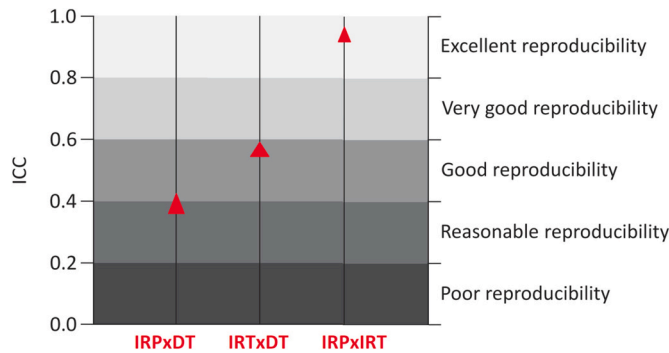


Fig. 4. Intra-class correlation coefficients (ICC) between infrared pyrometer (IRP), infrared thermographic (IRT), and digital thermometer (DT).

this size (1 cm) several meters away. IRT is non-invasive and capable of analysis in different areas (Graciano, 2013).

The analysis of agreement limits between infrared methods indicates the ideal measurement shift for different anatomical regions. Altman plots show that the eyes and anus are the best regions for evaluation, as they are less influenced by environmental variations and present lower CST values. The most consistent results occurred in the afternoon, but the morning measurements for these regions still remained within acceptable agreement limits (Zaki et al., 2012). High environmental temperatures and solar radiation cause variations in blood flow, leading to peripheral vasodilation, which helps maintain consistent measurements (Athaide et al., 2015).

The intraclass correlation coefficients (ICC) indicate good to excellent reproducibility between methods and a greater sensitivity of the IRT to the thermal environment. The method confirms reliability through repeated analyzes in their respective shifts and anatomical regions according to each measurement method. It is also noteworthy, as with other analysis methods, that in the ability to reproduce tests, some factors are taken into account, such as the accessibility of the animal's anatomical region. In this context, in terms of reproduction of methods, the regions which stand out are: Muzzle in the afternoon shift, Vulva in the morning shift and Eyes in the afternoon shift. The excellent reproducibility between IRT and IRP suggests that both methods are consistent in measuring CST; however, the issue of pixel variety and distance measurement capacity must be taken into account, as previously mentioned, which also favors IRT.

The low reproducibility between the digital thermometer and infrared methods can be attributed to the different measurement methods and objectives, as the thermometer performs body measurement and not CST measurement compared to the imaging approach of infrared devices, (Bouzida et al., 2009).

The canonical relationship between eye temperature and THI is explained because out of all the anatomical regions under study, the eyes present the closest temperature approximation = close to the ideal (real temperature) for measuring and predicting physiological changes between CST, being justified due to the high variability of CST when exposed to environmental changes (Johnson et al., 2011). Cook et al. (2001) highlighted that the eyes may have localized thermal regulation. The fact that the eyes have high vascularization means that thermal anomalies can be detected more effectively. When combined with the hypothalamic-pituitary-adrenocortical (HPA) axis, responsible for eye health mainly in sheep, it allows metabolic activity controlling the maximum temperature of the eye, allowing a more accurate measurement of physiological temperature in the heat. Furthermore, other temperature regions may interfere with the animal's hair, while the ear does not have vascularization, therefore, eye temperature is an indicator of the temperature of the animal's central core.

In the association between thermoregulatory responses and environmental variables (Fig. 6), we can observe similarities and differences between the measurement methods. Although DT presents similar components to IRT, a more uniform response pattern or correlation was observed in IRT. The IRP, on the other hand, presents a less centralized response pattern of the analyzed variables, making it difficult to understand the temperature measurement correlation. As the IRT has a greater relationship not only with the environment, but also with the CST, when measuring across an area, a relationship with the ROI can be observed, explained by the better precision of temperature measurement by the thermographic camera. Physiologically, the association of temperatures with environmental data is justified because animals are a thermodynamic system, which means they regulate their temperature depending on the environment, so the association of parameters will occur through the dilation of the small blood vessels in the skin, which allows greater blood flow to peripheral tissues resulting in balance or heat transfer between the body and the environment through the effectiveness of the convective pathway (Shilja et al., 2016; de Vasconcelos et al., 2019, 2020). However, with the point pyrometer, convergent results appear, for example, an association between RH and eye temperature, which demonstrates how inefficient this method is for measuring the temperature of the animals' eyes. A more dispersed

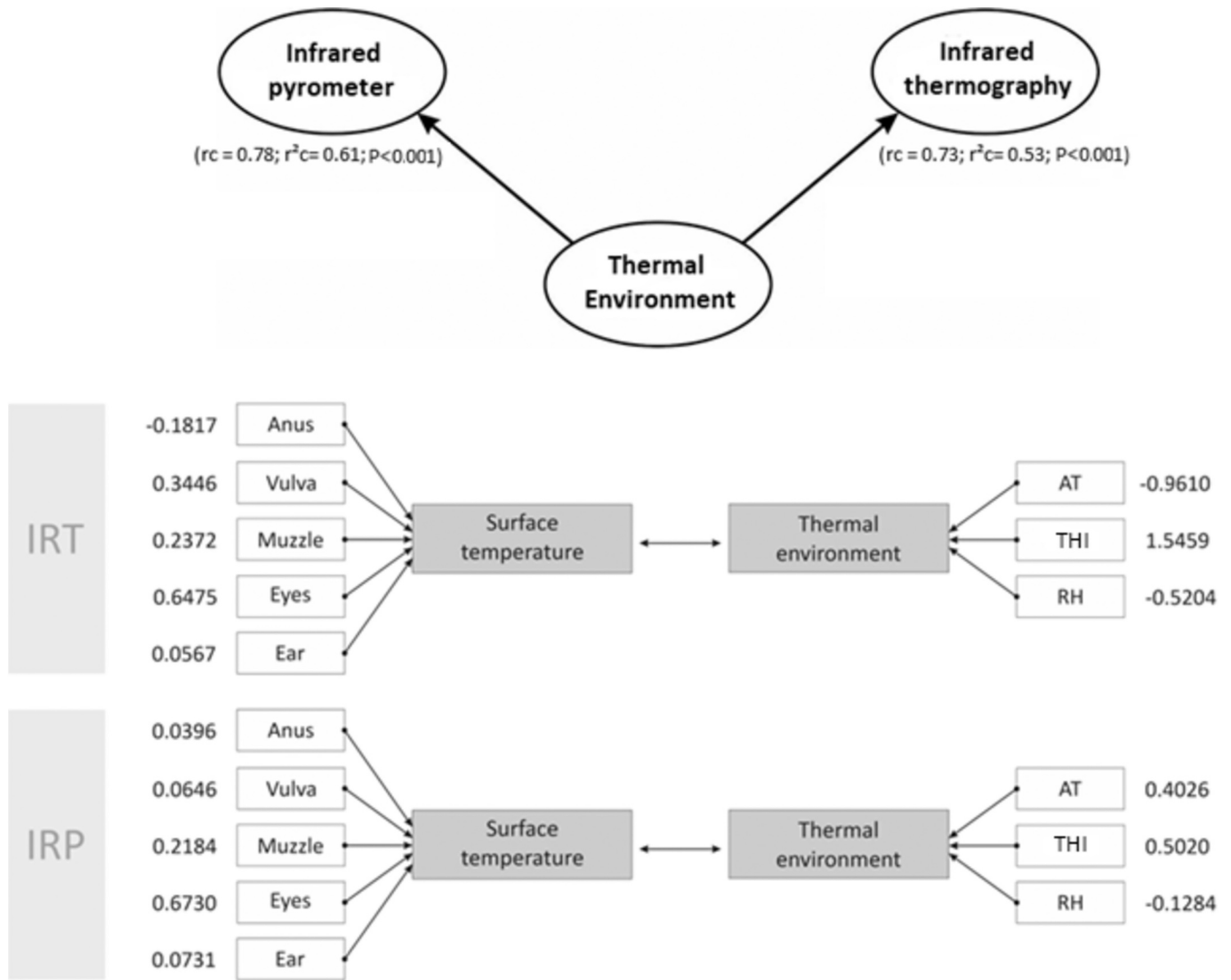


Fig. 5. Graphical representation of the first canonical function of the relationship between the surface temperature of the different anatomic regions and thermal environment.

Thermal environmental: air temperature (A_T , °C), relative humidity (R_H , %), Temperature humidity index (THI).

Surface temperature: Anus (°C), Vulva (°C), Muzzle (°C), Eyes (°C), Ear (°C).

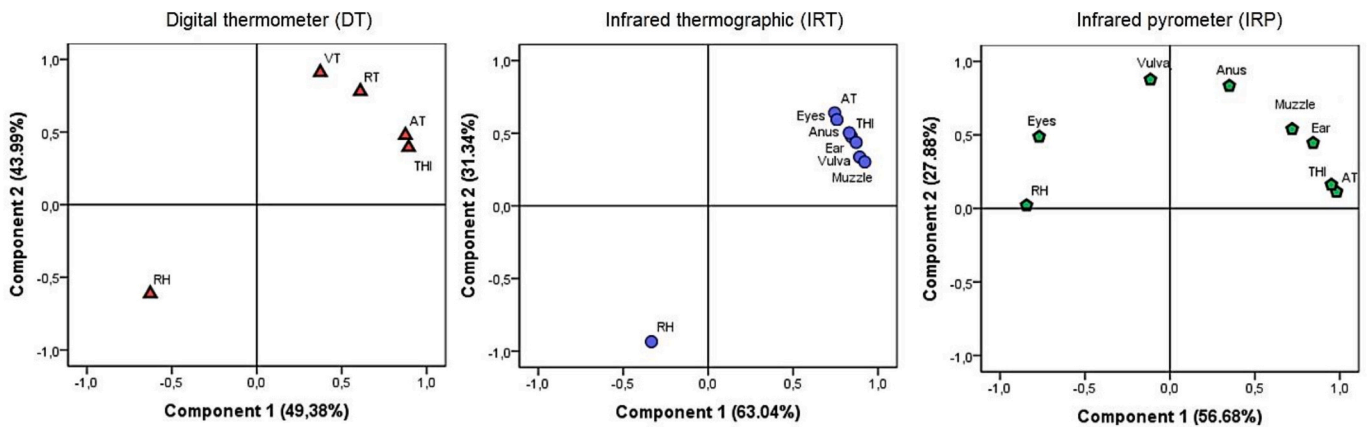


Fig. 6. Biplot of the thermoregulatory responses and surface temperatures of the different body regions of ewes together with the variables of the thermal environment according to the pyrometer and the thermographic.

Thermoregulatory response: Rectal temperature (°C) and Vagina temperature (°C); *Surface temperatures:* Muzzle (°C), Ear (°C), Eyes (°C), Rectum (°C) and Vulva (°C); *Thermal environment:* Air temperature (A_T , °C), Relative humidity (R_H , %), Temperature Humidity Index (T_{HI}).

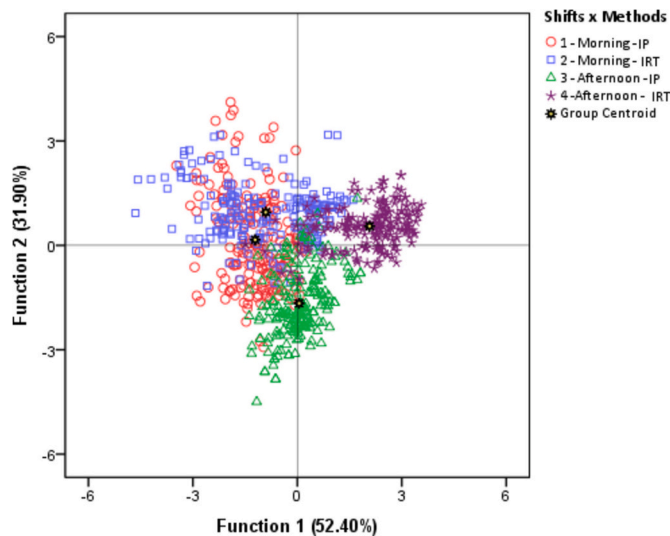


Fig. 7. Dynamics of surface temperatures of different anatomical regions of ewes according to the infrared method /day shift.

response pattern is also observed in IRP, which is justified by its lower precision in measuring the animals' body temperature when compared to IRT.

The differences between the methods and shifts throughout the day are presented through canonical discriminant analysis. We observed that in the morning shift, both IRP and IRT can accurately measure the TSCs, as the points intersect with each other and the centroids are close together. The greater accuracy of the IRT in measuring the TSCs is evident in the afternoon, here, the values between equipment are distant (from their centroids), which means that the environmental temperatures were higher and only the IRT monitored these variations efficiently, which suggests that IRT is more accurate at high temperatures, compared to IRP, demonstrating its effectiveness in more challenging environmental conditions and its technical superiority as TSC measuring equipment.

5. Conclusion

The IRP and IRT have good agreement and reproducibility, but in IRT the sensitivity is greater, allowing better measurement and greater precision in situations of high thermal conditions, especially in regions with hair. The IRP is not recommended for measuring the eye and ear temperature of animals.

This research contributes valuable information to the area of precision livestock, providing guidance on the best choices and ideal methods for better measuring body surface temperature in relation to the environment. It is important to understand and recognize the nature of this research due to its samples, weather conditions, and study limitations.

CRediT authorship contribution statement

Wilder Hernando Ortiz Vega: Formal analysis, Conceptualization. **Robson Mateus Freitas Silveira:** Formal analysis, Data curation, Conceptualization. **Ana Carolina Barros de Freitas:** Methodology, Investigation. **Celia Raquel Quirino:** Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no conflicts of interest.

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