Changes in skin temperature and behaviors of preweaned Holstein calves under hot environment monitored by a multimodal tail-attached device

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Abstract: This study aimed to determine the applicability of a tail-attached device in monitoring animal-based indicators (ABIs) associated with changes in environmental conditions in calves, through investigating the relationship between sensor-derived ABIs and the temperature–humidity index (THI). Furthermore, to identify significant ABIs indicative of heat stress status, sensor-derived ABIs of calves under differing heat stress levels based on rectal temperature (RT) were compared. The tail-attached device, which is capable of measuring skin temperature (ST), activity intensity, and roll angle along the longitudinal axis of the tail at 3-min intervals, was attached to 99 preweaned female Holstein calves for an average of 4 weeks (26.4 ± 6.8 d). After selecting data from mild to hot days (daily average THI of ≥55), physiological (daily maximum tail ST) and behavioral (daily average activity intensity, daily total lying time, and daily total body position change) ABIs were computed, and their relationship with the daily average THI was determined using piecewise regression analysis. Additionally, during the hot season, RT of 20 randomly selected tested calves were measured thrice a week (every 2.4 ± 0.5 d), and a comparison was conducted between the ABIs of calves with normal RT (<39.5°C) and those with high RT (≥39.5°C), utilizing data from days characterized by potential heat stress (daily average THI of ≥75). During the study, ambient temperature (°C) and relative humidity (%) were recorded every 10 min using an automatic digital data logger, from which the daily average THI was calculated. Piecewise regression analysis identified THI breakpoints of 73.6 for tail ST, 79.1 for average activity intensity, 72.3 for lying time, and 79.1 for position change. All the tested ABIs tended to increase as THI increased, and this trend was pronounced in tail ST, activity intensity, and position change after the breakpoint. These 3 ABIs were significantly higher in calves with high RT compared with those with normal RT, while lying time shared similar values between the RT groups. Overall, these findings suggest that the tail-attached device can simultaneously monitor both physiological and behavioral ABIs in calves, and among the ABIs, tail ST, activity intensity, and position change are the significant ABIs indicative of heat stress status.

Global warming has emerged as an issue that can significantly affect dairy farm production (Berman, 2019). Although calves are not highly susceptible to heat stress due to their large surface-to-mass ratio and the absence of additional heat load related to lactation (Wang et al., 2020), heat stress can, nevertheless, negatively impact calf performance by reducing their feed intake (Dado-Senn et al., 2020) and decreasing their daily weight gain (Broucek et al., 2008). In general, heat stress is a significant concern for animal welfare (Polsky and von Keyserlingk, 2017). Therefore, the precise and timely detection of heat stress in calves is of critical importance for reducing economic losses and improving animal welfare.

Indicators of heat stress level in animals can be divided into 2 categories: environmental (e.g., the temperature–humidity index, THI) and animal-based (ABIs), and between the 2, ABIs are considered superior indicators because they reflect the actual heat stress status in individual animals (Islam et al., 2021). In cows, various physiological (e.g., respiration rate and body temperature) and behavioral (e.g., lying time and lying bout) parameters have been reported as possible ABIs of heat stress (Hoffmann et al., 2020). However, information regarding ABIs in calves is limited compared with cows. Most previous studies in calves have focused solely on physiological ABIs such as respiration rate, heart rate, body temperature, and salivary cortisol (Dado-Senn et al., 2020; Dado-Senn et al., 2023a; Kovács et al., 2020), or behavioral ABIs such as lying time and bout (Kovács et al., 2018; Dado-Senn et al., 2022). Although studies such as Carter et al. (2014), Bakony et al. (2021), and Kamal et al. (2016) investigated both physiological (respiration rate and serum cortisol etc.) and behavioral (proportion of standing and lying etc.) ABIs simultaneously, it remains unclear which ABI is the better indicator of heat stress level in calves. This limitation is primarily attributed to the lack of multimodal sensing devices applicable for calves (Costa et al., 2021).

Recently, a multimodal tail-attached device with a thermistor and 3-axis accelerometer was developed (Higaki et al., 2021) and validated for the simultaneous monitoring of physiological (tail skin temperature: tail ST) and behavioral (activity intensity, lying time, and body position changes, i.e., standing to lying or

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device wirelessly transmitted the data to the receiver in real-time

y-axis, with values ranging from −3 to +3 rad) (Figure 1B). The

102.3), and roll angle (i.e., rotation of the x- and z-axes about the

THI was then calculated as follows: THI = 0.8 × T

-0.3 corresponded to lying left, standing, and lying right body

positions, respectively. We calculated the daily total lying time and
total number of position changes (standing to lying down and vice
versa and lying right to left and vice versa) based on the predicted
position data. While the daily maximum ST was determined from
the 3-min interval sensor data, the daily average activity intensity,
daily total lying time, and daily total position changes were calcu-
lated from the 3-min interval data after excluding data at the time
of feeding (0500–0659 and 1600–1759 h), due to its impact on the
overall activity patterns of calves. During the potential heat stress
period (summer to fall), we randomly selected 20 calves and mea-
sured their RT thrice a week (every 2.4 ± 0.5 d) at around 1100 h
(between 1030 h and 1130 h) using a digital thermometer (TV714J,
Measure Technology Co., Ltd., Taipei, Taiwan).

In the analysis regarding the impact of hot environments on
ABIs, data from mild to hot days (daily average THI of ≥55)
(Hahn, 1999) were selected, and the resulting data from 99 calves
were analyzed. The regression analysis of ABIs on THI used the
piecewise linear regression method (Muggeo, 2008), correcting for
the fixed effect of age and the random effect of calf (Dado-Senn et
al., 2023a) as follows:

\[
ABI_{ij} = \beta_0 + \beta_1 THI_{ij} + \beta_2 \left(THI_{ij} - THI_{b_{ij}}\right)THI_k + \beta_3 AGE_{ij} + CALF_j + \epsilon_{ij},
\]

where \(ABI\) is the sensor-derived ABIs, \(\beta_0\) is the population
intercept, \(\beta_1\) is the left slope, \(THI\) is the daily average THI, \(\beta_2\) is
the difference between the left and the right slopes, \(THI_{b_{ij}}\) is
the breakpoint, \(THI_{k}\) is the dummy variable, \(\beta_3\) is the slope for age,
\(AGE\) is the calf age (days), \(CALF\) is an individual calf as a random
intercept effect, and \(\epsilon_{ij}\) is the random error for \(i\)-th observation
in \(j\)-th calf. An a priori sample size calculation was not conducted as
there is no established calculation method for piecewise regression
analysis.

The association between heat stress and sensor-derived ABIs
was evaluated by analyzing data obtained during days with a daily
average THI of ≥75 (Hahn et al., 2009), consisting of 108 d of
data from 20 individual animals. This data was then categorized
into low and high heat stress groups, based on an RT threshold of
39.5°C (Bakony et al., 2023). This sample size was determined
based on our preliminary data to detect a difference of 6.8 daily
total position change (\(\sigma^2 = 100\)) between the low and high heat stress
groups when expecting the high RT (≥39.5°C) frequency of 21%.

We used the previously described multimodal tail-attached de-
vice equipped with a thermometer and 3-axis accelerometer (Higaki
et al., 2021). The device, which measures 21.0 mm × 26.0 mm ×
9.7 mm and weighs 5.8 g, including the battery, was attached as
previously (Higaki et al., 2021). In brief, the device was inserted into a pocket in a silicone rubber belt and sealed with a
urethane gel sheet. The silicone rubber belt was wrapped around
the tail base with the sensor positioned at the ventral side. The belt
was then stabilized in place with a hook-and-loop fastener. The x-,
y-, and z-axes of the 3-axis accelerometer were oriented to measure
lateral, proximal/distal, and dorsoventral accelerations relative to
the tail, respectively (Figure 1A). This device also measures ST
(ranging from 20°C to 45°C), activity intensity (ranging from 0 to
102.3), and roll angle (i.e., rotation of the x- and z-axes about the
y-axis, with values ranging from −3 to +3 rad) (Figure 1B).

The device wirelessly transmitted the data to the receiver in real-time

at 3-min intervals, which were then uploaded to the cloud server
via 3G/LTE.

The tail-attached device was attached to all calves, and sensor
data were collected for an average period of 4 weeks (26.4 ± 6.8 d);
the calves reached an average age of 43.3 ± 10.1 d at the end of the
experiment. Roll angle data were used to determine each animal’s
body positions (standing, lying left, and lying right) at each 3-min
time point, as described in a previous study (Higaki et al., 2021)
and using threshold values suitable for identifying the calves’ body
positions. Specifically, radians of ≥0.3, between −0.3 and 0.3, and
< −0.3 corresponded to lying left, standing, and lying right body
positions, respectively. We calculated the daily total lying time and
total number of position changes (standing to lying down and vice
versa and lying right to left and vice versa) based on the predicted
position data.
The estimated sample size was 103 d of data using 95% confidence and 80% power. The regression of ABIs on RT used linear mixed models, which accounted for the fixed effect of age and the random effect of calf as follows:

\[ ABI_{ij} = \beta_0 + \beta_1 RT_{ij} + \beta_2 AGE_{ij} + CALF_j + \varepsilon_{ij} \]

where \( RT \) is the categorical RT levels of calves (<39.5°C or ≥39.5°C). Because the animal’s core body temperature is maintained within a normal range until the heat load reaches a certain threshold level (Silanikove, 2000), the RT values of calves were divided into normal (<39.5°C) and high (≥39.5°C) temperature groups. No data in each RT group were excluded from the analysis. The model assumption of normality of residuals were visually examined using quantile-quantile plot. All statistical analysis was performed with R (version 4.3.0) using “nlme” and “segmented” packages (Muggeo, 2008). Differences were considered significant at P-values of <0.05. All values presented in the text represent the mean ± standard deviation.

Attaching sensors to the calves did not result in any severe lesions throughout the experimental period, although all calves experienced temporary depilation. None of the calves exhibited severe symptoms of diseases requiring veterinary treatment.

THI breakpoints for the daily maximum tail ST, daily average activity intensity, daily total lying time, and daily total position change were detected at 73.6, 79.1, 72.3, and 79.1, respectively (Figure 2). The ABI values at the corresponding THI breakpoints were as follows: the daily maximum tail ST was 38.7°C, the daily average activity intensity was 10.3, the daily total lying time was 16.4 h, and the daily total position change was 38.8 times, when adjusted for age to the average age of calves in the entire data set, 27.7 d (Figure 2). The slope for the tail ST was considerably higher after the breakpoint (0.119) compared with before (0.035), suggesting a disruption in the regulation of body temperature under high THI conditions. We found no comparable data on the THI breakpoint for tail ST in the literature. However, Dado-Senn et al. (2020) reported the absence of THI breakpoints for rump, neck, and ear STs under a daily average THI ranging from approximately 60 to 90. Additionally, Dado-Senn et al. (2023a) did not find a THI breakpoint for rump ST under a daily average THI ranging from approximately 61 to 78. In contrast, Kovács et al. (2020) reported a THI breakpoint of 83.0 for ear ST within a daily average THI range of approximately 76 to 92. The discrepancy regarding the presence of THI breakpoints and the relatively lower THI breakpoint for tail ST observed in this study indicate that the tail, particularly its ventral side, may have a limited capacity for heat dissipation compared with other exposed skin areas. This means that tail ST is a better indicator of core body temperature than the STs on other body parts, which is supported by the high correlation (R² = 0.8) previously observed between the daily maximum tail ST and daily maximum RT (Nogami et al., 2013). Indeed, the THI breakpoint value that we observed for tail ST is similar to that for RT (69) determined under comparable THI conditions (i.e., daily average THI of 60.8–77.3: Dado-Senn et al., 2023a). As RT is considered the standard for assessing homeothermy and heat stress (Dado-Senn et al., 2020), our results indicate that monitoring ST of the tail using a tail-attached device is a more reliable approach for assessing...
the heat stress levels compared with monitoring that of other body parts.

Although we detected a breakpoint for daily total lying time, its slope remained nearly constant under the tested THI conditions (slopes before and after the breakpoint were 0.014 and −0.061, respectively). Meanwhile, the increases in daily total position changes during increasing THI tended to become more pronounced after the breakpoint (slopes before and after the breakpoint were 0.590 and 5.515, respectively). These findings align with those of previous studies. For instance, Kovács et al. (2018) reported that calves under nonshaded conditions (daily average THI of 78.1) changed their positions to lying down about 80% more frequently than calves under shaded conditions (daily average THI of 71.3), although the lying times of the nonshaded and shaded calves were similar. The pronounced increase in positional changes after the THI breakpoint likely reflects the increasing discomfort and frustration of calves under high heat stress (Kovács et al., 2018, Nordlund et al., 2019, Dado-Senn et al., 2022). This significant increase in position changes could explain the pronounced increase in daily average activity intensity observed above the THI breakpoint (slopes before and after the breakpoint were 0.126 and 0.419, respectively). However, Rice et al. (2023) reported similar activity indices between days with high (≥70) and low (<70) daily average THI in calves monitored using a leg-attached accelerometer. This discrepancy may be attributable to the reference value of THI; namely, we accounted the breakpoint (THI of 79), whereas Rice et al. (2023) used a relatively low threshold (THI of 70).

The breakpoints for calves identified in the present study are consistent with the THI threshold of 75, as defined by the Associated Livestock Weather Safety Index (Hahn et al., 2009). Therefore, THI can serve as a valuable environmental indicator for effective heat stress management in calf herds. Interestingly, data from 108 d of monitoring 20 calves under high THI conditions (THI ≥75) included 61 d of data from 19 individuals that had normal RTs (<39.5°C) and 47 d of data from 15 individuals that had high RTs (≥39.5°C) (Figure 3). Thus, based on heat stress conditions evaluated at a specific time of day considering the diurnal variation of RT, the present results indicated a lack of uniformity in the way that calves experience heat stress under high THI conditions, even in the same individual. However, more frequent RT measurements may be necessary in future studies to accurately determine the detailed heat stress conditions of individual calves. This is because the diurnal rhythm of RT could be affected by the microclimate of individual hutches (temperature and humidity etc.) (Dado-Senn et al., 2023b), which was not assessed in this study. Nevertheless, the present results may indicate that the THI alone cannot be used to precisely detect heat-stressed individuals. In contrast, continuous monitoring of ABIs is more useful for identifying heat-stressed individuals. In the present linear mixed models, the estimated coefficients of the RT group for the ABIs were 0.60 [95% confidence interval (CI): 0.41, 0.78] for daily maximum tail ST, 0.78 (95% CI:

![Figure 2](image_url)

**Figure 2.** Relationship between daily average temperature–humidity index (THI) and sensor-derived animal-based indicators (ABIs). Relationships between THI and the ABIs were estimated using piecewise regression models. Open circles represent the observed values. Regression lines in each graph represent the predicted ABI derived from THI values in calves 27.7 days old (the average age of calves in the total data set). Solid circles and lines above the x-axis represent breakpoints and their 95% confidence intervals, respectively.
0.04, 1.52) for daily average activity intensity, 0.16 (95% CI: −0.17, 0.49) for daily total lying time, and 10.35 (95% CI: 5.87, 14.83) for daily total position change (Figure 3). Thus, we found that the daily maximum tail ST, daily average activity intensity, and daily total position change were significantly higher in heat-stressed calves (RT ≥39.5°C) compared with normal calves (RT <39.5°C), while the daily total lying time was similar in both groups. These findings suggest that among the ABIs, tail ST, activity intensity, and position change are the reliable and effective ABIs indicative of heat stress status in calves. Moreover, the tail-attached device can serve as a valuable tool for monitoring and detecting changes in these key ABIs.

In the present study, we examined the sensor-derived ABIs for its association with THI as well as heat stress conditions, on a daily basis. This is because the ABIs and THIs over relatively short time periods varied and might not accurately reflect the actual heat stress status. Indeed, in mature cattle, it has been reported that the heat stress level is higher when both daytime and nighttime THI are elevated, compared with situations where only daytime THI is high (Mader et al., 2006). However, in actual farm situations, calves experiencing heat stress should be detected in a timely manner, to provide early intervention, lower morbidity and mortality rates directly and indirectly related to the heat stress, and thereby reduce economic loss of the farm (Roland et al., 2016). Therefore, additional experiments should be conducted in smaller time intervals, through examining detailed sequential changes of ABIs and comparing them with the heat stress status at specific intervals based on frequent RT measurements.

In conclusion, we have demonstrated the applicability of a tail-attached device for monitoring both physiological (tail ST) and behavioral (activity intensity, lying time, and body position change) ABIs in preweaned calves. Among these ABIs, tail ST, activity intensity, and position change are reliable and effective ABIs indicative of heat stress status in calves. Use of the tail-attached device, with its ability to automatically and continuously monitor ABIs in individual calves, has the potential to precisely detect heat-stressed calves in a timely manner, thereby reducing economic losses and enhancing animal welfare.

References

Figure 3. Relationship between rectal temperature (RT) levels and the sensor-derived animal-based indicators (ABIs) in calves growing under high temperature–humidity index (THI) conditions. The relationship between heat stress levels and the sensor-based ABIs was analyzed using calf data generated during days with a daily average THI of ≥75, with high and low heat stress groups defined by a threshold RT of 39.5°C. The relationship between RT levels (≥39.5°C and <39.5°C) and the sensor-based ABIs was examined using linear mixed models. The results are displayed as a beeswarm boxplot, where the horizontal lines of the box indicate the quartiles, and the whisker extends to 1.5 times the interquartile range or the maximum/minimum value, whichever is shorter. *P < 0.05 and **P < 0.001.
Notes

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