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Evaluation of the thermoregulatory response of goats naturally exposed to the tropical climate using longitudinal data

Avaliação da resposta termorregulatória de cabras expostas naturalmente ao clima tropical a partir do uso de dados longitudinais

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Highlights

The three physiological parameters have different residual covariance structures.
The heterogeneous compound symmetry matrix showed good modeling fit for RT data.
The heterogeneous autoregressive matrix showed good modeling fit for RR and HR data.

Abstract

Rectal temperature (RT), heart rate (HR), and respiratory rate (RR), determined as repeated measurements over time in female goats, were used to identify covariance matrices that best fit the data for residual modeling on these three traits. Then, based on this result, the goats' responses to heat were evaluated. Five matrices were found with convergence for the three traits. The Heterogeneous Compound Symmetry matrix showed a good fit for modeling the residual associated with RT, whereas the Heterogeneous

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Autoregressive matrix had a better fit for RR and HR, according to the Akaike Information Criteria (AIC), corrected AIC (AICc), and Schwarz Bayesian Information Criterion (BIC) used. After adjusting the residual data for these three traits, a mixed-model analysis was used to evaluate collection period (3), physiological stage (3), and animal age (3) as fixed effects. Residual modeling interfered differently with the p-value associated with the fixed effects studied. Collection period and interactions did not influence the variation in RT (P>0.761), which was within the standard range for goats in the tropics, while the physiological stage of the goats affected it (P<0.05). Rectal temperature, HR, and RR tend to show covariance structures that can be modeled using specific residual covariance matrices, that is, the heterogeneous compound symmetry matrix best suits RT data, whereas the heterogeneous autoregressive matrix is better suited for HR and RR, which are usually correlated. The goats of the evaluated breed maintain RT within the range of variation displayed by breeds adapted to a hot environment, regardless of their physiological condition. Variations occur in RR and HR, without, however, exceeding the normal range for goats. Pregnancy causes goats to raise their RR in the rainy season of the year in the region in order to maintain RT within the normal range for the species.
Key words: Covariance structure. Physiological parameters. Repeated measurements. Thermal stress.

Resumo

Utilizou-se a Temperatura retal (TR), Frequências cardíaca (FC) e respiratória (FR) aferidas como medidas repetidas no tempo em fêmeas caprinas, objetivando-se identificar matrizes de estruturas de covariância que melhor se ajustou aos dados para modelagem do resíduo nessas três características e, em seguida, avaliou-se a respostas de cabras ao calor, com base nesse resultado. Constatou-se cinco matrizes com convergência nas três características. A Simétrica composta heterogênea ajustou-se bem para modelagem do resíduo associado a TR, enquanto a Autorregressiva heterogênea ajustou-se melhor para a FR e FC, de acordo com os critérios de informação de Akaike (AIC), Akaike corrigido (AICc) e o Bayesiano de Schwarz (BIC) utilizados. Com o resíduos de dados dessas três características ajustados, utilizou-se uma análise com modelos mistos para avaliar a Época de coleta (3), Estado fisiológico (3) e Idade do animal (3) foram como efeitos fixos. Constatou-se que a modelagem do resíduo interferiu de modo diferenciado no p valor associado aos efeitos fixos estudados. A época da coleta e interações não influenciaram a variação da TR (P>0,761), que oscilou dentro da faixa padrão para caprinos nos trópicos, mas o Estágio fisiológico da cabra sim (P<0,05). A Temperatura retal e as Frequências cardíaca e respiratória tendem a apresentar estruturas de covariâncias modeláveis com utilização de matrizes de covariâncias residuais especificas, ou seja, a matriz Simétrica composta heterogênea mais adequada para dados da Temperatura retal, enquanto a Autorregressiva heterogênea para as Frequências cardíaca e respiratória, geralmente correlacionas. As cabras da raça avaliadas mantêm a temperatura retal dentro da amplitude de variação apresentada por raças adaptadas a ambiente quente. Isso ocorre independente da condição fisiológica que se encontra, mas com ocorrência de variação na frequência respiratória e cardíaca, não excedendo, no entanto, a faixa normal para caprinos. A gestação condiciona a cabra a elevar a FR na época chuvosa do ano na região para manter a TR na faixa de amplitude normal para caprinos.
Palavras-chave: Estresse térmico. Estrutura de covariância. Medidas repetidas. Parâmetros fisiológicos.

Introduction

Livestock farming with a focus on increasing productive capacity generally faces environmental conditions as a limiting factor or as a factor that may influence the main productive indices of the activity. In view of this, studies on the adaptive capacity of animals have gained more prominence (J. H. G. M. Leite et al., 2021), and many of them have focused on the interaction between the animal and its environment, since physiological and behavioral responses are triggered when they seek to maintain body homeostasis (Gupta et al., 2018; Hooper et al., 2020).

In order to produce in a tropical environment, the animal requires thermal comfort, with balance between heat loss and gain. In regions with prolonged droughts, high temperatures during the year do not limit goat farming, as these animals are able to survive in adverse environments. However, in resorting to physiological mechanisms of adaptation, performance is oftentimes compromised (Rashamol et al., 2020).

The temperature and relative humidity of the tropics influence the caloric balance of animals throughout the year. Evaporative heat loss is hindered in the rainy season but favored in the dry season, as it does not depend on temperature differential (Souza et al., 2012). As for the animal category, females that remain in the herd for a long time must adapt to environmental fluctuations, even though their sensitivity to stress varies during the reproduction cycle (Mousinho et al., 2014). In this context, the use of repeated measurements of physiological parameters can increase the chances of detecting the interaction between the animal and climatic variations.

Nonetheless, longitudinal data exhibit a hierarchical structure, since repeated measurements on an individual may show dependence between residuals, but are independent between individuals (Santos et al., 2016). The correlation between consecutive measurements and variances that change over time can interact, forming a complex covariance structure such that standard methods of analysis of variance, based on least squares, for instance, tend to generate biased results as basic assumptions are not met, limiting inferences if the covariance structure is not modeled (Sarmento et al., 2016).

This topic has been approached in several areas of knowledge with the use of the residual covariance matrix as a way to identify a structure that properly explains the variability of the data and correlations between consecutive measurements taken on the same animal at different moments over time. As available options in the literature, there exist around 40 matrices with different residual covariance structures (Santos et al., 2016), which are chosen by different criteria, such as the Akaike Information Criterion (AIC and AICc) and the Schwarz Information Criterion (BIC).

On this basis, this study investigated the sensitivity of goats to heat based on the traits of rectal temperature, heart rate, and respiratory rate after evaluating the influence of residual modeling on the significance of collection period, physiological stage, and goat age, included as fixed effects in a mixed model.

Material and Methods

This study was approved by the Ethics Committee at the Federal University of Piauí (UFPI) and developed based on the norms set forth by the Animal Ethics and Experimentation Committee at this higher education institution (approval no. 045/2017). The information used in the study referred to the physiological parameters of Anglo-Nubian goats that belong to the database of the Experimental herd of the Department of Animal Science at UFPI, located in the municipality of Teresina - PI, Brazil (5°5′20″ S and 42°48′07″ W).

The climate at the study site is classified as tropical dry, with two distinct seasons: rainy (in summer and fall) and dry (in winter and spring). Average annual reference precipitation is 1,300 mm, but irregularly distributed and concentrated in the period from January to May. Average annual temperature is 27 °C, which is higher in the second half of the year.

In the reproductive management throughout the year, the females were divided into two lots that entered the reproductive stage in different semesters. Matings in one lot coincided with lactation in the other, thereby ensuring contemporary animals to be evaluated in the stages termed *non-pregnant, pregnant,* and *lactating,* in the dry and rainy seasons of the year.

Rectal temperature (RT), heart rate (HR), and respiratory rate (RR) data that make up the herd's database were collected under the following criteria: measurement performed in the afternoon (14h00 to 17h00), with the animals restrained in the pen, on dates throughout the breeding season of each semester, over three years. The first collection (over three consecutive days) took place at the beginning of the season; the second in the final third of pregnancy; and the third until the second week after kidding.

Rectal temperature was measured using a digital thermometer that was inserted into the animal's rectal ampulla and remained until the emission of the sound signal indicating stabilization of the temperature. To measure HR, a manual stethoscope was used positioned on the left thoracic region, at the height of the aortic arch, for one minute, with results expressed in beats per minute (beats/min). Respiratory rate was measured by directly counting the movements of the flank during one minute, with results expressed in movements per minute (mov. min^{-1}).

In editing the files for statistical analysis, information collected in five semesters of three consecutive years was included, forming a data structure with repeated measurements over time from animals of different ages and at different physiological stages. The file was formatted with the following organization: animal; father; dates of birth, kidding, and data collection; as well as RT, HR, and RR values. Using these data, the fixed effects of *collection period* (CP), *physiological stage* (PS), and *age class* (AC) of the goats at the time of collection were defined for each animal.

To evaluate the effect of the period of the year in which the data were collected, three periods were considered, as follows: CP1 - collections from January to May, i.e. the rainy and hot season; CP2 - June and July, dry season with mild-temperature nights; and CP3 - August to December, i.e. the dry and hot season in the region, with *n* equal to 202, 94, and 304 measurements, respectively.

To evaluate the effect of physiological condition within the collection period, the goats were divided into three physiological stages: PS - non-pregnant (goat without confirmation of pregnancy or lactation), PS2 - pregnant (goats in the final two-thirds of gestation); and PS3 - lactating (goats with kid by their side), with *n* equal to 218, 175, and 204 measurements, respectively. For the analysis of the age effect, the animals were grouped into four classes: AC1 - from one to less than two years; AC2 - from two to less than three years; AC3 - from three to five years; and AC4 - older than five years, with n equal to 131, 105, 204, and 170 measurements, respectively.

Collections began in a breeding station that was installed during the dry season of the year. At this station, on six alternate days in the month of September, the physiological parameters were measured on all the dams in the lot that started reproduction (PS1 - non-pregnant). The collection was repeated 90 days later, at the end of the dry season, in goats with confirmed pregnancy (PS2). The same collections were repeated after the first week of lactation (PS3), totaling 42 animals in this lot (36 goats and 6 doelings), on which RT, RR, and HR were measured in the three physiological stages.

This data collection process was repeated in the following two years, with these and other goats that participated in the breeding stations installed in the rainy and dry seasons of those years, in an equivalent number of animals in the two lots that entered the reproduction stage one in each semester. Data on the three physiological stages on each collection date were provided.

To address the effect of modeling the covariance structure of each trait on the efficiency of the F-test, residual modeling was carried out with seven covariance matrices among 40 available to the user in the MIXED routine of SAS® University Edition (SAS, 2002), namely, Compound Symmetry, Autoregressive, Variance Component, Heterogeneous Compound Symmetry, Heterogeneous Autoregressive, Toeplitz, and Unstructured.

To compare the fit provided by the matrices of different structures, the Akaike Information Criteria (AIC), the corrected AIC (AICc), and the Schwarz Bayesian Information Criteria (BIC) were used, which were defined respectively as:

$$AIC = -2 \log L + 2p;$$

$$AICc = -2 \log L(\theta) + 2(p) + 2p(p+1)/(n-p-1);$$

$$BIC = -2 \log_e L + p \log(N - r(X)),$$

in which p = number of parameters estimated; N = number of observations; r(X) = rank of the incidence matrix of the fixed effects of the model; and $\log_e L$ = logarithm of the constrained maximum likelihood function.

The lowest AIC, AICc, and BIC values indicate the most suitable model among those tested. Using the SAS PROC MIXED procedure, which implements random and fixed effects in the statistical model to model the covariance structure of the residuals and thus compute efficient estimates of fixed effects, the mixed model was applied to analyze the variance of the three traits with the five covariance matrices that converged.

The mixed linear model can be represented in matrix notation as follows:

$$Y = Xb + Zu + e,$$

in which b is the vector of parameters associated with fixed effects; *u* = random effects; and *e* = vector of random errors, with *u* and *e* being uncorrelated, with null expectations and covariance matrices X and Z, respectively.

The following mixed linear model was used:

$$Y_{ijklm} = \mu + P_i + A_j + CP_k + PS^l + AC_m + (CP{*}PS) + (PS{*}AC) + \varepsilon_{ijklm},$$

in which Y_{ijklm} = measured in the daughter of sire i, year j, collection period k, physiological stage l, age class m; P^i = random effect of parent i; A_j = random effect of measurement in year j; CP_k = fixed effect of the measurement in collection period k; PS_l = fixed effect of the measurement on goat at physiological stage l; ACm = fixed effect of the measurement on goat of age class m; (CP*PS) and (PS*AC) = interaction effects; and ε_{ijklm} = random error associated with each measurement, which was modeled under different variance and covariance structures.

The influence of modeling the residual covariance structure of each trait on the identification of significance of the fixed effects included in the model (*p*-value of the F-test) was assessed using two matrices that showed the best fit to the data and the matrix that exhibited the poorest fit among the five that converged. To analyze the goats' response to the three fixed effects included in the model, the modeling of the covariance structure provided by the Heterogeneous Compound Symmetry matrix was used for the RT trait, whereas for HR and RR, the Heterogeneous Autoregressive matrix that fit the data structure for each trait was adopted.

In the comparisons of means, significance was considered at $p<0.05$ using Fischer's least significant difference (DIFF option available in the LSMEANS function of SAS).

Results and Discussion

Rectal temperature (RT), heart rate (HR), and respiratory rate (RR) measured as longitudinal data in Anglo-Nubian goats showed a residual covariance structure that required modeling. Modeling, in turn, interfered with the significance level indicated by the statistical test (p-value) that was used to qualify the influence exerted by the collection period (CP), physiological condition (PS), and goat age factors (AC), when included in the mixed model as fixed effects, on the behavior of these traits in a study of the goats' response to heat.

The modeling of the residual covariance structure of each trait influenced the identification of significance of the fixed effects included in the model (p-value of the F-test) when they were evaluated using the Heterogeneous Compound Symmetry (HCS) and Heterogeneous Autoregressive (HAR) matrices, which displayed the best fit to the data. Conversely, the variance component (VC) matrix showed the poorest fit among those that converged.

Regarding this contrast, the complexity of the residual covariance structure, caused by the interaction of the correlation between consecutive measures and variances that change over time, in traits of this nature, may compromise the quality of the results if subjected to the use of standard variance analysis methods, since some basic assumptions were not met.

Table 1 describes the results related to the choice of the best covariance matrix structure to represent the variability of the data and the correlations between consecutive measurements in the evaluated traits, considering the goodness-of-fit of the AIC, AICc, and BIC criteria. Convergence occurred simultaneously in five of the covariance matrices tested for RT, RR, and HR, which is an indication of similar complexity of the data structure of these traits. This is due to the direct contribution of the animal and the environment, which leads measurements close in time to be more correlated, although variances tend to change over time.

Table 1
Values for the Akaike Information (AIC), Corrected AIC (AICc), and Bayesian Schwarz Information (BIC) criteria of the covariance matrix structure for residual modeling of rectal temperature, respiratory rate, and heart rate in Anglo-Nubian goats

Covariance structure	Rectal temperature			Respiratory rate			Heart rate		
	AIC	AICc	BIC	AIC	AICc	BIC	AIC	AICc	BIC
Heterogeneous Compound Symmetry	**415.3**	**416.9**	**435.1**	4361.4	4363.1	4381.3	4550.2	4551.9	4570.1
Heterogeneous Autoregressive	416.6	418.3	436.5	**4359.8**	**4361.3**	**4378.7**	**4547.9**	**4549.6**	**4567.7**
Autoregressive	502.4	502.4	506.1	4380.8	4380.8	4383.6	4609.8	4609.8	4613.6
Compound Symmetry	519.3	519.4	523.1	4381.9	4381.9	4383.8	4617.2	4617.3	4621.0
Variance Component	520.6	526.6	529.4	4411.2	4411.3	4413.1	4619.0	4619.1	4621.8
Toeplitz	493.3	494.8	512.2	-	-	-	-	-	-

Akaike Information Criterion (AIC); Corrected AIC (AICc), Schwarz Bayesian Information Criterion (BIC).

The AIC, AICc, and BIC criteria did not differ in the identification of the matrices that converged for each evaluated trait (RT, RR, and HR), which facilitated the identification of covariance structures that can be more parsimonious to properly represent the variability present in the residuals—a necessary condition to improve the quality of inferences to be made on the parameters included in the proposed model. With regard to this result, it should be considered that there is an equivalence between the AIC and AICc tests. The Bayesian Information Criterion, on the other hand, may not have shown a tendency to penalize the matrices with more parameters, as they are parsimonious and favored mainly if the longitudinal data analyzed exhibit a regular structure.

By this argument, it is also convenient to remember that this study deals with matrices with properties that contrast the homogeneity with the heterogeneity of variances of residuals. The properties of these matrices support the assumption that the both heterogeneity of residual variance and correlation patterns between close measurements were well evidenced in these traits, which, in turn, can combine into a complex structure of covariances and, consequently, also of correlations.

Regarding the quality of the different fits evaluated (Table 1), the covariance structure with HCS matrix provided the best result for the RT trait, as it generated the lowest AIC, AICc, and BIC values, followed by the ARH model. On the other hand, for RR and HR, the HAR model showed the lowest AIC, AICc, and BIC values, proving to be the most efficient, followed by the HCS model.

The finding that the HCS and HAR matrices had the best fit for the RT, RR, and HR of the goats does not agree with the data simulation performed by Santos et al. (2016). These authors evaluated the covariance structure for carcass traits and body size with repeated measurements in sheep of different genetic groups and indicated the Compound Symmetry matrix as the one that best represents the residual variation.

As can be seen in Table 1, the Toeplitz matrix did not converge for RR or HR, which are highly correlated traits when animals are subjected to heat stress (Kaushik et al., 2020). Based on the properties of this matrix, this result suggests that the occurrence of variation in the correlation between these traits may not be constant as the distances between times grow. In other words, RR and HR oscillate in response to an increase in RT, which, in turn, will tend to decrease as a thermoregulatory response stemming from increased respiratory movements. Therefore, they are interrelated with a variation in the same direction, occurring simultaneously in the thermolysis process, but likely with different functions.

The RT of an animal throughout a hot day is related to variations in ambient temperature and relative humidity, as well as to HR and RR increase reactions, which are associated with thermolysis by peripheral dilation and evapotranspiration, respectively (N. L. Ribeiro et al., 2016; Rashamol et al., 2020).

The first two matrices that fitted the data indicate the presence of heterogeneous variances in the residuals of RT with longitudinal data structures. In contrast, the Variance Component (VC) matrix, which is the structure assumed in conventional ANOVA, always tends to converge due to its simple structure. Despite this, it provided one of the worst modeling results, that is, it is apparently unsuitable for this case.

Our finding that the HCS and HAR matrices had the best fit for RT, RR, and HR does not agree with the data simulation carried out by Amaral et al. (2009), who indicated Compound Symmetry as the matrix that best represents the residual variation of RT, which would be similar to analyzing it in split-plots. These authors also disagreed with respect to HR and RR being better represented by the Unstructured matrix, which was the best qualified in the simulation and did not converge in our study.

The fact that the Unstructured matrix did not converge does not imply inadequacy, as it involves estimating a greater number of parameters. Thus, the difficulty of convergence is greater, especially when the data structure is real and collected in the field and more complex statistical models with various fixed and random effects are used.

The inclusion of the effects of collection period, animal age, and physiological stage (which is a particularity of females) in the model makes the analysis performed in this study more parameterized than the analysis of the study that used data simulation. This parameterization contributes to the discordance of the compared results, coupled with the fact that the study involving simulation included only three covariance matrices for residual modeling.

Rectal temperature, HR, and RR are the most used phenotypic traits in studies of thermoregulation in domestic animals (Giannetto et al., 2017; Vasconcellos et al., 2022). These are typically employed as one-off measurements, which is a more limited data structure compared with the use of repeated measurements. Thus, based on the discovery of heterogeneous variances, to more efficiently assess the tolerance of animals to heat, one must resort to fitting to take advantage of the longitudinal data structure, since this has been the standard procedure in diverse traits that are repeated over time, regardless of the area of knowledge.

Considering that the maintenance of body homeostasis is a requirement to produce under high ambient temperature (Souza et al., 2012; J. H. G. M. Leite et al., 2018), with the use of longitudinal data from RT, HR, and RR, the properties of the matrices studied here may be useful to explore particularities of environmental covariances inherent to the thermolysis process, which occurs by conduction or by evapotranspiration.

By detailing these results, we found that the F-test value was sensitive to changes in the matrix used for residual modeling. Differences in the significance level of the fixed effects on RT, HR, and RR, indicated by the p-value of the F-test, mainly of interactions, are observed in Table 2 with the HCS and HAR matrices, which were the best fit and exhibit properties that advocate heterogeneous residual variance; and also with the VC matrix, which showed the lowest goodness-of-fit among those that converged, possibly because it advocates homogeneous variances in the residuals and independence.

Table 2

Estimates of the *P*-value of the F-test of fixed effects included in the mixed model for analysis of rectal temperature, respiratory rate, and heart rate as longitudinal data in Anglo-Nubian goats

Covariance structure	*P*-value of F-test for fixed model effects				
	CP	Physiological stage	Age	CP*PS	PS*AC
		Rectal temperature			
Heterogeneous Compound Symmetry	0.822	0.0040	0.1134	0.2468	0.1501
Heterogeneous Autoregressive	0.8001	0.0043	0.0583	0.3011	0.3567
Variance Component	0.9834	0.0396	0.0022	0.5008	0.0002
		Heart rate			
Heterogeneous Autoregressive	<.0001	<.0001	0.0012	0.1987	0.0949
Heterogeneous Compound Symmetry	<.0001	<.0001	0.0074	0.1687	0.0385
Variance Component	<.0001	<.0001	0.0002	0.3256	0.0202
		Respiratory rate			
Heterogeneous Autoregressive	<.0001	0.001	0.0293	0.0001	0.2763
Heterogeneous Compound Symmetry	<0.0001	0.0015	0.0534	0.0002	0.1408
Variance Component	<.0001	0.001	0.0187	0.0001	0.7963

Collection period (CP); physiological stage (PS); age class (AC).
Significance declared by Fisher's F test.

Thus, regardless of the greater or lesser robustness of the use of the residual covariance matrix, it does not suffice to consider the RT, HR, and RR variances unequal as the distance between times increases, but rather to interpret them in the appropriate structure, given their genetic and environmental causes (Kaushik et al., 2020). Irrespective of breed, the rearing environment and its climatic variables trigger physiological changes whose action to maintain homeothermy is yet to be elucidated (Souza et al., 2012).

Variations in RT can simultaneously trigger changes in heart and respiratory rates, as thermolysis mechanisms. In this way, the convergence with the same covariance matrices can be regarded as an indication of residual variance heterogeneity with a similar pattern in these traits.

Table 2 shows disagreement based on the p-value calculated with the different residual modelings assumed to qualify the influence of a certain factor included as fixed in the mixed model as significant or not significant. Altering the covariance matrix led to a change in the detection of significance by the F-test, such that the effect of the evaluated factor changed from significant to not significant, or vice versa. This occurred differently for each trait, due to the variation in the complexity of the data covariance structure.

When the HCS and HAR matrices were used, the AC and PS × AC interaction effects were not significant for RT ($P>0.05$), but were significant using the VC matrix ($P<0.05$), which suggests a type-I error. In the analysis of HR, the PS × AC interaction effect was not significant ($P>0.05$) by HAR, whereas the HCS and VC matrices revealed significant effects ($P<0.05$). When RR was analyzed using HCS, the age effect was not significant ($P>0.05$), while the HAR and VC matrices indicated significance ($P<0.05$).

Regardless of the matrix, the CP and CP × PS interaction effects on RT were considered not significant ($P>0.05$). Likewise, the PS × AC interaction effect was not significant on RR. On the other hand, $P<0.05$ was detected, characterizing significance, for the effects of PS on RT; CP, PS, and AC on HR; and CP, PS, and CP × PS interaction on RR.

Therefore, the present covariance structure is of importance, and residual modeling cannot be relegated to the background, that is, one should not just resort to the use of any matrix, since a wrong inference can cause losses. This is because, irrespective of the breed, climatic variables can trigger physiological changes with the potential to impact production (Souza et al., 2012; M. N. Ribeiro et al., 2018).

Researchers have investigated the direct or isolated influence of the effects of year, collection period, and animal age on the variation of physiological parameters in ruminants in tropical environments (N. L Ribeiro et al., 2016; Miranda et al., 2019). The physiological stage, which is a particularity of females that is associated with altered immunity (Oliveira et al., 2019), has been little studied for this purpose, with the exception of works such as those of Façanha et al. (2012) and Mousinho et al. (2014).

Thus, in this study, the need for residual modeling was evident to circumvent limitations caused by the heterogeneity of variances and correlations between measurements on the same animal for the three traits studied. Considering this perspective, the goats' sensitivity to heat was evaluated based on the results presented in Tables 3, 4, and 5, respectively, with the RT, RR, and HR means estimated after adequate residual modeling.

The mean RT of the goats was 39.10 ºC, and the range of variation from 38.40 to 39.14 ºC did not exceed the 38.5 to 40.0 ºC determined in different goat breeds in Brazil using one-off measurements performed in regions with average ambient temperature above 30 ºC that was higher in the dry season of the year (J. R. D. S. Leite et al., 2012; M. N. Ribeiro et al., 2018).

Three results presented in Table 3 are noteworthy: the lack of a significant effect of CP on the amplitude of variation of RT, which can be explained by the fact that it was measured in the afternoon, with the ambient temperature above 30 ºC; the observed effect of PS, which associates peripartum with sensitivity to stress (Oliveira et al., 2019), but also greater metabolic activity to maintain pregnancy and lactation with increased RT; and the effect of AC, with animals up to two years old differing from the others, possibly due to the presence of doelings in that class.

Table 3
Estimated means for rectal temperature in Anglo-Nubian goats as a function of collection period, physiological stage, and goat age resulting from analysis of longitudinal data with residual fitting from the Heterogeneous Compound Symmetry structure

Source of variation	Factor level	Mean (ºC)	Pr> |F|
Collection period	January to May	39.11^{a}	0.822
	June and July	39.09^{a}	
	August to December	39.12^{a}	
Physiological stage	Non-pregnant or lactating	39.07^{b}	0.004
	Pregnancy	39.20^{a}	
	Lactating	39.06^{b}	
Age class	≥1 and <2 years old	39.05^{b}	0.012
	>2 and ≤3 years old	39.10^{ab}	
	>3 and ≤5 years old	39.20^{a}	
	>5 years old	39.09^{ab}	

[a-b] Means followed by different letters in the column, by source of variation, are significantly different by Fischer's test (p<0.05).

Table 4

Estimated means for respiratory rate in Anglo-Nubian goats as a function of collection period, physiological stage, and goat age resulting from analysis of longitudinal data with residual fitting from the Heterogeneous Autoregressive structure

Source of variation	Factor level	Mean (mov. min^{-1})	Pr> |F|
January to May	Non-pregnant or lactating	47.65[b]	0.007
	Pregnant	60.47[a]	
	Lactating	42.24[bc]	
June and July	Non-pregnant or lactating	36.00[c]	
	Pregnant	40.73[bc]	
	Lactating	40.26[bc]	
August to December	Non-pregnant or lactating	44.29[bc]	
	Pregnant	42.41[bc]	
	Lactating	42.11[bc]	
Age class	≥1 and <2 years old	41.76[b]	0.029
	>2 and ≤3 years old	44.95[ab]	
	>3 and ≤5 years old	46.23[a]	
	>5 years old	43.37[ab]	

[a-c] Means followed by different letters in the column, by source of variation, are significantly different by Fischer's test ($p<0.05$).

Another perspective to be considered is to approach these three results as a reaction of the goats by demonstrating their ability to reduce RT when subjected to heat, which can be viewed as an indication of physiological adaptation. However, this is linked to behavioral and physiological adjustments and the environmental conditions of the rearing location (Sousa et al., 2015), since RT was maintained in the range of 38.5 to 40.5 ºC, which has been the standard for goats in high-ambient-temperature conditions, according to studies by Façanha et al. (2012), J. R. D. S. Leite et al. (2012), and Alves et al. (2021).

The ability of the animals to respond to heat, with changes occurring mainly in RR and HR, may have been the moderating factor responsible for the maintenance of RT throughout the year ($p>0.05$), which is in agreement with statements by Indu et al. (2015). The high temperature of the environment in the dry season of the year directly influenced the variation in the RT of the animals. In the rainy season, the RT variation was also influenced by relative humidity, which was higher, reducing heat loss (Souza et al., 2012; Miranda et al., 2019).

Table 5
Estimated means for heart rate in Anglo-Nubian goats as a function of collection period, physiological stage, and goat age resulting from analysis of longitudinal data with residual fitting from the Heterogeneous Autoregressive structure

Source of variation	Factor level	Mean (beats/min.)	Pr> |F|
Collection period	January to May	96.70[a]	0.0001
	June and July	81.00[b]	
	August to December	83.50[b]	
Physiological stage	Non-pregnant or lactating	83.50[b]	0.0001
	Pregnant	94.60[a]	
	Lactating	83.10[b]	
Age class	≥1<2 years old	84.60[b]	0.0012
	2≥3 years old	90.00[a]	
	3≥5 years old	89.00[a]	
	>5 years old	84.50[b]	

[a-b] Means followed by different letters in the column, by source of variation, are significantly different by Fischer's test ($p<0.05$).

This argument is based on the significance of CP on RR, which was lower in the months of June and July, when the ambient temperature was milder in relation to the rainy and dry seasons in the region. Nonetheless, the higher values in these two seasons are not a guarantee of heat stress, since the intensity of the adverse effect of high ambient temperature on the animal depends on the efficiency of thermoregulatory mechanisms to maintain homeothermy (Indu et al., 2015).

The mean RR of the goats using data collected as repeated measurements was 42.5 mov. min^{-1}. The range of variation was from 36.1 to 57.6 mov. min^{-1}, which did not exceed the variation range of 20 to 61 mov. min^{-1} described in a survey by M. N. Ribeiro et al. (2018) and Miranda et al. (2019) with different goat breeds in Brazil using one-off values measured in places with average ambient temperature above 30 ºC.

In the analysis of RR variation, the effects of CP and PS were significant ($p<0.05$), but depended on one another (Table 4), as indicated by the occurrence of a significant interaction ($p<0.007$). The direct effects of AC and interactions were not significant for the variation in RR ($p>0.05$).

The significant effect of CP on the variation of the goats' RR may also be because the data were collected in the afternoon, with ambient temperature above 30 °C. The significance of the PS effect can be attributed to the need to control the increase in RT, due to the greater metabolic activity during pregnancy and lactation (Vasconcellos et al., 2022).

Respiratory rate stands out as one of the main characteristics in studies of thermoregulation with ruminants, as it efficiently indicates heat loss by evapotranspiration (Indu et al., 2015) in the range of thermal variation in the tropics. The significance of the interaction effect between CP and PS on RR ($p<0.001$) is important information for the management of females in this environment, since they are exposed to climatic oscillations when handled in the field without receiving special attention in the phase of greatest sensitivity to stress (Mousinho et al., 2014).

However, it is important to consider that if the variation in parameters during the peripartum period is associated with stress and an increase in basal metabolic rate, this occurs at a time when the goat is physiologically fragile and care related to thermal comfort is essential for adequate productive performance (Oliveira et al., 2019).

Even if we consider RR an important biomarker of physiological adaptation to heat stress (Indu et al., 2015), an increase in RR does not necessarily mean that the animal is under such a condition, as it may be a resource it uses to lose body heat, which is hampered by the high air humidity in the rainy season.

Animal age had a significant direct effect ($p<0.029$) on RR, but its interaction with physiological stage did not influence ($p>0.05$) this variable. The lower value detected in animals aged up to two years, which differed from the others, is possibly influenced by the participation of doelings in this class. However, regardless of the physiological condition, the three- to five-year-old goat tended to have a higher RR value.

The most important traits for studying the adaptation of animals to heat are generally available to the breeder in the form of indices combining temperature, relative humidity, precipitation, and other factors (Façanha et al., 2013; Habeeb et al., 2018). Nevertheless, the thermal stress to which females have been subjected has not received attention in the sense of being included in selection indices or a scale for classifying the degree of stress that takes into account the effects of the physiological stage.

The mean HR of the goats using data collected as repeated measurements was 87.0±4.3 beats/min. The range of variation from 76.0 to 106.0 beats/min did not exceed the 69 to 121 beats/min described in a survey by M. N. Ribeiro et al. (2018) with goats of different breeds in Brazil using one-off values measured in regions with average ambient temperature above 30 ºC. However, the literature has a lot of discrepancy in values for this trait, with the prevailing explanation still being the difference in the environmental conditions where they were obtained (Kaushik et al., 2020; Cardoso et al., 2021).

As reported in Table 5, the three factors included as fixed in the model had significant isolated effects on HR, but no significance was detected for the analyzed interactions.

The significance of the collection period on HR, whose values were higher in the rainy season of the year ($P<0.001$), may indicate that thermolysis by peripheral dilation to maintain body temperature was more difficult than in the dry season. In this case, the air temperature being close to that of the animal's body did not favor thermolysis. Thus, heat loss was most effective by the evaporative mechanism, as it does not depend greatly on the temperature differential between the animal and the environment (Miranda et al., 2019).

Conclusion

The use of a residual covariance matrix to fit the data structure allowed us to conclude that, when resorting to altering their respiratory rate, goats manage to maintain rectal temperature within the range shown by this species in a tropical environment, denoting adaptation to the conditions of the environment where they were evaluated.

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References

Alves, M. S., Dantas, R. A. A., Cruz, R. O., Pereira, V. C., Souza, M. A., Fº., Silva, I. N. G., Gaudêncio, S., Neto, Tavares, K. C. S., Martins, L. T., & Araújo, A. A. de. (2021). Physiological impact of the environment on the welfare of transgenic goats raised in a tropical climate. *International Journal of Biometeorology, 65*(12), 2147-2155. doi: 10.1007/s00484-021-02177-y

Amaral, W. O., Vale, R. S., Araújo, C. V., Krag, M. N., & Costa, N. R. (2009). Estruturas de covariância na análise de dados simulados do comportamento fisiológico dos ovinos em sistema silvipastoril na região nordeste do estado do Pará. *Anais do Congresso Brasileiro de Sistemas Agroflorestais,* Luziânia, GO, Brasil, 7.

Cardoso, E. D. A., Furtado, D. A., Ribeiro, N. L., Saraiva, E. P., Barbosa do Nascimento, J. W., Medeiros, A. N. de, Sousa, F. A., & Pereira, P. H. B. (2021). Intake salinity water by creole goats in a controlled environment: Ingestive behavior and physiological variables. *Tropical Animal Health and Production, 53*(3), 1-7. doi: 10.1007/s11250-021-02754-8

Façanha, D. A. E., Chaves, D. F., Morais, J. H. G., Vasconcelos, Â. M. D., Costa, W. P., & Guilhermino, M. M. (2013). Tendências metodológicas para avaliação da adaptabilidade ao ambiente tropical. *Revista Brasileira de Saúde e Produção Animal, 14*(1), 91-103. doi: 10.1590/S1519-99402013000100011

Façanha, D. A. E., Vasconcelos, A. M. de, Lima, F. R., Eloy, A. M. X., Oliveira, A. L., Guilhermino, M. M., & Landim, A. V. (2012). Características termorreguladoras e desempenho de cabras leiteiras no terço inicial da lactação em clima tropical. *Revista Portuguesa de Ciências Veterinárias, 111*(583-584), 151-156.

Giannetto, C., Arfuso, F., Fazio, F., Giudice, E., Panzera, M., & Piccione, G. (2017). Rhythmic function of body temperature, breathing and heart rates in newborn goats and sheep during the first hours of life. *Journal of Veterinary Behavior, 18*(C), 29-36. doi: 10.1016/j.jveb.2016.12.002

Gupta, D., Ashutosh, M., Kashyap, G., Punetha, M., Patel, B., Ashutosh, L., Para, I., Tejaswi, V., Ahirwar, M., & Jalmeira, N. (2018). Physiological response to transportation stress at different flocking densities in hot humid and winter seasons in goats and assessment of pretreatment of vitamin C, electrolyte and jaggery. *Indian Journal of Animal Research, 53*(3), 299-306. doi: 10.18805/ijar.B-3497

Habeeb, A. A., Gad, A. E., & Atta, M. A. (2018). Temperature-humidity indices as indicators to heat stress of climatic conditions with relation to production and reproduction of farm animals. International. *Journal of Biotechnology and Recent Advances, 1*(1), 35-50. doi: 10.18689/ijbr-1000107

Hooper, H. B., Silva, P. dos S., Oliveira, S. A., Meringhe, G. K. F., Lacasse, P., & Negrão, J. A. (2020). Effect of heat stress in late gestation on subsequent lactation performance and mammary cell gene expression of Saanen goats. *Journal of Dairy Science, 103*(2), 1982-1992. doi: 10.3168/jds.2019-16734

Indu, S., Sejian, V., Kumar, D., Pareek, A., & Naqvi, S. M. K. (2015). Ideal proportion of roughage and concentrate for Malpura ewes to adapt and reproduce in a semi-arid tropical environment. *Tropical Animal Health and Production, 47*(8), 1487-1495. doi: 10.1007/s11250-015-0889-1

Kaushik, R., Goel, A., & Rout, P. K. (2020). Establishing the genetic variation in physiological response in response to heat stress in semi-arid region in Jamunapari goats. *Biological Rhythm Research, 51*(1), 1-14. doi: 10.1080/09291016.2018.1499218

Leite, J. H. G. M., Façanha, D. A. E., Bermejo, J. V. D., Guilhermino, M. M., & Bermejo, L. A. (2021). Adaptive assessment of small ruminants in arid and semi-arid regions. *Small Ruminant Research, 203*(18), 106497. doi: 10.1016/j.smallrumres.2021.106497

Leite, J. H. G. M., Façanha, D. A. E., Costa, W. P., Chaves, D. F., Guilhermino, M. M., Silva, W. S. T., & Bermejo, L. A. (2018). Thermoregulatory responses related to coat traits of Brazilian native ewes: an adaptive approach. *Journal of Applied Animal Research, 46*(1), 353-359. doi: 10.1080/09712119.2017.1302877

Leite, J. R. D. S., Furtado, D. A., Leal, A. F., Souza, B. B., & Silva, A. S. D. (2012). Influência de fatores bioclimáticos nos índices produtivos e fisiológicos de caprinos nativos confinados. *Revista Brasileira de Engenharia Agrícola e Ambiental, 16*(4), 443-448. doi: 10.1590/S1415-43662012000400015

Miranda, J. R., Furtado, D. A., Lopes, J. P., Neto, Nascimento, J. W. B., & Malheiros, J. R., Fº. (2019). Variáveis fisiológicas, produção e qualidade do leite de cabras parda alpina no período seco do semiárido. *Energia na Agricultura, 34*(1), 48-57. doi: 10.17224/EnergAgric.2019v34n01p48-57

Mousinho, L. R. B., Campelo, J. E. G., Sousa, S. C. D., Jr., Azevêdo, D. M. M. R., Leal, T. M., & Moura, R. M. D. A. D. S. (2014). Respostas fisiológicas de cabras Anglonubianas a condições ambientais com temperatura elevada. *Revista Brasileira de Saúde e Produção Animal, 15*(1), 160-171. doi: 10.1590/S1519-99402014000100005

Oliveira, D. P., Dias, D. C. R., Silva, M. O., Donner, A. C., Ribeiro, J. D., Fº., Fonseca, L. A. D., Alves, S. R., & Ermita, P. A. N. (2019). Avaliação do período periparto por parâmetros clínicos e hematológicos em cabras leiteiras. *Ciência Animal Brasileira, 20*(e-37548), 1-12. doi: 10.1590/1809-6891v20e-37548

Rashamol, V. P., Sejian, V., Bagath, M., Krishnan, G., Archana, P. R., & Bhatta, R. (2020). Physiological adaptability of livestock to heat stress: an updated review. *Journal of Animal Behaviour and Biometeorology, 6*(3), 62-71. doi: 10.26667/2318-1265 jabb.v6n3p62-71

Ribeiro, M. N., Ribeiro, N. L., Bozzi, R., & Costa, R. G. (2018). Physiological and biochemical blood variables of goats subjected to heat stress–a review. *Journal of Applied Animal Research, 46*(1), 1036-1041. doi: 10.1080/09712119.2018.1456439

Ribeiro, N. L., Costa, R. G., Pimenta, E. C., Fº., Ribeiro, M. N., Crovetti, A., Saraiva, E. P., & Bozzi, R. (2016). Adaptive profile of Garfagnina goat breed assessed through physiological, haematological, biochemical and hormonal parameters. *Small Ruminant Research, 144*(ref.32), 236-241. doi: 10.1016/j.smallrumres.20 16.10.001

Santos, N. P. D. S., Guimarães, F. F., Sarmento, J. L. R., Sousa, A. D., Jr., Rego, A. D. A., Neto, Sena, L. S., & Santos, G. V. D. (2016). Covariance structure for carcass and body size traits with repeated measures in sheep from different genetic groups. *Revista Brasileira de Saúde e Produção Animal, 17*(4), 652-665. doi: 10.1590/ S1519-99402016000400009

Sarmento, J. L. R., Torres, R. A., Sousa, W. H., Lôbo, R. N. B., Albuquerque, L. G., Lopes, P. S., Santos, N. P. S., & Bignard, A. B. (2016). Random regression models for the estimation of genetic and environmental covariance functions for growth traits in Santa Ines sheep. *Genetics and Molecular Research, 15*(2), 1/15025749-13. doi: 10.4238/gmr.15025749

Sousa, B. B., Benicio, A. W. A., & Benicio, T. M. A. (2015). Caprinos e ovinos adaptados aos trópicos. *Journal of Animal Behaviour and Biometeorology, 3*(2), 42-50. doi: 10.14269/2318-1265/jabb.v3n2p42-50

Souza, P. T. D., Salles, M. G. F., & Araújo, A. A. D. (2012). Impacto do estresse térmico sobre a fisiologia, reprodução e produção de caprinos. *Ciência Rural, 42*(10), 1888-1895. doi: 10.1590/S0103-84782012005 000072

SAS. Statistical Analyses System - SAS (2002), SAS/STAT User's guide. Version 9.0. (4ª.ed.). v.2. Cary.

Vasconcellos, M. L., Silva, P. S., Merighe, G. K. F., Oliveira, S. A., & Negrão, J. A. (2022). Cumulative effect of different acute stressors on physiological and hormonal responses and milk yield in lactating Saanen goats. *Semina: Ciência Agrárias, 43*(5), 1891-1906. doi: 10.5433/1679-0359.2021v43n5p1891