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Evaluating phenotypes associated with heat tolerance and identifying moderate and severe heat stress thresholds in lactating sows housed in mechanically or naturally ventilated barns during the summer under commercial conditions

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Abstract

An accurate understanding of heat stress (**HS**) temperatures and phenotypes that indicate HS tolerance is necessary to improve swine HS resilience. Therefore, the study objectives were 1) to identify phenotypes indicative of HS tolerance, and 2) to determine moderate and severe HS threshold temperatures in lactating sows. Multiparous (4.10 ± 1.48) lactating sows and their litters (11.10 ± 2.33 piglets/litter) were housed in naturally ventilated (n = 1,015) or mechanically ventilated (n = 630) barns at a commercial sow farm in Maple Hill, NC, USA between June 9 and July 24, 2021. In-barn dry bulb temperatures (**T_{DB}**) and relative humidity were continuously recorded for naturally ventilated (26.38 ± 1.21 °C and 83.38 ± 5.40%, respectively) and mechanically ventilated (26.91 ± 1.80 °C and 77.13 ± 7.06%, respectively) barns using data recorders. Sows were phenotyped between lactation days 11.28 ± 3.08 and 14.25 ± 3.26. Thermoregulatory measures were obtained daily at 0800, 1200, 1600, and 2000 h and included respiration rate, and ear, shoulder, rump, and tail skin temperatures. Vaginal temperatures (**T_V**) were recorded in 10 min intervals using data recorders. Anatomical characteristics were recorded, including ear area and length, visual and caliper-assessed body condition scores, and a visually assessed and subjective hair density score. Data were analyzed using PROC MIXED to evaluate the temporal pattern of thermoregulatory responses, phenotype correlations were based on mixed model analyses, and moderate and severe HS inflection points were established by fitting T_V as the dependent variable in a cubic function against T_{DB}. Statistical analyses were conducted separately for sows housed in mechanically or naturally ventilated barns because the sow groups were not housed in each facility type simultaneously. The temporal pattern of thermoregulatory responses was similar for naturally and mechanically ventilated barns and several thermoregulatory and anatomical measures were significantly correlated with one another ($P < 0.05$), including all anatomical measures as well as skin temperatures, respiration rates, and T_V. For sows housed in naturally and mechanically ventilated facilities, moderate HS threshold T_{DB} were 27.36 and 26.69 °C, respectively, and severe HS threshold T_{DB} were 29.45 and 30.60 °C, respectively. In summary, this study provides new information on the variability of HS tolerance phenotypes and environmental conditions that constitute HS in commercially housed lactating sows.

Lay Summary

Climate change and the associated increase in global temperatures have a well-described negative impact on swine production. Therefore, improving swine heat stress resilience is of utmost importance to reduce the deleterious effects of heat stress on swine health, performance, and welfare. Genomic selection for heat stress resilience may be a viable strategy to improve swine productivity in a changing climate. However, identifying environmental conditions that constitute heat stress and deriving novel traits that can be easily collected on farm and provide accurate and precise predictions of heat stress tolerance is a necessary step. The present study demonstrated that housing conditions had a limited influence on heat stress tolerance phenotypes, several anatomical and thermoregulatory measures were correlated, and housing conditions impacted heat stress threshold temperatures. Results from this study may be applied to large-scale phenotyping initiatives to develop or refine genomic selection indexes for heat stress resilience in pigs.

Key words: climatic resilience, closer-to-biology phenotypes, heat stress, phenomics

Abbreviations: BCS_{Cal}, caliper body condition score; BCS_{Vis}, visual body condition score; bpm, breaths per minute; CIDR, controlled internal drug releasing device; EA, ear area; EL, ear length; HD, hair density; HS, heat stress; PS, panting score; RH, relative humidity; RR, respiration rate; T_{DB}, dry bulb temperature; T_{DP}, dew point temperature; T_{ES}, ear skin temperature; T_{RS}, rump skin temperature; T_{SS}, shoulder skin temperature; T_{TS}, tail skin temperature; T_V, vaginal temperature

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Introduction

Climate change induced heat stress (**HS**) compromises animal health, productive efficiency, and welfare resulting in economic losses and reduced food security (Johnson, 2018; Thorton et al., 2021). The effects of increasing environmental heat loads on swine production may be exacerbated by rapid genetic progress for performance traits over the past few decades, as well as nutritional strategies and management practices that have increased pig performance leading to more efficient meat production, faster growth rates, and greater lactation output by sows to support larger litter sizes (Solá-Oriol and Gasa, 2017; Strathe et al., 2017; Wu et al., 2020). These advancements contribute to the long-term sustainability and profitability of the swine industry. However, greater performance is directly linked with greater overall metabolic heat production in pigs (Stinn and Xin, 2014; Cabezon et al., 2017). Consequently, this reduces the thermal gradient between the pig and the external environment (Curtis, 1983). As a result, recent research by our group demonstrates that reproductively active sows have become more HS sensitive (McConn et al., 2022) than what previous reports had indicated (Federation of Animal Science Societies, 2020). Therefore, it is likely that lactating sows are even more HS susceptible due to the aforementioned increase in lactation output to support greater litter sizes (Cabezon et al., 2017) and the associated increase in metabolic heat production associated with advancing lactation (Johnson et al., 2019; Zhang et al., 2020).

Genetic and genomic selection has resulted in greater litter sizes (and consequently piglets with reduced and/or more variable birth weights; Bérard et al., 2008), which demands greater milk production to maximize piglet body condition, growth, and survival. In this context, commercial primiparous and multiparous sows have been estimated to produce 24% and 39% more metabolic heat, respectively, when compared to sows from >30 yr ago (Cabezon et al., 2017). As such, it is necessary to maintain the in-barn environment at temperatures that promote a balance between heat loss and heat gain (e.g., from metabolic processes and the environment) to optimize performance (Curtis, 1983). The most effective way to improve this thermal balance is by decreasing the environmental heat load in swine facilities through cooling technologies. However, these cooling technologies (e.g., evaporative cooling pads, fans, sprinklers) primarily rely on thermal and evaporative heat loss gradients and are less effective as temperature and humidity rise. Furthermore, guidelines for what are considered HS temperatures for lactating sows are based on outdated information (26- to 42-yr-old data; Federation of Animal Science Societies, 2020), and to our knowledge, no differentiation by facility type exists.

In addition to improving our understanding of what constitutes HS for lactating sows with current genetics, it is also important to understand the interactions between phenotypic characteristics and the corresponding risk factors for succumbing to HS. When genetically selecting for thermotolerance traits, swine breeders refine their overall breeding goals and selection indexes according to the priorities of consumers and industry stakeholders. As such, balancing improved productive efficiency under HS conditions with phenotypic indicators of climatic resilience and overall animal welfare is a priority for the industry sustainability (Merks et al., 2011). However, thermotolerance is a polygenic trait (Tiezzi et al., 2020) that can be moderately antagonistic to traditional performance metrics (e.g., growth performance, milk production; Carabano et al., 2019). Therefore, effective genetic selection for improved thermotolerance requires the integration (through selection indexes) of several close-to-biology phenotypes that encompass thermoregulatory, performance, health, and welfare mechanisms (Carabano et al., 2019; Brito et al., 2020).

Two study objectives were defined based on the need to identify HS threshold temperatures in lactating sows with current genetics and identify phenotypes encompassing thermoregulatory, performance, health, and welfare mechanisms to determine the risk of succumbing to HS. The first study objective was to develop (or adapt) comprehensive protocols to identify phenotypes that contribute to HS tolerance. The second study objective was to determine moderate and severe HS threshold temperatures in lactating sows during mid- to late-lactation based upon methods previously described by our group (McConn et al., 2022). Similar to previous studies in nonpregnant and gestating sows with current genetics (McConn et al., 2022), it was hypothesized that lactating sows with current genetics would have HS threshold temperatures that were lower than what is currently recommended (Federation of Animal Science Societies, 2020) and that phenotypic risk factors associated with HS tolerance could be easily measured under commercial production conditions and would be indicative of greater or reduced risk of succumbing to HS. Study objectives and hypotheses were applied to 1,645 sows (Landrace × Large White) and their litters during mid- to late-lactation housed in either mechanically or naturally ventilated barns under commercial production conditions during natural summer HS in North Carolina, USA.

Materials and Methods

Animals and housing

The Purdue University Animal Care and Use Committee approved all procedures involving pigs (protocol #1912001990). Animal husbandry and use protocols were based on the "Guide for the Care and Use of Agricultural Animals in Research and Teaching" (Federation of Animal Science Societies, 2020). A total of 1,645 multiparous lactating sows (Large White × Landrace) and their litters were housed within individual farrowing crates (2.0 × 1.8 m) at a commercial sow farm in Maple Hill, North Carolina, USA (34.70738°, −77.73653°). Sows and litters were housed in either a naturally ventilated (n = 1,015 sows and litters; n = 12 naturally ventilated rooms) or mechanically ventilated (n = 630 sows and litters; n = 13 mechanically ventilated rooms) farrowing barn. Naturally ventilated buildings are defined as facilities with fresh air supply provided through passive means such as wind speed or thermal buoyancy. Within the naturally ventilated facility used in the present study, stir fans and drip coolers were in use during the study. Mechanically ventilated buildings are defined as facilities that use electrically powered fans to provide fresh air and control in-barn temperature as ambient conditions allow. In the mechanically ventilated facility used in the present study, all fresh air was provided to the farrowing rooms through ceiling inlets with air passing over evaporative cooling pads prior to entering the rooms. Minimum summer ventilation rates were set at 1.68–2.1 m^3/min for the mechanically ventilated facility. Sows and litters were selected so that parity (4.10 ± 1.48) and piglets per litter

(11.10 ± 2.33 piglets/litter) were similar between barn type and all sows and litters were on trial for 4 d between 11.28 ± 3.08 and 14.25 ± 3.26 d of lactation. Novel phenotypes associated with heat tolerance were measured between June 9, 2021 and July 24, 2021.

Environmental data collection

Weather station and in-barn environmental data were collected throughout the length of the trial. Environmental data are presented in Figures 1, 2, and 3. The weather station (Albert Ellis Airport, Jacksonville, NC, USA; 34.83333°, −77.61667°) was located approximately 14 km from the commercial sow farm. Weather station data included dry bulb temperature (**T_{DB}**), dew point temperature (**T_{DP}**), and relative humidity (**RH**). During the course of the trial, windspeed was 9.5 ± 6.9 km/h and wind direction was 136 ± 100° from true North. For in-barn environmental data, four data loggers per farrowing room (Hobo model #MX1101; data logger temperature/RH; accuracy ±0.20 °C and ±2% RH; Onset; Bourne, MA, USA) were mounted at sow height to record T_{DB} and RH, which were used to calculate T_{DP} using the equations described by Buck (1981). Environmental data from each of the four in-barn data loggers were averaged on a per room basis.

Thermoregulatory data collection

Respiration rate (**RR**), ear skin temperature (**T_{ES}**), shoulder skin temperature (**T_{SS}**), rump skin temperature (**T_{RS}**), and tail skin temperature (**T_{TS}**) were measured on all sows throughout the trial. Vaginal temperatures (**T_V**) were collected on 1,381 sows (n = 865 sows in naturally ventilated barn with 569,576 records and n = 516 sows in mechanically ventilated barn with 362,630 records) throughout the trial. Respiration rate was collected on 1,644 sows (n = 1,014 sows in naturally ventilated barn with 15,935 records and n = 630 sows in mechanically ventilated barn with 9,877 records) by counting flank movements for 15 s and multiplying by 4 to calculate breaths per minute (**bpm**) at 0800, 1200, 1600, and 2000 h daily as previously described (Johnson et al., 2016; Kpodo et al., 2019). In addition, a subjective panting score (**PS**) was developed specifically for this study and assessed at 1200 h each day using three categories: 0 = mouth closed and slow relaxed breathing, 1 = elevated breathing with rapid flank movements and closed mouth, and 2 = elevated breathing with rapid flank movements and open mouth (Table 1). Panting score was collected on a total of 1,644 sows (n = 1,014 sows in naturally ventilated barn with 4,049 records and n = 630 sows in mechanically ventilated barn with 2,516 records). An infrared thermometer (Raytek model ST61; accuracy = ±1%; emissivity = 0.98; resolution = 0.10 °C; Raytek Corporation, Fluke Process Instruments, Everett, WA, USA) was used to measure T_{ES} at the back of the ear on 1,644 sows (n = 1,014 sows in naturally ventilated barn with 15,690 records and n = 630 sows in mechanically ventilated barn with 9,872 records), T_{SS} at the point of the shoulder on 1,644 sows (n = 1,014 sows in naturally ventilated barn with 15,693 records and n = 630 sows in mechanically ventilated barn with 9,873 records), T_{RS} at the top of the rump on 1,643 sows (n = 1,014 sows in naturally ventilated barn with 15,693 records and n = 629 sows in mechanically ventilated barn with 9,872 records), and T_{TS} at the base of the tail on 1,643 sows (n = 1,014 sows in naturally ventilated barn with 15,691 records and n = 629 sows in mechanically ventilated barn with 9,872 records) on clean and dry skin at 0800, 1200, 1600, and 2000 h daily. Vaginal temperature was monitored in 10 min intervals using calibrated thermochron temperature recorders (iButton model DS1921H, calibrated accuracy ± 0.15 °C; resolution = 0.125 °C; Dallas Semi-conductor, Maxim, Irving, TX, USA) attached to a modified blank controlled internal drug releasing device (**CIDR**) designed for use in cattle (EAZI-BREED CIDR; Zoetis; Parsipanny, NJ, USA) similar to previous reports (Burdick et al., 2012; Johnson and Shade, 2017) and illustrated in Figure 4. For construction, the progesterone containing silicone layer was removed from the CIDR, the wings were cut to 3.81 cm in length and the CIDR wing ends were rounded using a rotary tool (Dremel model #3000-1/24; Racine, WI, USA) with a filing attachment (Dremel model #407 sanding band; Racine, WI, USA) and then manually sanded with fine grit sandpaper (220 Fine Grit Sandpaper, model #26220PGP-4; 3M; St. Paul, MN, USA) to prevent vaginal abrasions during insertion and removal. The thermochron temperature recorder was placed within the CIDR slot and attached using electrical tape (Cambridge Vinyl Electrical Tape; model #CET-01BLK-SL6; Cambridge Resources; Belmont, MA, USA) as illustrated in Figure 4.

Prior to insertion, the vulvas of unrestrained sows were cleaned by three alternating rounds of povidone-iodine (Betadine solution; 5% povidone-iodine; Purdue Pharma L.P.; Stamford, CT, USA) and 70% EtOH. Vaginal implants were sterilized by submerging in chlorhexidine gluconate (chlorhexidine solution; 2% chlorhexidine gluconate; Durvet, Inc.; Blue Springs, MO, USA) for approximately 5 min, and then inserted approximately 16.5 cm into the vagina of unrestrained sows using a lubricated (OB Lube; Huvepharma, Inc.; St. Joseph, MO, USA) cattle CIDR applicator (Eazi-Breed CIDR Applicator; Zoetis; Parsipanny, NJ, USA). The vaginal monitors were removed at the end of the data collection period and no signs of infection (e.g., discolored vaginal discharge and fever) or localized inflammation (e.g., redness and swelling) were observed for any sow.

Sow anatomical characteristic data collection

The ability of an animal to dissipate body heat depends on anatomical characteristics such as the animal's surface area, hair density, and body mass (Curtis, 1983; Sejian et al., 2018). A greater surface area to mass ratio is associated with decreased HS sensitivity (Epstein et al., 1983), and greater hair covering may be a disadvantage for dissipating body heat through the skin (Sejian et al., 2018). Therefore, anatomical characteristics associated with heat dissipation capacity including ear size, hair density, and body condition were recorded in all sows for comparison against thermoregulatory metrics. For ear size measures, a 10.2 × 15.2 cm grid card containing 1 cm × 1 cm squares was placed next to the sows' ear and a photo was taken with a digital camera to evaluate ear area (**EA**) and ear length (**EL**) using Image J (National Institutes of Health; Bethesda, MD, USA). Hair density (**HD**) was evaluated using a subjective visual score from 0 to 2 whereby 0 = hairless or limited hair cover, 1 = normal or moderate hair cover, and 2 = sow with greater than normal hair cover. Body condition score was evaluated using a sow caliper (**BCS_{Cal}**; Knauer and Baitinger, 2015) and a visual body condition score (**BCS_{Vis}**) was recorded based on five categories: 1 = emaciated, 2 = thin, 3 = ideal, 4 = fat, and 5 = overly fat (Iowa State University, 2011).

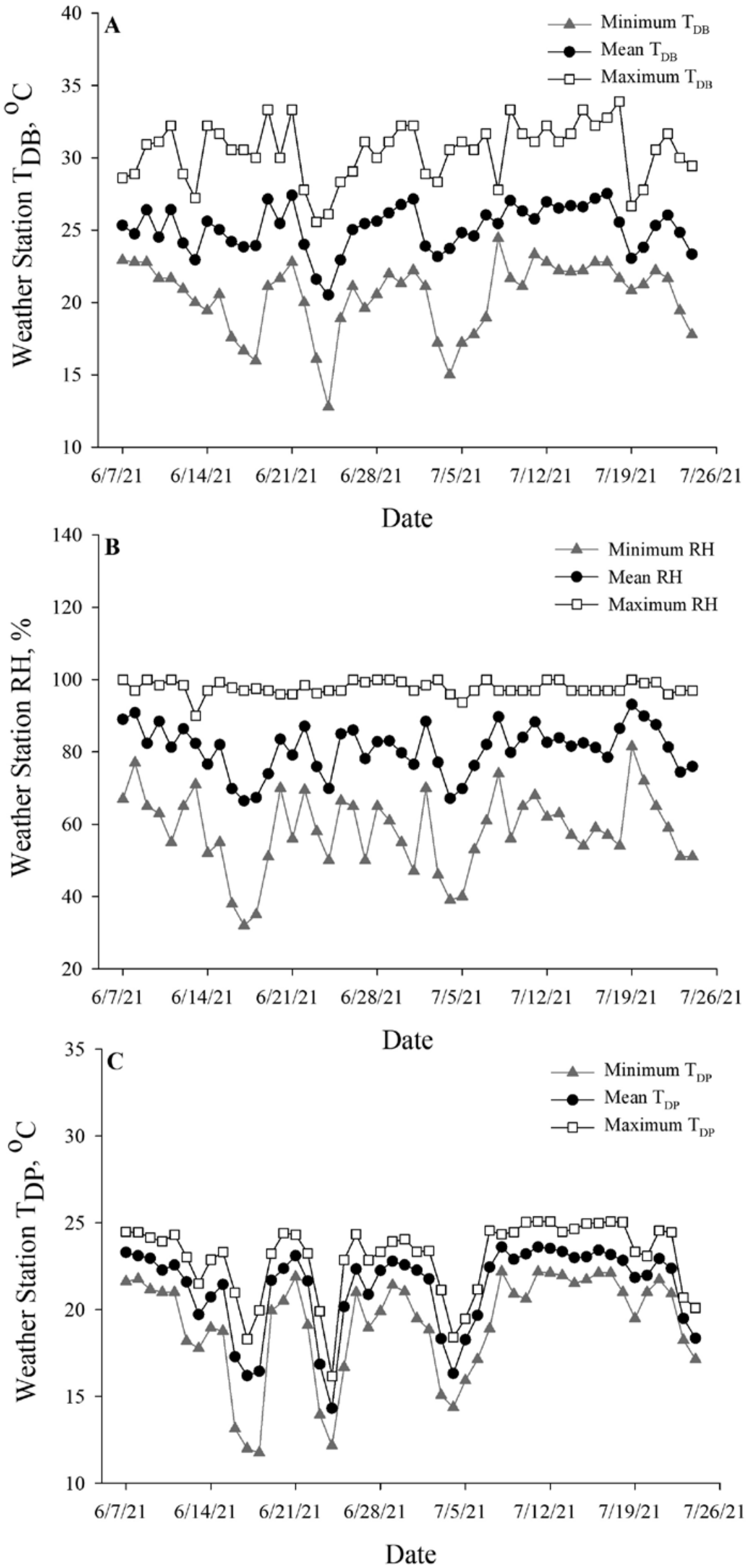

Figure 1. Minimum, mean, and maximum (A) weather station dry bulb temperature (***T*DB**), (B) weather station relative humidity (**RH**), and (C) weather station dew point temperature (***T*DP**) by date of the study.

Statistical analyses

Multiparous lactating sows housed in either mechanically or naturally ventilated barns were on trial over a 46-d period during the summer of 2021 at a commercial sow farm in North Carolina, USA, with individual sows tested in 4 d increments during mid- to late-lactation. During this period, due to logistical and biosecurity issues associated with conducting research in commercial swine facilities, sow groups

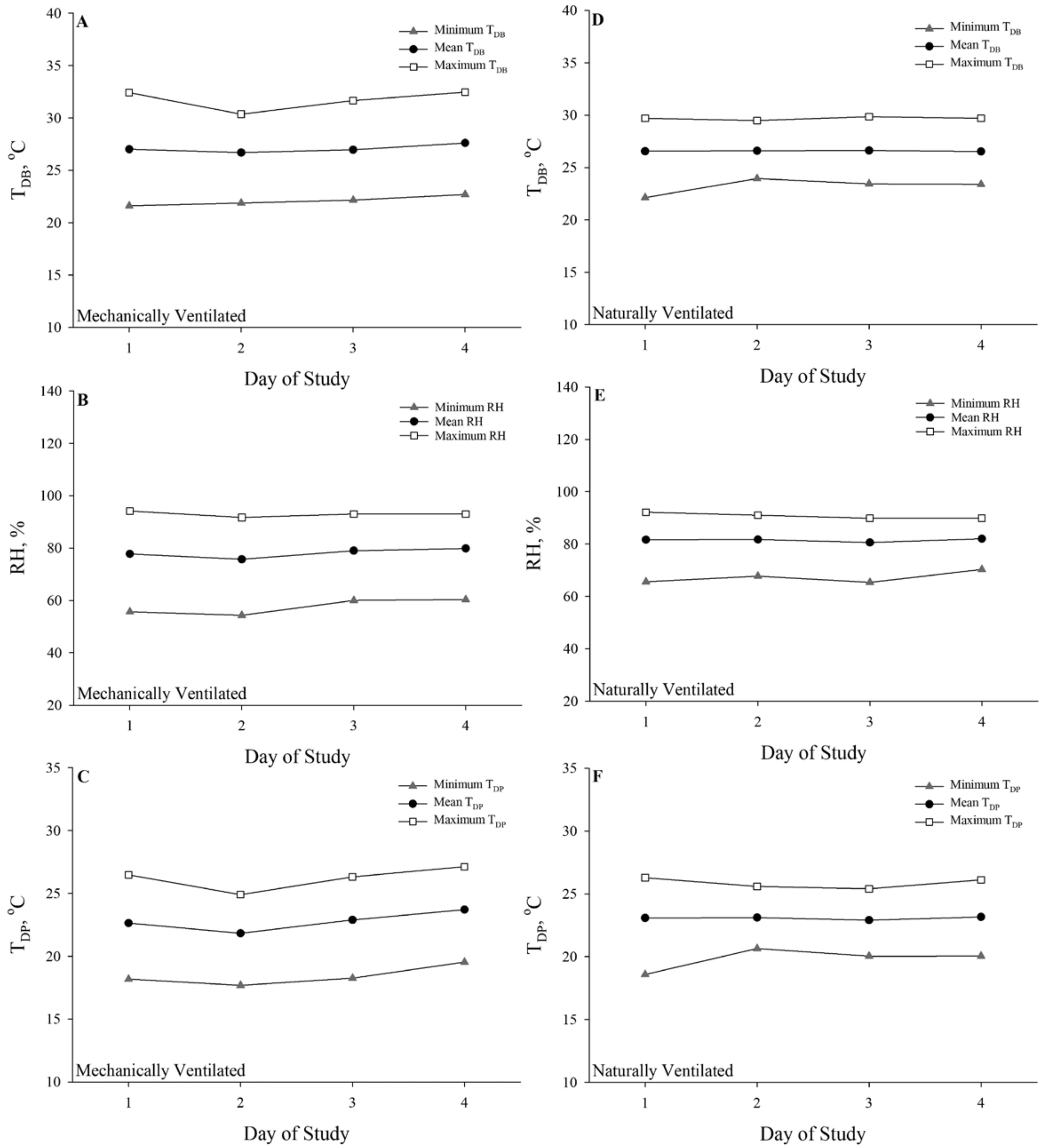

Figure 2. Minimum, mean, and maximum (A) mechanically ventilated barn dry bulb temperature (***TDB***), (B) mechanically ventilated barn relative humidity (**RH**), (C) mechanically ventilated barn dew point temperature (***TDP***), (D) naturally ventilated barn T_{DB}, (E) naturally ventilated barn RH, and (F) naturally ventilated barn T_{DP} by day of study during the 4-d period of lactating sow measurements.

were not housed within each barn type at the same time. Therefore, data were collected on sows housed in mechanically and naturally ventilated barns during different time periods. As such, statistical analyses for parameters measured in sows housed in mechanically and naturally ventilated barns were performed separately. Correlations between thermoregulatory and anatomical characteristics were performed based on a mixed model analyses using the BLUPF90+ software (Lourenco et al., 2022). The significance of the phenotypic correlation between traits was based on the highest posterior density interval. Effects considered for each trait are presented in Table 2. Correlations between weather station and in-barn environmental data (e.g., T_{DB} and RH%) were performed using the Pearson correlation coefficient.

Sow was the experimental unit for all analyzed parameters. Skin temperatures (T_{ES}, T_{SS}, T_{RS}, T_{TS}), RR, and T_V data collected for each sow were averaged by hour and then analyzed using the MIXED procedure in SAS 9.4 (SAS Institute Inc., Cary, NC, USA). Hour was considered as a fixed effect, while parity, location (e.g., barn and room within barn), week of study, and

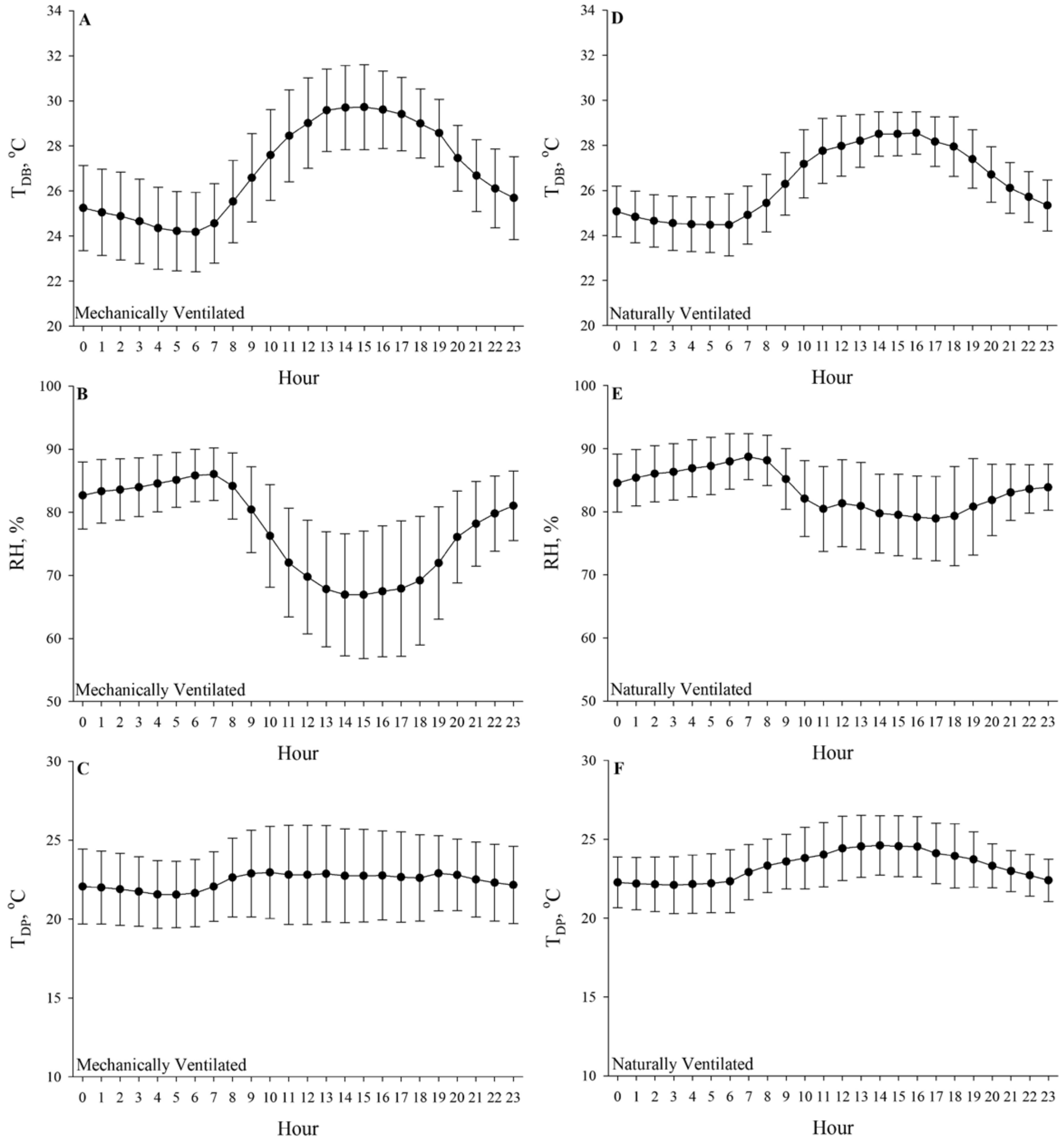

Figure 3. The daily pattern of (A) mechanically ventilated barn dry bulb temperature (***T*DB**), (B) mechanically ventilated barn relative humidity (**RH**), (C) mechanically ventilated barn dew point temperature (***T*DP**), (D) naturally ventilated barn T_{DB}, (E) naturally ventilated barn RH, and (F) naturally ventilated barn T_{DP} by hour of the day. Data are presented as arithmetic means ± standard deviation.

individual sow were considered random effects. All data resulting from analyses are reported as least squares means (LSmeans) ± standard error (SE), and significance was set at $P \leq 0.05$.

To investigate the relationship between T_V and environmental variables (T_A and T_{DP}) under different barn types (mechanically vs. naturally ventilated), PROC NLIN and NLMIXED procedures in SAS 9.4 (SAS Institute Inc., Cary, NC, USA) were used as previously described in detail by our group (McConn et al., 2022). Briefly, the environmental variables fitted a cubic function for T_V based on the Akaike information criterion and residual variance as previously described (McConn et al., 2022). Inflection points for T_V as a function of T_{DB} and T_{DP} were calculated with the determined function using breakpoint analyses when the first derivative equaled zero as previously described (McConn et al., 2022), and the slope of the model equaled zero before the inflection point. The inflection point was considered to be the T_{DB} associated with moderate HS (i.e., the point at which physiological heat loss mechanisms fail) in sows as previously described (McConn et al., 2022). Furthermore, severe HS (i.e., an abrupt uncontrolled increase in T_V) was calculated as a 0.20 °C increase in T_V above the inflection point as previously reported (McConn et al., 2022).

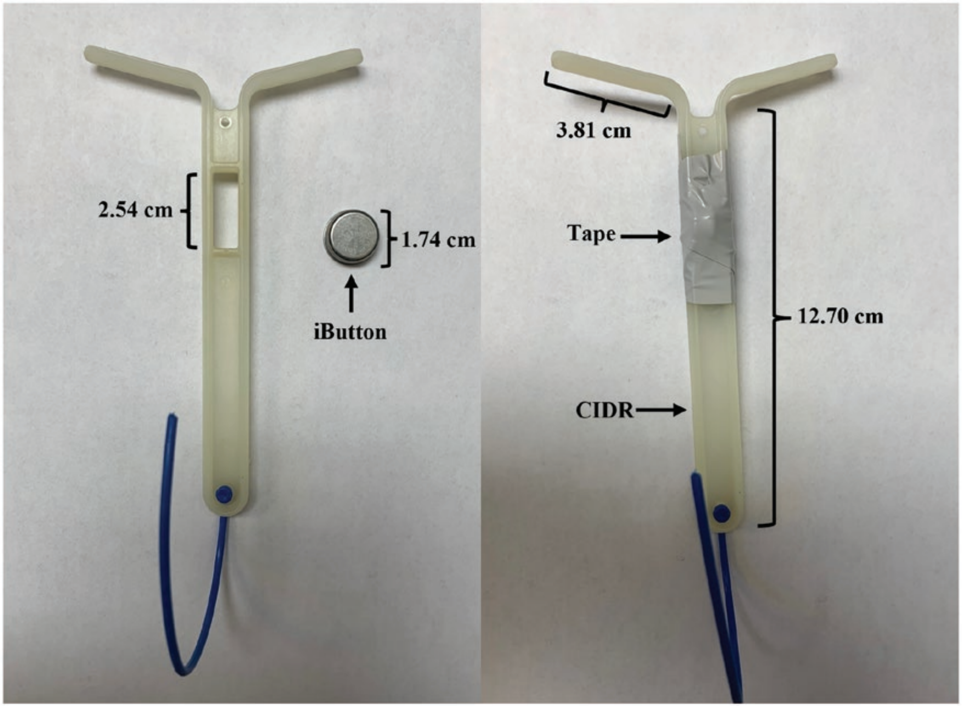

Figure 4. Vaginal temperature monitor.

Table 1. Descriptive statistics for anatomical traits and panting scores in lactating sows

Characteristic	*N*	Mean	Minimum	Maximum	SD
[1]EA, cm^2	705	309.0	183.2	487.9	53.6
[2]EL, cm	713	25.0	14.8	34.3	2.8
[3]BCS_{Vis}	1,598	2.0	1.0	3.0	0.6
[4]BCS_{Cal}	1,614	11.8	6.0	15.0	2.1
[5]HD	1,344	1.9	1.0	3.0	0.6
[6]PS	1,644	1.0	0.0	2.0	0.6

[1]Ear area.
[2]Ear length.
[3]Visual body condition score.
[4]Caliper body condition score.
[5]Hair density.
[6]Panting score.

Table 2. Effects considered in the analyses for each trait measured in lactating sows under heat stress conditions

Trait	Systematic effects	Random effects
[1]T_{ES}	[13]TREC, [14]WDT, [15]PAR, [16]DIL, [17]LOC, [18]CLIM	[21]a, [22]pe
[2]T_{SS}	TREC, WDT, PAR, DIL, LOC, CLIM	a, pe
[3]T_{RS}	TREC, WDT, PAR, DIL, LOC, CLIM	a, pe
[4]T_{TS}	TREC, WDT, PAR, DIL, LOC, CLIM	a, pe
[5]T_V	WD, PAR, LOC, CLIM	a, pe
[6]RR	TREC, WDT, PAR, DIL, LOC, CLIM	a, pe
[7]PS	TREC, WD, PAR, DIL, LOC, CLIM	a, pe
[8]BCS_{Cal}	TREC, [19]W, PAR, LOC, DIL	a
[9]BCS_{Vis}	TREC, W, PAR, LOC, DIL	a
[10]HD	TREC, PAR	a
[11]EA	TREC, [20]PQ	a
[12]EL	TREC, PQ	a

[1]Ear skin temperature, °C.
[2]Shoulder skin temperature, °C.
[3]Rump skin temperature, °C.
[4]Tail skin temperature, °C.
[5]All measures (each 10 min) of vaginal temperatures during 4 d, °C.
[6]Respiration rate, breaths per minute.
[7]Panting score.
[8]Caliper body condition score.
[9]Visual body condition score.
[10]Hair density score.
[11]Ear area, cm^2.
[12]Ear length (cm).
[13]Trait recorder.
[14]Concatenation of week, day and time of measurement.
[15]Parity.
[16]Days in lactation.
[17]Concatenation of barn type and room.
[18]In-barn environmental variable.
[19]Week of measurement.
[20]Picture quality.
[21]A direct additive genetic effect.
[22]Permanent environmental effect.

Results and Discussion

Improving lactating sow management practices and HS resilience is an important step to improving swine industry profitability and sustainability, especially as severe HS events are increasing in frequency (Habeeb et al., 2015). This is because lactating sows are highly susceptible to HS, with reduced milk production (Black et al., 1993; Johnson et al., 2021) and decreased litter growth performance (Guo et al., 2018) frequently cited as consequences. Therefore, the present study sought to evaluate phenotypic characteristics associated with HS tolerance and sensitivity and identify temperatures at which lactating sows would be considered at moderate and severe levels of HS using methods previously established by our group (McConn et al., 2022). Identifying novel traits that can be added to genomic selection schemes is the first step for developing or refining selection indexes for breeding pigs for improved climatic resilience.

Skin temperatures, RR, and T_V were continuously monitored throughout the trial. It was determined that sows housed in a mechanically ventilated barn had T_{ES}, T_{SS}, T_{RS}, and T_{TS} of 36.61 ± 0.10, 36.31 ± 0.12, 37.12 ± 0.08, and 36.77 ± 0.08 °C, respectively, with peak skin temperatures occurring between 1200 and 1600 h regardless of skin temperature measurement location (Figure 5). For sows housed in a naturally ventilated barn, the T_{ES}, T_{SS}, T_{RS}, and T_{TS} of sows

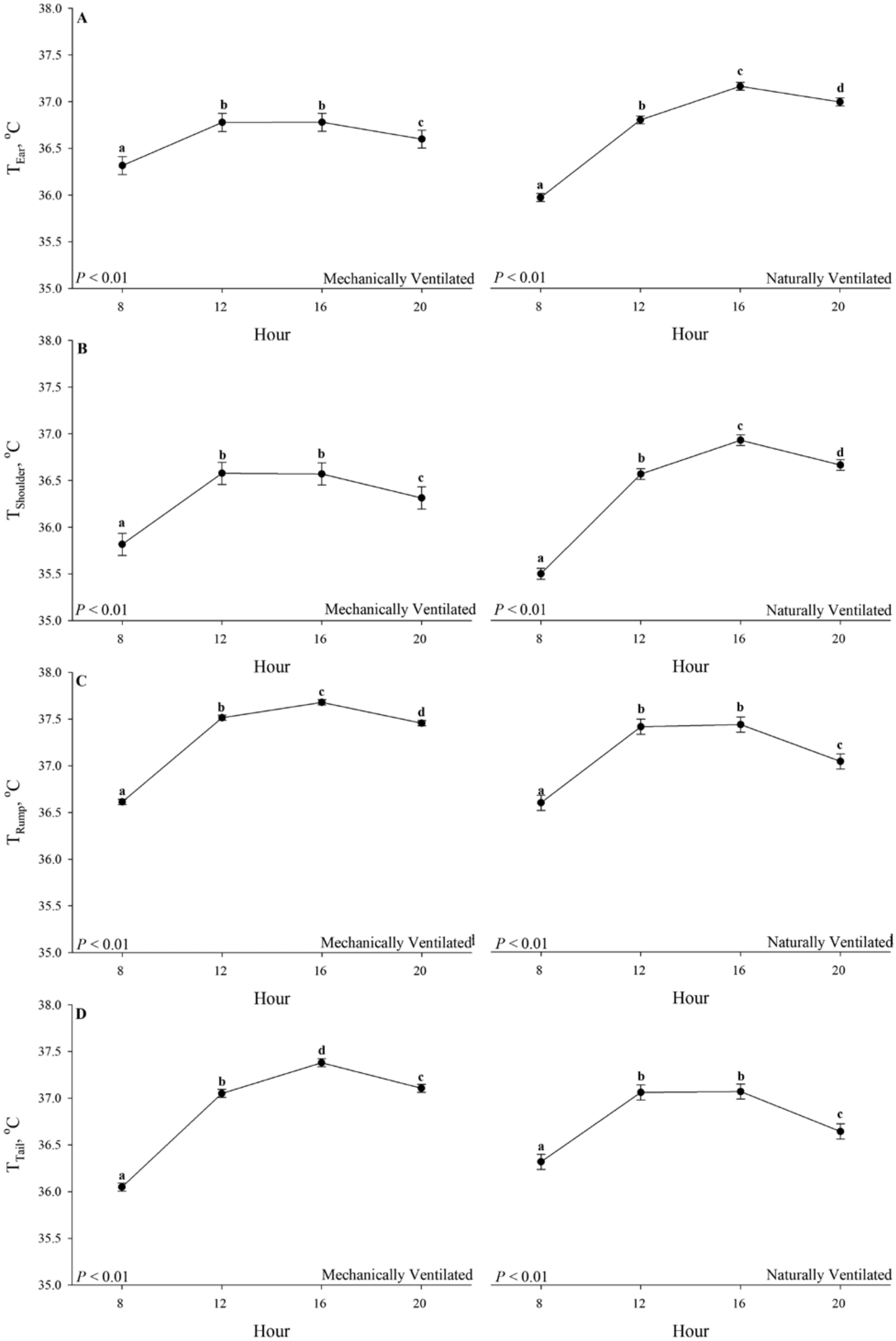

Figure 5. The (A) ear skin temperature (***TES***), (B) shoulder skin temperature (***TSS***), (C) rump skin temperature (***TRS***), and (D) tail skin temperature (***TTS***) of lactating sows housed in either mechanically ventilated or naturally ventilated barns by hour of the day. [a,b,c]Letters indicate differences ($P < 0.01$) by hour. Data are presented as LSmeans ± SE.

were 36.73 ± 0.04, 36.41 ± 0.06, 37.20 ± 0.06, and 36.90 ± 0.04 °C, respectively, with peak skin temperatures occurring between 1200 and 1600 h regardless of skin temperature measurement location (Figure 5). The hours in which peak skin temperature occurred (e.g., 1200 and 1600 h) corresponded with the peak T_{DB} for mechanically ventilated (Figure 3A) and naturally ventilated (Figure 3D) barns. This response was expected when considering the direct role T_{DB} plays in influencing skin temperature measures independent of core body temperature (McConn et al., 2022). Furthermore, based on similarities in daily T_{DB} patterns between mechanically and naturally ventilated barns (Figure 3) and numerical similarities in absolute skin temperatures within each group (Figure 5), it may be suggested that the environment within each barn type had a limited influence on lactating sow skin temperature in the present study.

Sows housed in mechanically ventilated facilities had an overall RR of 70 ± 3 bpm (Figure 6A), whereas sows housed in naturally ventilated facilities had an overall RR of 73 ± 2 bpm (Figure 6B). In addition, the pattern of daily RR response for both mechanically and naturally ventilated barns followed a similar statistical pattern, whereby RR measured at 0800 h was the lowest, the 1200 and 2000 h RR measures were intermediate but similar, and the 1600 h RR measure was the greatest (P < 0.01; Figure 6). The peak RR measure for both barn types taken at 1600 h corresponded with the peak T_{DB} for both mechanically (Figure 1A) and naturally (Figure 1D)

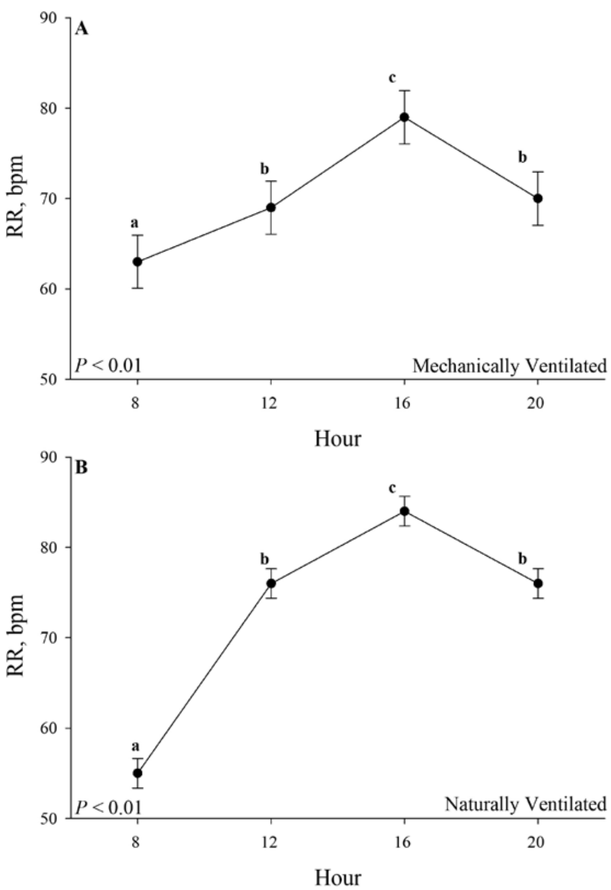

Figure 6. The respiration rate (**RR**) of lactating sows housed in either (A) mechanically ventilated or (B) naturally ventilated barns by hour of the day. [a,b,c]Letters indicate differences (P < 0.01) by hour. Data are presented as LSmeans ± SE.

ventilated barns. These data suggest that RR measures taken on sows housed within either mechanically or naturally ventilated facilities may respond similarly to daily temperature patterns during hot summer months independent of barn type environment.

When considering T_V, it was determined that sows housed in a mechanically ventilated barn had an overall T_V of 39.78 ± 0.11 °C (Figure 7A) and sows housed in a naturally ventilated barn had an overall T_V of 39.71 ± 0.10 °C (Figure 7B). When considering the temporal pattern of T_V response, the minimum T_V for mechanically and naturally ventilated barns occurred at 0800 h and were 39.06 ± 0.10 and 39.21 ± 0.10 °C, respectively (Figure 7). The maximum T_V response for sows housed in a mechanically ventilated barn occurred at 0000 h (P < 0.01; 40.13 ± 0.11 °C; Figure 7A) and at 1900 h (P < 0.01; 40.19 ± 0.10 °C; Figure 7B) for sows housed in a naturally ventilated barn. The differential barn type response for peak T_V was unexpected when considering the relatively similar daily T_{DB} pattern and means for mechanically (26.91 ± 1.80 °C) and naturally (26.38 ± 1.21 °C) ventilated barns (Figure 3). However, this discrepancy may be explained by the differential daily RH% pattern, dissimilar correlations with outside RH% measured by weather station data (Table 3), and absolute response between the mechanically and naturally ventilated barns (Figure 3). Greater RH% reduces the ability of sows to lose excess heat through evaporative heat exchange (i.e., increasing RR) resulting in greater T_V at lower or similar T_{DB} (McConn et al., 2022). Therefore, because RH% remained consistently higher and was more closely correlated with outside RH% in naturally ventilated barns (83.38 ± 5.40%) when compared to mechanically ventilated barns (77.13 ± 7.06%), and this difference was particularly noticeable between 0800 and 2300 h, this likely explains the differential peak T_V response (Table 2; Figs. 1, 2, 3, 7). With this in mind, it is possible that the timing of T_V measures for phenotyping lactating sows may be impacted by the barn type environment. Therefore, in commercial conditions, barn type should be considered when phenotyping sows for core body temperature metrics (e.g., vaginal or rectal temperatures).

Large-scale phenotyping for HS tolerance under commercial production conditions is logistically challenging and requires a significant labor input that, in practice, may not be feasible for all researchers. Therefore, identifying phenotypes that are easily obtained (i.e., taken at a single timepoint and/or anatomical location) is necessary. To address this concern, phenotypic correlations among thermoregulatory indicators of heat stress were performed (Table 4). It was determined that skin temperature measures at all locations (e.g., T_{ES}, T_{SS}, T_{RS}, T_{TS}) were positively correlated with each other ($P \leq 0.05$), with moderate to high correlations ranging from 0.56 to 0.76 (Table 4). These data may suggest that some skin temperatures may be taken at only one location for large-scale phenotyping, especially for breeding purposes. Although, the somewhat lower correlations for T_{ES} vs. T_{SS}, T_{RS}, and T_{TS} (r = 0.56–0.59) may require this temperature to be taken independently. When comparing skin temperature measures to T_V, all skin temperature locations were positively correlated ($P \leq 0.05$) with T_V and the correlations were moderate and ranged from 0.37 to 0.51 (Table 4). It should be noted that previous research indicates that skin temperature is more directly affected by changing environmental conditions rather than physiological changes in the pig HS response (McConn et al., 2022). Therefore, the use of skin temperature as a direct

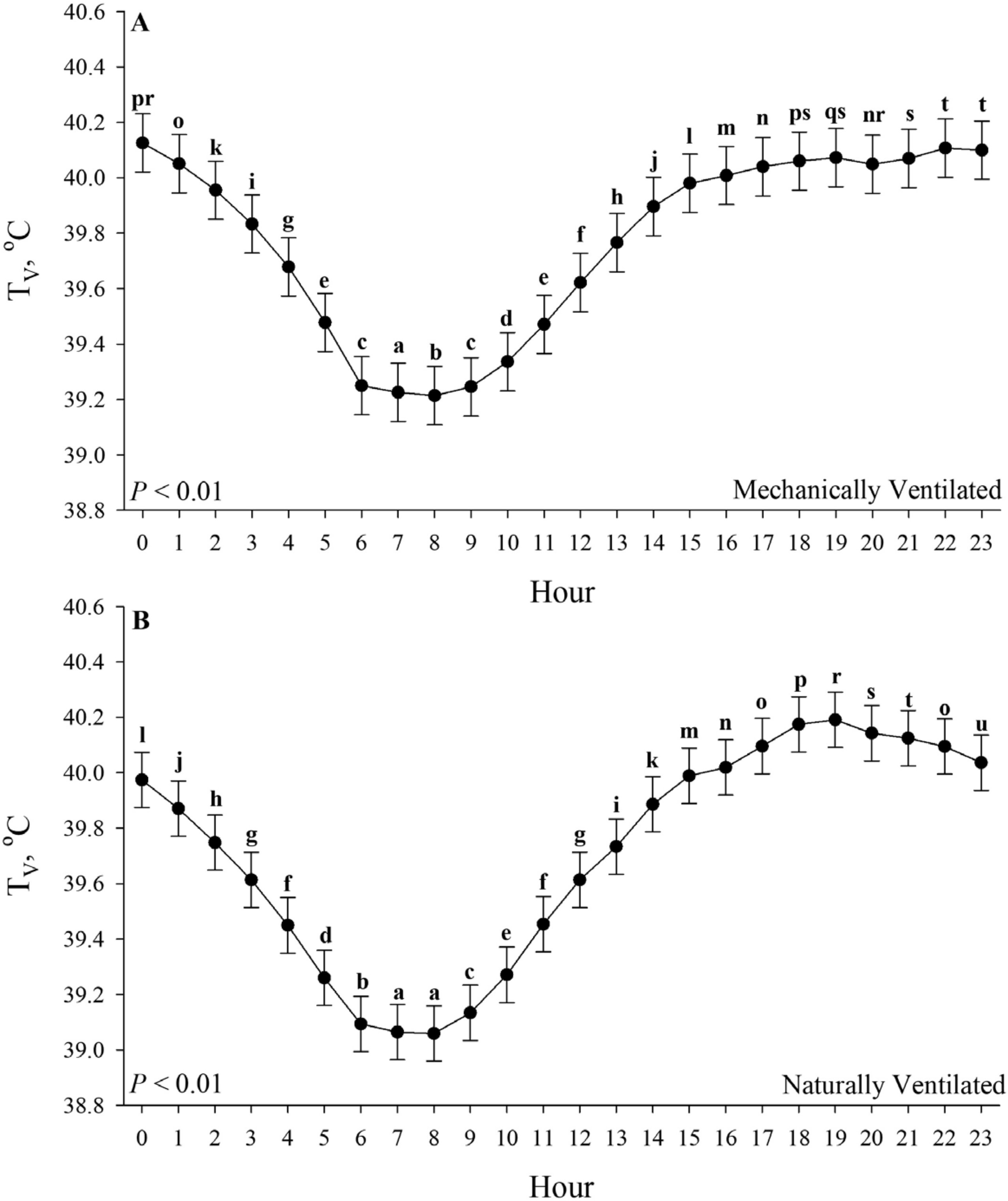

Figure 7. The vaginal temperature (***TV***) of lactating sows housed in either (A) mechanically ventilated or (B) naturally ventilated barns by hour of the day. [a-t]Letters indicate differences ($P < 0.01$) by hour. Data are presented as LSmeans ± SE.

Table 3. Correlations between in-barn vs. weather station T_{DB} and RH% for mechanically and naturally ventilated barns

Barn type	T_{DB}	RH%
Mechanically ventilated barn	0.81	0.48
Naturally ventilated barn	0.85	0.79

indicator of core body temperature response should be done with caution as environmental factors (i.e., radiant heat load, air speed, etc.) may play a larger role in influencing skin temperature response. Furthermore, it was determined that RR and PS were positively correlated ($P \le 0.05$) with all skin temperature measures and with T_V. However, these correlations were low and ranged from 0.15 to 0.26 for RR and

Table 4. Phenotypic correlations among physiological indicators of heat stress in lactating sows under heat stress conditions

Traits	[1]T_{SS}	[2]T_{RS}	[3]T_{TS}	[4]T_V	[5]RR	[6]PS	[7]BCS_{Cal}	[8]BCS_{Vis}	[9]EA	[10]EL	[11]HD
[12]T_{ES}	0.58*	0.59*	0.56*	0.37*	0.15*	0.11*	−0.01	−0.52*	0.04*	0.17*	−0.05*
T_{SS}		0.72*	0.65*	0.43*	0.17*	0.13*	−0.01	−0.60*	0.02	0.20*	0.05
T_{RS}			0.76*	0.51*	0.21*	0.15*	−0.02	−0.12*	0.03	0.26*	−0.01
T_{TS}				0.43*	0.19*	0.12*	−0.01	−0.21*	0.01	0.18*	0.05*
T_V					0.26*	0.19*	−0.16	0.05	0.05	0.07	−0.08*
RR						0.21*	0.07	−0.35	0.05*	0.04*	0.49
PS							0.04	−0.31	0.04	0.01	−0.66*
BCS_{Cal}								0.70*	0.07	−0.03	−0.06
BCS_{Vis}									0.05	−0.01	−0.05
EA										0.78*	0.01
EL											−0.03

[1]Shoulder skin temperature, °C.
[2]Rump skin temperature, °C.
[3]Tail skin temperature, °C.
[4]Vaginal temperature, °C.
[5]Respiration rate, breaths per minute.
[6]Panting score.
[7]Caliper body condition score.
[8]Visual body condition score.
[9]Ear area, cm^2.
[10]Ear length, cm.
[11]Hair density.
[12]Ear skin temperature, °C.
*Indicates the significant phenotypic correlations based on the highest posterior density interval, which does not include the zero value.

0.11 to 0.19 for PS (Table 4). This response was expected considering that panting (e.g., increasing RR) is a form of latent heat loss (e.g., evaporative heat exchange) rather than sensible heat loss (e.g., heat exchange through thermal gradients; Morimoto, 1998). Therefore, RR may not be directly impacted by changes in core body temperature and other factors such as individual animal behavioral response may have a greater influence on changes in RR under heat stress (Hill et al., 2021). Finally, while RR and PS were positively correlated ($P \le 0.05$), this correlation was relatively low ($R = 0.21$) indicating that PS as measured in the present study may not be a suitable substitute for RR (Table 4).

Correlations between anatomical characteristics that may impact thermoregulatory abilities of sows (e.g., EA, EL) and thermoregulatory measures (e.g., RR, T_V) were made to identify whether these characteristics could be used to predict sow thermotolerance or sensitivity (Table 4). As expected, anatomical characteristics directly related to sow size were positively correlated ($P \le 0.05$) with one another, including BCS_{Vis} and BCS_{Cal} and EA and EL (Table 4). As for correlations with thermoregulatory measures, BCS_{Vis} was negatively correlated ($P \le 0.05$) with all skin temperature measures with correlations ranging from −0.52 to −0.12 (Table 4). Because skin temperature response is directly related to vasodilation at the skin (Blatteis, 1998), and factors such as body condition and/or greater subcutaneous fat cover can reduce the ability of sows to lose heat through vasodilation at the skin (Ingram, 1974; Blatteis, 1998), larger sows with greater BCS_{Vis} and potentially subcutaneous fat would likely have lower skin temperature relative to thinner sows. Therefore, greater BCS_{Vis} may be associated with a reduced ability to dissipate heat through the skin that could impact thermoregulatory abilities of lactating sows.

Ear size and HD measures were compared against thermoregulatory metrics (Table 4). It was expected that greater ear size and decreased HD would be positively associated with measures of heat dissipation through the skin (e.g., skin temperature) due to associations with a greater surface area to mass ratio for ear size and lower insulation via greater HD. As expected, EL was positively associated ($P \le 0.05$) with all skin temperature measures ($r = 0.17$–0.26) and EA had a low positive correlation ($P \le 0.05$) with T_{ES} (Table 4), indicating that greater ear size yielded greater skin temperatures, and subsequently, increased heat dissipation capacity. In addition, HD had a low negative correlation ($P \le 0.05$) with T_{ES}, and low positive correlations ($P \le 0.05$) with T_{TS} and T_V (Table 4). However, considering that these correlations were nearly 0 and ranged from −0.08 to 0.05, the relative importance may be limited.

In addition to elucidating phenotypes that best evaluate HS tolerance and sensitivity in lactating sows, it is necessary to understand what temperatures constitute HS in lactating sows to determine when phenotyping might be more appropriate. Recent research by our group has established a protocol to determine when sows are suffering from moderate and severe HS using cubic regression analyses to fit T_V as a function of T_{DB} and T_{DP} (McConn et al., 2021, 2022). The statistical protocol (McConn et al., 2022) was implemented in the present study for lactating sows housed in mechanically and naturally ventilated facilities. It was determined that lactating sows housed in a mechanically ventilated barn had a moderate HS threshold temperature of 26.69 °C (Figure 8A) and lactating sows housed in a naturally ventilated barn had a moderate HS threshold temperature of 27.36 °C (Figure 8B). The moderate HS threshold temperatures for lactating sows in the present study were 0.74 and 1.41 °C lower for lactating sows housed in mechanically and naturally ventilated barns, respectively, when compared to nonpregnant sows in the previous report (McConn et al., 2022). However, it was determined that the moderate HS threshold temperatures for sows in the present study were similar to previously established moderate HS thresholds for mid-gestation sows and greater than late-gestation sows (McConn et al., 2022). This observation was unexpected when considering the greater metabolic heat production of lactating vs. gestating sows (as reviewed by Ramirez et al., 2022), which would likely have reduced the moderate HS threshold temperatures for lactating relative to nonpregnant and gestating sows. However, this discrepancy may be explained by procedural differences between the present study and the previous reports (McConn et al., 2021, 2022). This is because lactating sows in the present study were phenotyped during natural summer HS conditions as opposed to controlled conditions during the winter and early spring in the previous study (McConn et al., 2022). As a result, lactating sows in the present study may have been HS acclimated resulting in an improved ability to lose heat via thermoregulatory mechanisms (e.g., increasing RR). In turn, this may have delayed the T_V increase in response to greater environmental heat loads thereby increasing the moderate HS threshold temperatures of lactating sows in the present study beyond that of nonacclimated lactating sows. Nevertheless, these data improve our understanding of when lactating sows are suffering from moderate HS and have implications towards the timing of phenotyping for HS tolerance and sensitivity during the summer months under commercial production conditions.

When considering severe HS thresholds, it was determined that lactating sows housed in mechanically ventilated barns had a severe HS threshold temperature of 30.60 °C (Figure 8A) and lactating sows housed in naturally ventilated barns had a severe HS threshold temperature of 29.45 °C (Figure 8B). As expected, based on the aforementioned increase in metabolic heat production and subsequently HS sensitivity for lactating vs. nonpregnant and gestating sows (Ramirez et al., 2022), severe HS threshold temperatures for lactating sows in the present study were lower than those previously observed in nonpregnant and gestating sows (McConn et al., 2022). Additionally, severe HS threshold temperatures for lactating sows in the present study were lower when compared against the current lactating sow severe HS threshold temperature (32 °C) as defined by the "Guide for Care and Use of Agricultural Animals in Research and Teaching" based upon 26- to 42-yr-old data (Federation of Animal Science Societies, 2020). This discrepancy may be due to advances in genetic selection that have improved sow productivity (e.g., litter sizes and milk production) and metabolic heat production in modern sows (Stinn and Xin, 2014; Cabezon et al., 2017). It should be mentioned that the severe HS threshold temperatures established by this current study may be greater than that of non-HS acclimated sows considering that sows in the present study were tested under natural summer HS conditions. Therefore, future research should identify whether acclimation level influences both moderate and severe HS threshold temperatures.

Although no direct statistical comparison could be established due to experimental design, a visual comparison of moderate and severe HS threshold temperatures between mechanically and naturally ventilated barns yielded numerical HS threshold temperature differences that are of interest. When comparing moderate and severe HS threshold temperatures, lactating sows housed in a mechanically ventilated barn had a 0.67 °C numerically lower moderate HS threshold temperature and 1.15 °C numerically higher severe

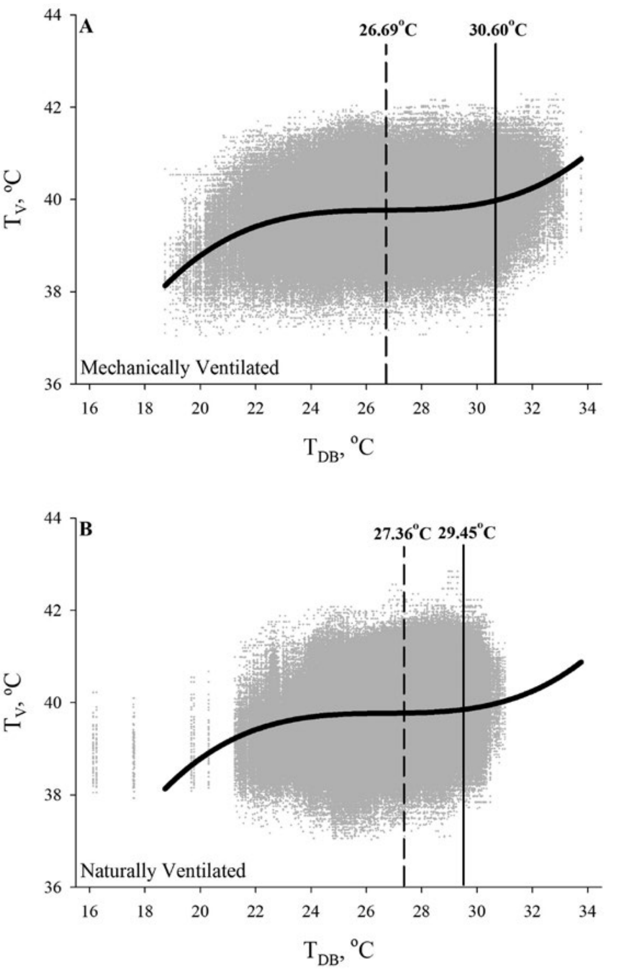

Figure 8. Cubic regression analysis of lactating sow vaginal temperature (***TV***) as a function of dry bulb temperature (***TDB***) in (A) mechanically ventilated and (B) naturally ventilated barns. Dashed lines within the figures indicate the inflection points and solid lines within the figures indicate the point at which the T_V increased abruptly (+0.20 °C) above baseline T_V. The T_{DB} associated with these points are indicated above each line.

HS threshold temperature when compared to lactating sows housed in a naturally ventilated barn. This observation may be explained, in part, by the variable effects of radiant heat load on the sows' abilities to thermoregulate. In naturally ventilated facilities, sunlight is allowed to enter the barn when the curtains are dropped, which in turn, may increase the radiant heat load from natural sunlight for sows on the periphery. As such, it is possible that the increased radiant heat load for lactating sows housed in naturally ventilated facilities may have resulted in greater acclimatization over time and allowed sows housed in naturally ventilated barns to lose excess heat more effectively and delayed the rise in T_V with increasing T_{DB} when compared to mechanically ventilated facilities (Figure 8). However, this effect was likely not observed for the severe HS threshold temperature because the severe HS threshold temperature is based upon the rate at which T_V increases 0.20 °C above the moderate HS threshold temperature. Therefore, once naturally ventilated sows had reached the point at which thermoregulatory mechanisms failed (moderate HS; McConn et al., 2022), the combination of high T_{DB} and greater radiant heat load likely reduced the severe HS threshold temperature. However, these hypotheses would have to be tested in subsequent experiments.

Conclusions

An accurate and precise evaluation of phenotypes associated with HS under variable commercial conditions is necessary to identify novel traits that can be added to genomic selection schemes to breed more HS resilient pigs. Furthermore, updated knowledge of environmental conditions that constitute HS in pigs with modern genetics is required to implement large-scale phenotyping of HS-related traits. In the present study, it was determined that, in general, temporal patterns of HS response were similar for lactating sows regardless of barn type environment and significant correlations between thermoregulatory measures and among anatomical characteristics exist. Additionally, within the context of the present experiment, moderate and severe HS threshold temperatures for lactating sows housed varied slightly based on barn type environment and this may have been related to acclimatization. Together, these data improve our understanding of lactating sow HS response under commercial production conditions.

Supplementary Data

Supplementary data are available at *Journal of Animal Science* online.

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Conflict of Interest Statement

No conflict of interest, financial, or otherwise are declared by the author(s). Mention of trade names or commercial products in this article is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture. All opinions expressed in this paper are the authors' and do not necessarily reflect the policies and views of the USDA. The USDA is an equal opportunity lender, provider, and employer.

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