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Effect of heat stress during early, late, and entire dry period on dairy cattle

Thiago F. Fabris, Jimena Laporta, Amy L. Skibiel, Fabiana N. Corra, Bethany D. Senn, Stephanie E. Wohlgemuth, and Geoffrey E. Dahl*
Department of Animal Sciences, University of Florida, Gainesville 32611

ABSTRACT

Cooling during the entire dry period abates the negative effects of heat stress postpartum, yet the temporal relationship of cooling (i.e., early or late dry period) to performance is unknown. We evaluated the effect of heat stress early, late, and for the entire dry period on subsequent performance. Cows were selected based on mature-equivalent milk yield and dried off 45 d before expected calving. Cows were blocked by parity, previous 305-d mature equivalent milk yield, and body weight (BW) and randomly assigned to cooling (shade, fans, and soakers; CL) or heat stress (shade; HT). Treatments included CL (n = 20) or HT (n = 18) during the entire dry period, HT during the first 3 wk dry and then CL until calving (HTCL, n = 21), or CL during the first 3 wk dry period and then HT until calving (CLHT, n = 19). Heat stress increased rectal temperature (RT; CL, 38.8; HT, 39.1 ± 0.04°C) and respiration rate (RR; CL, 52.9; HT, 70.5 ± 1.9 breaths/min) during the early dry period. In the late dry period, HT increased RT and RR relative to CL cows (RT = CL, 38.7; HT, 39.1; CLHT, 39.1; HTCL, 38.9 ± 0.05°C; RR = CL, 47; HT, 64; CLHT, 66; HTCL, 53 ± 2.1 breaths/min). During the early dry period, HT decreased dry matter intake (CL, 11.8; HT, 10.5 ± 0.35 kg/d) but dry matter intake did not differ among treatments during late dry period (HT, 10.7; HTCL, 11.1; CL, 11.2; CLHT, 10.1 ± 0.55 kg/d). Cows exposed to prepartum cooling during the entire dry period had increased dry matter intake compared with cows exposed to heat stress during the late dry period (CL vs. CLHT, 11.2 ± 0.55 and 10.1 ± 0.55 kg/d, respectively). Heat stress at any time reduced gestation length compared with cows under prepartum cooling during the entire dry period (CL, 277 vs. HT, 274; CLHT, 273; and HTCL, 274 ± 1.17 d). Dry period length decreased by approximately 4 d if cows were exposed to HT at any time. During the early dry period, HT decreased BW, whereas CL increased BW relative to that at dry-off (CL, 6.9; HT, −9.4 ± 3.7 kg). In the late dry period, we detected no differences in BW gain among treatments, but cows exposed to prepartum cooling for the entire dry period tended to have increased BW gain compared with HT and HTCL. Prepartum cooling during the early or late dry period alone partially rescued milk yield only in the first 3 wk of lactation (CL, 32.9; HT, 26.6; CLHT, 29.7; HTCL, 30.7 ± 1.37 kg/d). Cooling for the entire dry period increased milk yield up to 30 wk into lactation compared with all other treatments. Thus, HT at any time during the dry period compromises performance of cows after calving.
Key words: heat stress, performance, dry period, yield

INTRODUCTION

Climate change has captured the attention of the international scientific community and the dairy industry during the last decade, and hotter summers have become more frequent worldwide. Heat stress negatively affects the profitability of dairy farms in the United States. According to St-Pierre et al. (2003), hot weather reduces milk yield, and the estimated total economic losses during the summer for the US dairy industry exceeds $897 million annually. In Florida and Texas, economic losses on a lactating cow basis have been estimated at $337 and $383/cow per year, respectively (St-Pierre et al., 2003).

Heat stress abatement using cooling systems may overcome some of the negative effects of heat stress and reduce economic losses (St-Pierre et al., 2003). Heat stress during the dry period (the nonlactating period of dairy cattle) reduces milk yield in the next lactation (Tao et al., 2012; Fabris et al., 2017). A recent economic study estimated that if cows are not cooled during the dry period, economic losses to the United States dairy industry could be as much as $810 million annually (Ferreira et al., 2016). Thus, heat stress during the dry period has a significant negative effect on dairy farm profitability, similar to that of heat stress during lactation.

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*Corresponding author: gdahl@ufl.edu

Mammary gland involution and redevelopment are important for optimal milk yield in the subsequent lactation (Hurley, 1989). A nonlactating period between successive lactations, known as the "dry period," is an important phase of the production cycle for dairy cows but because it is a nonproductive period, active management during this stage is often neglected by farmers (Smith and Todhunter, 1982). During the dry period, the mammary gland goes through 3 processes: active involution, which starts right after the cessation of milk removal and represents the period of transition of the tissue from a lactating to a nonlactating state; steady state of involution, which represents the nonlactating state; and finally, the redevelopment (growth) phase, when much of lactogenesis and colostrogenesis occur (Smith and Todhunter, 1982; Hurley, 1989). Therefore, the negative outcome of heat stress during the dry period may be related to compromised involution and proliferation throughout the dry period or at a specific period. Thus, it is important to understand whether prepartum cooling during the early or late dry period abates the negative effect of heat stress.

In contrast to lactating cows, dry cows generate less metabolic heat (West, 2003) and have a higher upper critical temperature (Hahn, 1999). Despite these advantages, environmental heat stress during the dry period negatively affects performance in the subsequent lactation. Still, the underlying biological mechanisms, whereby heat stress during the dry period impairs the subsequent milk yield of dairy cows, are largely unknown. Previous studies demonstrated that heat abatement through cooling applied during the entire dry period in summer resulted in an increased milk production of 4 to 7.5 kg/d in the subsequent lactation relative to cows that were not cooled (reviewed in Dahl et al., 2017). In contrast, when active cooling was applied only during the close-up period of the dry period (i.e., the last 2–4 wk of gestation), milk yield was improved by only 1.4 kg/d in the next lactation (Urdaz et al., 2006; Gomes et al., 2013). Therefore, cooling for the entire dry period appears to induce higher yield responses than late dry period cooling, and so the effect of heat stress during the involution phase of the dry period may be greater than that during the proliferative phase. Such a time dependency was also observed for photoperiod, another environmental cue, during the dry period. Cows exposed to a short-day photoperiod during the entire dry period of 42 to 60 d had improved mammary growth in the late dry period (Wall et al., 2005), which was associated with approximately 3.3 kg/d more milk in the next lactation compared with cows maintained under a long-day photoperiod (reviewed in Dahl et al., 2012). However, application of short-day photoperiod to cows only during the last 21 d of the dry period had no effect on subsequent milk production (Reid et al., 2004). Therefore, disregarding the early dry period when making environmental interventions to improve milk yield can profoundly reduce their effects on subsequent lactation performance. We hypothesized that heat stress during the entire dry period compromises subsequent milk yield of dairy cows and that prepartum evaporative cooling only in the early or late dry period would not rescue milk yield in the subsequent lactation.

MATERIALS AND METHODS

Treatments, Experimental Design, and Animals

The experiment was conducted during one summer (2016) at the University of Florida Dairy Unit (Hague, FL). All of the treatments and procedures were approved by the University of Florida institutional animal care and use committee. A completely randomized design was used to evaluate the effects of heat stress during the early or late dry period on performance of dairy cows. All cows were dried off ~45 d before expected calving. Weekly cohorts of cows were blocked by lactation number, previous 305-d mature-equivalent yield, and BW and randomly assigned to 1 of 4 treatments. Treatments were as follows: cooling during the entire dry period with shade, fan and soakers (**CL**, n = 20), heat stress during the entire dry period, with shade only (**HT**, n = 18), CL during the first 3 wk after dry-off and then HT until calving (**CLHT**, n = 19), and HT during the first 3 wk after dry-off and then CL until calving (**HTCL**, n = 21).

After parturition, all cows were moved to a common pen and provided with cooling systems (shade, fans, and soakers) during the entire lactation. During lactation, cows were milked twice a day, and DMI was recorded up to 42 d in milk, whereas milk yield recording extended to 30 wk in lactation. Cows were housed in a sand-bedded freestall barn during the dry period and lactation. The temperature-humidity index (**THI**) was calculated based on the equation reported by Dikmen et al. (2008): $THI = (1.8 \times T + 32) - [(0.55 - 0.0055 \times RH) \times (1.8 \times T - 26)]$, where T = air temperature (°C) and RH = relative humidity (%). During the dry period, the pens in the present study were equipped with active cooling devices; that is, shade, fans, and soakers, and managed as described by Fabris et al. (2017). Air temperature and relative humidity of each pen in the barn for dry cows were recorded every 15 min by using Hobo Pro series Temp probes (Onset Computer Corp., Pocasset, MA). All cows were fed a common TMR during the entire dry period and lactation (Table 1). Daily DMI of individual cows was measured from dry-off to calving and from calving up to 42 DIM using a Calan gate system (American Calan Inc., Northwood, NH). Rectal temperature (**RT**, °C) and respiration rate (**RR**, breaths/min) were also measured for all cows during the dry period to confirm that cows were exposed to heat stress, as described by Fabris et al. (2017). Also during the dry period, blood samples were collected to evaluate the cows' hydration status through hematocrit and total protein analysis, as described by Fabris et al. (2017).

Statistical Analysis

Data were analyzed in 3 distinct periods: the early and late dry periods, when treatment with prepartum evaporative cooling was provided or not, and during lactation. Descriptive statistics were used to describe the daily means and respective standard deviations for THI. During the dry period, data were divided into 2 periods: first 3 wk of the dry period (early dry period; cows were exposed to either HT or CL) and from 3 wk until calving (late dry period; some cows were switched to either the HT or the CL pen according to the respective treatment, and some cows remained in the HT or CL pen during the entire dry period). The individual experimental treatments were applied to groups of animals because that was the only practical way to do so.

During the dry period, the responses of RT, RR, hematocrit, total protein, BW, BCS, and DMI were analyzed by mixed models using the MIXED procedure of SAS (version 9.4; SAS Institute Inc., Cary, NC). During the early dry period, the statistical model included the fixed effects of treatment (CL and HT), week prepartum (-7 to -4 wk), the interaction between treatment and week prepartum, and the random effect of cow nested within treatment. During the late dry period, the statistical model included the fixed treatment (CL, HT, CLHT, and HTCL), week prepartum (-4 to -1 wk), the interaction between treatment and week prepartum, and the random effect of cow nested within treatment. The THI was calculated for every hour throughout the experiment, and the mean THI value for each day was used as covariate for analyses of RT, RR, and DMI for early dry period analysis. During the late dry period analysis, the mean THI value for each day was used as covariate for analyses of RT and RR. The mean THI value was not significant in the analysis of DMI during the late dry period and was removed from the model. After parturition, milk yield, milk composition, BW, SCS, feed efficiency, and DMI were analyzed by mixed models using the MIXED procedure of SAS. The statistical model included the fixed effects treatment (CL, HT, CLHT, and HTCL), week postpartum (1 to 30 wk), the interaction between treatment and week postpartum, and the random effect of cow nested within treatment. Data on gestation length and dry period length were analyzed using the MIXED procedure of SAS with a statistical model that included the fixed effect of treatment (CL, HT, CLHT, and HTCL). Calf birth weight was analyzed by the MIXED procedure of SAS with a statistical model that included the fixed effects of calf sex (male vs. female) and treatment (CL, HT, CLHT, and HTCL). Models were fit to the data and distribution of residuals and homogeneity of variance were evaluated. The covariance structure that resulted in the best-fit model based on the smallest Akaike's information criterion was selected for the analysis of data with repeated measurements. Least squares means and standard errors of the mean are reported. Differences with $P \leq 0.05$ were considered statistically significant and between $0.05 \leq P \leq 0.10$ as a tendency.

RESULTS

Dry Period

Environmental conditions in the heat stress and cooling pens were similar during the entire dry period, as shown by the THI (Figure 1). The daily mean and respective standard deviation for THI during the entire experiment were always >68 (Figure 1), which indicates that the current experiment was appropriate for evaluating the effect of heat stress and evaporative cooling during the dry period. Heat stress at any point during the dry period reduced gestation length and dry period length compared with cows that received prepartum evaporative cooling for the entire dry period ($P = 0.05$ and $P < 0.05$, respectively; Table 2). Also, cows that experienced heat stress at any time during the dry period had calves with reduced birth weight relative to CL cows ($P < 0.05$; Table 2).

Early Dry Period

During the early dry period, we detected a significant effect of heat stress on RT and RR (Figure 2); HT cows had increased morning and afternoon RT ($P < 0.01$; Table 2) and RR ($P < 0.01$; Table 2). During the early dry period, HT decreased DMI compared with CL ($P < 0.01$; Table 2). Further, in the early dry period, HT cows had reduced BW compared with CL cows ($P < 0.01$; Table 2). However, during the early dry period, BCS did not differ between treatments (BCS; $P = 0.18$; Table 2). Hematocrit (CL = 30.31; HT = 30.03 ± 0.35; $P = 0.57$) and total protein (CL = 7.41; HT = 7.36 ± 0.07; $P = 0.60$) did not differ during the early dry period.

Table 1. Ingredient composition and nutrient content of prepartum and postpartum diets fed to cows exposed to heat stress during the early (−7 to −4 wk relative to calving), late (−4 to −1 wk relative to calving), or entire dry period

	Diet[1]	
Item	Prepartum	Postpartum
Ingredient, % of DM		
Corn silage	37.58	33.73
Bermuda grass hay	33.40	3.26
Alfalfa hay	—	10.88
Brewer's grains, wet	10.44	7.83
Corn, finely ground	—	16.32
Soybean hulls	—	5.44
Citrus pulp, dry	4.59	2.18
Soybean meal, solvent extract 47% CP	4.18	12.84
Saturated free fatty acids[2]	—	0.70
Mineral-vitamin premix, prepartum[3]	4.18	—
Acidogenic salt product[4]	5.01	—
Mineral-vitamin premix, early lactation[5]	—	5.44
Mycotoxin binder[6]	0.63	0.54
Nutrient content, DM basis		
NE_L,[7] Mcal/kg	1.48	1.74
OM, %	—	—
CP, %	14.11	17.54
NDF, %	45.15	30.38
Forage NDF, %	37.37	20.06
ADF, %	26.18	20.04
NFC,[8] %	32.02	39.14
Starch, %	13.23	23.19
Ether extract, %	4.74	5.41
Ca, %	0.68	0.88
P, %	0.32	0.44
Mg, %	0.51	0.42
K, %	1.32	1.57
S, %	0.32	0.22
Na, %	0.12	0.54
Cl, %	1.06	0.55
DCAD,[9] mEq/kg	−113	366

[1]Prepartum diet was fed from 231 d of gestation to calving and postpartum diet from calving to 42 DIM.

[2]Energy Booster Mag (Milk Specialties, Eden Prairie, MN).

[3]The prepartum mineral and vitamin supplement contained (DM basis) 64.1% corn gluten feed, 8.2% calcium carbonate, 15.7% magnesium sulfate heptahydrate, 6.0% magnesium oxide, 2.3% sodium chloride, 0.42% Sel-Plex 2000 (Alltech Biotechnology, Nicholasville, KY), 0.27% Intellibond Vital 4 (Micronutrients, Indianapolis, IN), 0.002% ethylenediamine dihydriodide, 0.66% of a premix containing vitamins A, D and E, 0.37% Rumensin 90 (Elanco Animal Health, Greenfield, IN), and 2.0% ClariFly Larvicide (Central Life Sciences, Schaumburg, IL). Each kilogram contained 13.6% CP, 3.7% Ca, 0.7% P, 5.5% Mg, 0.9% K, 1.1% Na, 1.6% Cl, 2.6% S, 788 mg of Zn, 180 mg of Cu, 581 mg of Mn, 9 mg of Se, 4.4 mg of Co, 16 mg of I, 104,000 IU of vitamin A, 30,000 IU of vitamin D, 1,500 IU of vitamin E, and 800 mg of monensin.

[4]SoyChlor (West Central Soy, Landus Cooperative, Ames, IA).

[5]The early lactation mineral and vitamin supplement contained (DM basis) 19.4% LysAAmet blood meal (Perdue Agribusiness, Salisbury, MD), 26.8% sodium sesquicarbonate, 14.4% DCAD Plus (Arm and Hammer Animal Nutrition, Trenton, NJ), 5.7% potassium chloride, 13.2% calcium carbonate, 4.0% dicalcium phosphate, 7.7% magnesium oxide, 6.6% sodium chloride, 0.22% Intellibond Vital 4 (Micronutrients), 0.39% Sel-Plex 2000 (Alltech Biotechnology), 0.0015% ethylenediamine dihydriodide, 0.32% of a premix containing vitamins A, D and E, 0.11% biotin 2%, 0.22% Rumensin 90 (Elanco Animal Health), and 1.0% ClariFly Larvicide (Central Life Sciences). Each kilogram contains 17.2% CP, 6.2% Ca, 0.9% P, 4.5% Mg, 10.4% K, 11.5% Na, 7.2% Cl, 0.2% S, 605 mg of Zn, 143 mg of Cu, 490 mg of Mn, 8 mg of Se, 4.4 mg of Co, 12 mg of I, 160,000 IU of vitamin A, 28,000 IU of vitamin D, 1,500 IU of vitamin E, and 460 mg of monensin.

[6]NovaSilPlus (BASF, Florham Park, NJ).

[7]Calculated using the NRC (2001) according to the chemical composition of the dietary ingredients and adjusted for 11 and 20 kg of DMI for pre- and postpartum periods, respectively.

[8]Calculated as follows: NFC = DM – (ash + CP + ether extract + NDF – NDF insoluble CP).

[9]Calculated as follows: DCAD = [(mEq of K) + (mEq Na)] – [(mEq of Cl) + (mEq of S)].

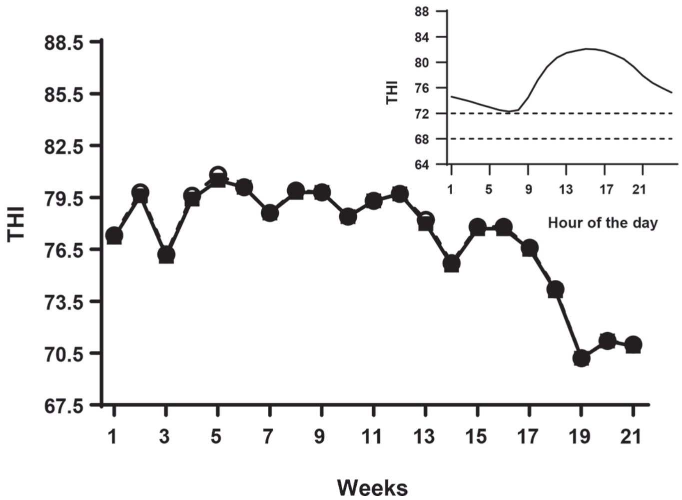

Figure 1. Average temperature-humidity index (THI) during the dry period of cooled (shade, fans, and soakers) and heat stressed (only shade) treatment pens. Open circles (○) and solid squares (■) represent cooled and heat stressed pens, respectively. The inset represents the average THI by hour of the day during the entire period. Temperature-humidity index was measured during the 21 wk in which heat stress and cooling treatments were applied. Dashed lines represent the traditional (72) and recent (68) thresholds when cows start to experience the effect of heat stress, and the solid line represents the daily average THI/hour.

Late Dry Period

During the late dry period, we observed a significant effect of heat stress on RT (morning and afternoon) and RR (Figure 2); HT cows had increased morning and afternoon RT ($P < 0.01$; Table 2) and RR ($P < 0.01$; Table 2). During the late dry period and approaching parturition, DMI did not differ among treatments ($P = 0.15$; Table 2). However, cows that were exposed to prepartum evaporative cooling during the entire dry period and in the late dry period had greater DMI than cows exposed to heat stress during the late dry period (CL vs. CLHT, 11.6 ± 0.55 and 10.1 ± 0.55 kg/d, $P = 0.03$; HTCL vs. CLHT, 11.4 ± 0.55 and 10.1 ± 0.55 kg/d, $P = 0.07$). No differences in BW change or BCS among treatments were observed during the late dry period ($P = 0.21$ and $P = 0.42$, respectively; Table 2). However, cows that were exposed to prepartum evaporative cooling during the entire dry period had greater BW gain than cows in the HT and HTCL treatments ($P = 0.07$; Table 2). There were no differences in hematocrit (CL = 29.48; HT = 29.36; CLHT = 29.37; HTCL = 29.06 ± 0.42, $P = 0.92$) or total protein (CL = 7.15; HT = 7.08; CLHT = 7.15; HTCL = 7.36 ± 0.09, $P = 0.22$) among treatments during the late dry period.

Table 2. Temperature-humidity index (THI) of heat stress and cooling pens, gestation length (GL), dry period length (DPL), calf birth weight (CBW), rectal temperature (RT), respiration rate (RR), BW change, and BCS during the early (−7 to −4 wk relative to calving) and late (−4 to −1 wk relative to calving) dry period of Holstein cows[1]

	Treatment (Trt)[2]					*P*-value	
Item	CL	HT	CLHT	HTCL	SEM	Trt	Trt × Time
GL, d	277.4[a]	275.1[c]	272.9[b]	274.0[c]	1.18	0.05	—
DPL, d	46.6[a]	44.1[c]	42.2[c]	44.0[c]	1.17	0.04	—
CBW, kg	42.6[a]	38.3[c]	39.0[c]	38.4[c]	1.19	0.04	—
Pen THI	74.4	74.6	—	—	3.53	—	—
Early dry period							
RT a.m., °C	38.4	38.5	—	—	0.03	<0.01	0.11
RT p.m., °C	38.8	39.1	—	—	0.04	<0.01	0.08
RR, breaths/min	52.9	70.5	—	—	1.90	<0.01	0.84
BW[3] change, kg	6.9	−9.4	—	—	3.70	<0.01	0.94
BCS	3.37	3.25	—	—	0.06	0.18	0.08
DMI, kg/d	11.8	10.5	—	—	0.35	<0.01	0.10
Late dry period							
RT a.m., °C	38.43[a]	38.63[b]	38.75[be]	38.46[a]	0.04	<0.01	0.65
RT p.m., °C	38.74[a]	39.07[b]	39.08[b]	38.82[a]	0.05	<0.01	0.75
RR, breaths/min	47.9[a]	64.6[b]	65.2[b]	50.8[a]	1.86	<0.01	0.27
BW[4] change, kg	26.85[a]	10.90[d]	16.83	11.50[d]	6.71	0.21	<0.01
BCS	3.42	3.26	3.45	3.33	0.09	0.42	0.20
DMI, kg/d	11.6[a]	11.0	10.1[c]	11.4[a]	0.56	0.15	0.61

[a–e]Means with different letters differ significantly (a vs. b, $P \leq 0.01$; a vs. c, $P \leq 0.05$; a vs. d, $P \leq 0.10$; b vs. e, $P \leq 0.05$).

[1]Data are presented as mean ± SEM.

[2]Treatments included cooling during the entire dry period (CL; n = 19), heat stress during the entire dry period (HT; n = 18), cooling during the first 3 wk of the dry period and then HT until calving (CLHT; n = 16), and heat stress during the first 3 wk of the dry period and then CL until calving (HTCL; n = 20)

[3]During the early dry period, prepartum cumulative BW change was calculated by subtracting data at −7, −6, and −5 wk relative to calving by data at dry-off.

[4]During late dry period, prepartum cumulative BW change was calculated by subtracting data at −4, −3, −2, and −1 wk relative to calving by data at dry-off.

Lactation

We detected no differences in parity among groups; parity averaged 2.75 ± 0.22 across all groups. During the first 21 d in milk, cows that received prepartum evaporative cooling during the early, late, or entire dry period produced at least 3 kg/d more than cows that were exposed to heat stress during the entire dry period (CL = 32.9 ± 1.38; CLHT = 29.7 ± 1.38; HTCL = 30.7 ± 1.38 kg/d vs. HT = 26.6 ± 1.38 kg/d; P = 0.02). However, this trend did not persist after wk 3 of lactation. Cows that were exposed to heat stress at any time of the dry period produced less milk than those that received prepartum evaporative cooling during the entire dry period ($P < 0.01$; Table 3, Figure 3). There were no differences in the percentage of milk components among treatments (Table 3). However, lactose yield differed among treatments ($P = 0.02$). Cows that received prepartum evaporative cooling during the entire dry period had increased lactose yield compared with cows that did not (CL = 1.83 ± 0.07; HT = 1.55 ± 0.07 kg/d; $P = 0.01$), but lactose yield did not differ among CL, CLHT, and HTCL treatments (Table 3). Fat yield did not differ among treatments ($P = 0.27$; Table 3). Cows that were exposed to heat stress during the late dry period tended to have reduced protein yield compared with CL cows ($P = 0.08$; Table 3); however, protein yield did not differ among CL, HT, and HTCL treatments (Table 3). No differences were observed in SCS among treatments ($P = 0.88$; Table 3). During the postpartum period, there were no differences in DMI or BW change among treatments (Table 3). There were, however, differences in feed efficiency among treatments ($P < 0.01$; Table 3). Specifically, CL cows had increased feed efficiency compared with cows in the HT and HTCL treatments ($P < 0.05$; Table 3).

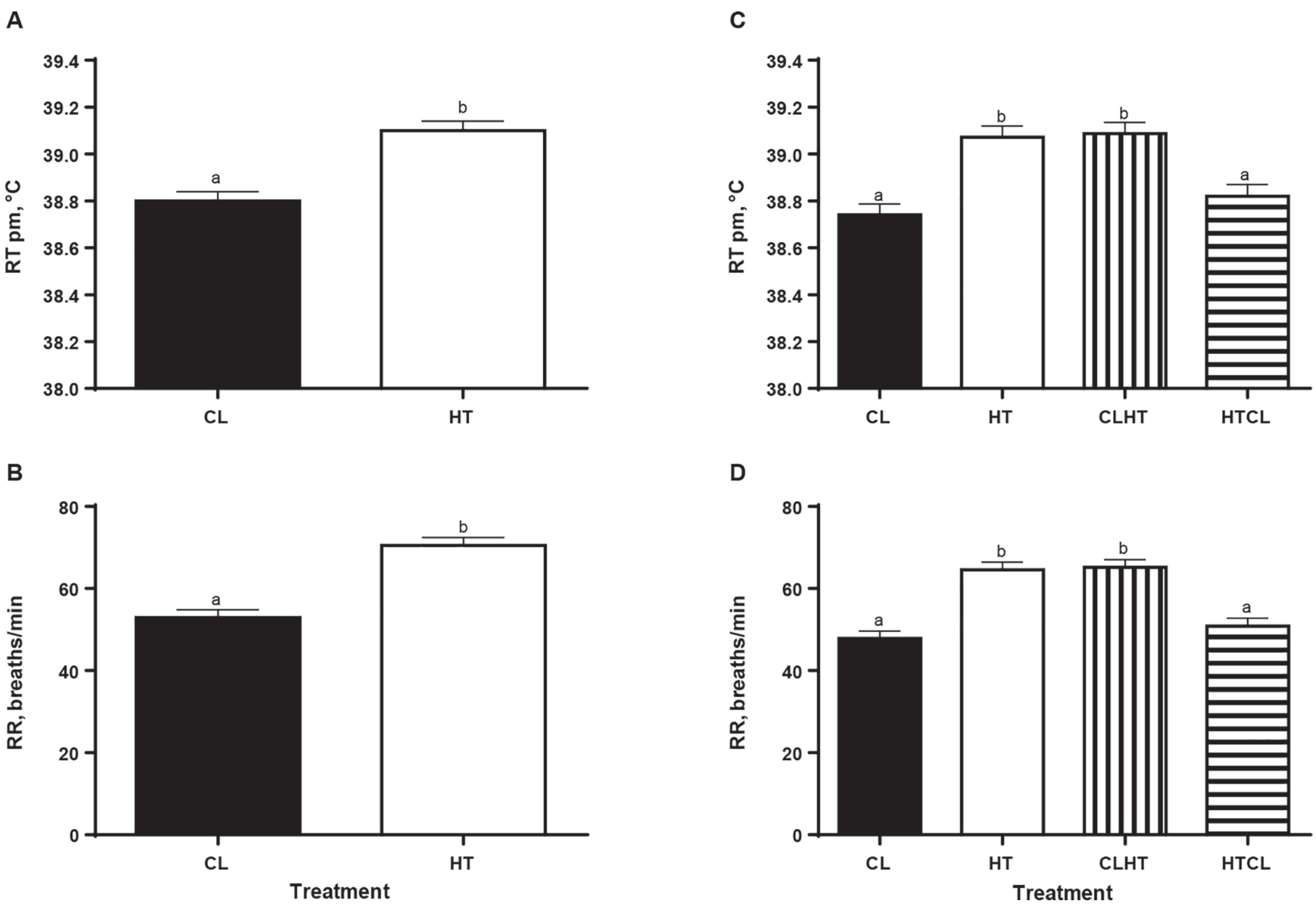

Figure 2. Effect of cooling (CL; n = 20) and heat stress (HT; n = 18) during the early dry period (A and B); and the effect of CL, HT, and combinations (CLHT; n = 19; HTCL; n = 21) during the late dry period (C and D) on rectal temperature (RT) and respiration rate (RR). During the early dry period, HT increased afternoon RT and RR (letters a and b in panels A and B: $P < 0.01$). During the late dry period, cows that were exposed to HT (HT or CLHT) had increased afternoon RT and RR (letters a and b in panels C and D: $P < 0.01$). Data are presented as mean ± standard error of the mean.

Table 3. Dry matter intake, milk yield, milk composition, SCS, BW change, and feed efficiency of cows exposed to prepartum evaporative cooling or heat stress during the dry period[1]

Variable	Treatment[2] (Trt)				SEM	P-value	
	CL	HT	CLHT	HTCL		Trt	Trt × Time
DMI, kg/d	17.52	17.60	17.01	18.29	0.65	0.62	0.29
Milk yield, kg/d	40.2[a]	36.3[b]	36.1[b]	36.3[b]	1.36	0.10	0.98
Fat, %	3.55	3.65	3.60	3.73	0.06	0.25	0.31
Protein, %	2.89	2.86	2.83	2.86	0.04	0.80	0.44
Lactose, %	4.42	4.52	4.48	4.49	0.03	0.23	<0.01
Fat yield, kg/d	1.43	1.31	1.28	1.36	0.05	0.27	0.27
Protein yield, kg/d	1.16[a]	1.03[ad]	1.01[d]	1.05[ad]	0.04	0.08	0.83
Lactose yield, kg/d	1.83[a]	1.55[c]	1.69[ac]	1.68[ac]	0.07	0.02	—
SCS	3.31	3.40	3.76	3.62	0.43	0.88	0.19
BW change,[3] kg	36.0	29.8	41.9	41.5	11.3	0.86	0.59
Feed efficiency[4]	2.4[a]	1.9[b]	2.3[ab]	1.9[b]	0.12	0.01	0.36

[a–d]Means with different letters differ significantly (a vs. b, $P \leq 0.05$; a vs. c; $P \leq 0.01$; a vs. d; $P \leq 0.10$).

[1]Data are presented as mean ± SEM.

[2]Treatments included cooling during the entire dry period (CL; n = 19), heat stress during the entire dry period (HT; n = 18), cooling during the first 3 wk of the dry period and then HT until calving (CLHT; n = 16), and heat stress during the first 3 wk of the dry period and then CL until calving (HTCL; n = 20)

[3]After calving, cumulative BW change was calculated by subtracting BW value at 1 to 30 wk relative to calving by BW value at calving.

[4]Feed efficiency = kilograms of 3.5% FCM per kilogram of DMI. Feed efficiency was calculated from calving until 42 d postpartum.

DISCUSSION

Heat stress during the entire dry period has a profound negative effect on the subsequent lactation of dairy cows (Tao et al., 2012b; Fabris et al., 2017). To the best of our knowledge, no studies have directly compared the timing (i.e., early or late dry period) of heat stress during the dry period on subsequent perfor-

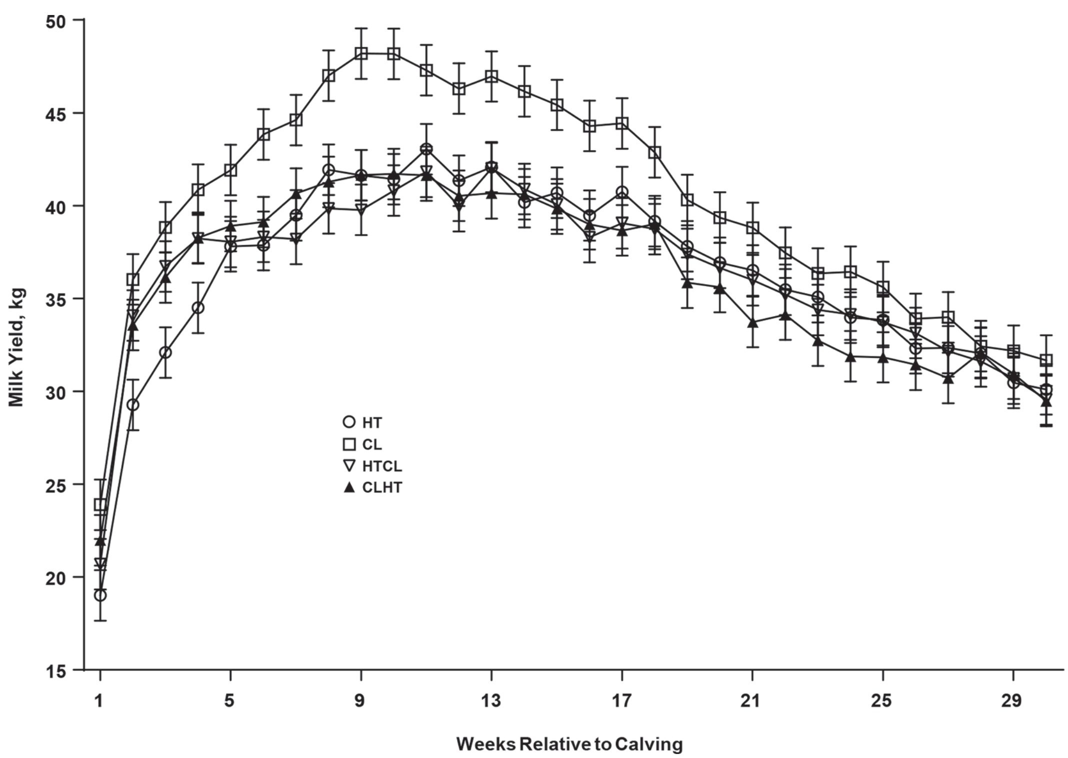

Figure 3. Effect of cooling (CL; n = 19), heat stress (HT; n = 18), and combinations (CLHT; n = 16; HTCL; n = 20) during a 45-d dry period on milk yield up to 30 wk postpartum. After calving, all cows were managed and housed under the same conditions. Data are presented as means ± overall standard error of the mean.

mance, although cooling during the last 21 d of the dry period has been studied (Urdaz et al., 2006; Gomes et al., 2013). The present study evaluated the importance of timing prepartum evaporative cooling on subsequent performance of dairy cows.

With heat stress exposure, cows experience increased RT and RR (Tao et al., 2012b; Fabris et al., 2017), which was confirmed in the present study. Under heat stress conditions, cows use thermoregulatory mechanisms to increase heat dissipation. These mechanisms include the reduction of metabolic rate, vasodilation, and changes in behavior (Legates et al., 1991; Renaudeau et al., 2012), altered blood hormone concentrations, increased RR and body temperature, and increased evaporative water loss (Armstrong, 1994). Thus, these physiological responses due to long-term heat stress in dairy cows can lead to reduced productivity because of the increase in energy required to drive heat loss.

Previous studies indicate that Holstein cows experience heat stress when the THI exceeds 68, which negatively affects lactation (Zimbelman et al., 2009; Fabris et al., 2017). In the present study, the average THI remained above 68 during the entire study period, during day and night, which is consistent with our previous study (Fabris et al., 2017). Evaporative cooling was effective to overcome the effect of heat stress at any time prepartum (during early or late dry period), as indicated by a reduction in RT and RR in the cows exposed to fans and soakers. Thus, the current design was appropriate to evaluate the effect of heat stress abatement during the early, late, and the entire dry period.

Long-term heat stress alters the thermoregulatory response of dairy cows during the dry period (Fabris et al., 2017). Under heat stress conditions, cows are less able to dissipate the heat increment of metabolism and digestion (Beede and Collier, 1986). Thus, under heat stress, there is a compensatory response by the cow, wherein she reduces DMI (do Amaral et al., 2009; Tao et al., 2011). In the present experiment, HT cows decreased DMI during the early dry period compared with CL cows, by approximately 1.3 kg/d, which is consistent with previous studies that evaluated the effect of heat stress during the dry period (do Amaral et al., 2009; Tao et al., 2011). During the late dry period, the reduction in DMI in cows of the CLHT treatment compared with the CL and HTCL treatments may be associated with the fact that the cows were exposed to heat stress during a time when cows already undergo a drop in DMI and the heat stress exposure during this period exacerbated this decrease. However, DMI did not differ among CL, HT, and HTCL treatments during the late dry period, which may be explained by the fact that cows have an inherent reduction in DMI as parturition approaches. Heat stress reduces BW compared with cows that received prepartum evaporative cooling although changes in BCS are inconsistent (Tao et al., 2011; Thompson et al., 2014; Fabris et al., 2017). In the present experiment, cooled cows had increased BW gain, but not BCS, during the early dry period compared with heat-stressed cows. These findings are consistent with the increased DMI (approximately 1.3 kg/d) of cooled cows. Further, the reduced BW gain of HT cows may result from increased energy expenditure because of the exposure to heat stress and the physiological decrease in DMI as parturition approaches.

Previous studies indicated that heat stress during the dry period reduces gestation length compared with that of cooled cows (do Amaral et al., 2009; Tao et al., 2012a). A novel and unexpected observation of the current study was the decrease in gestation length in cows that experienced HT at any time during the dry period. In ewes and cows, newborns of dams that were heat-stressed during late gestation had decreased birth BW relative to those born to cooled dams (Brown et al., 1977; Collier et al., 1982; Fabris et al., 2017). The reduction in calf birth weight is likely explained by the reduced gestation length and thus, dry period length, observed in the present experiment. Indeed, CL cows had heavier calves at birth than HT cows. These results are consistent with the longer gestation length of CL cows compared with cows that experienced HT at any time during the dry period.

Previous studies demonstrated that heat abatement through cooling applied during the entire dry period resulted in an increase in milk production of 4 to 7.5 kg/d in the subsequent lactation relative to cows that were not actively cooled (reviewed in Dahl et al., 2017). In contrast, when active cooling was applied only during the close-up phase of the dry period (i.e., the last 2–4 wk of gestation), milk production was improved by only 1.4 kg/d in the next lactation (Urdaz et al., 2006; Gomes et al., 2013). Following the same trend, improvements in milk yield were observed in cows exposed to a short-day photoperiod during the entire dry period (Miller et al., 2000; Auchtung et al., 2005; Velasco et al., 2008). However, there were no differences in milk yield when short-day photoperiod was applied only during the last 3 wk of the dry period (Reid et al., 2004).

Cows that received prepartum evaporative cooling during the entire dry period did not increase fat yield compared with cows that did not experience evaporative cooling during late (CLHT), early (HTCL), or entire (HT) dry period. This is consistent with previous studies that did not observe differences in fat yield between cows that were exposed to HT and CL during the dry period (Adin et al., 2009; Fabris et al., 2017). Similar to the present experiment, previous studies demonstrated that HT reduces protein yield compared with cooling (Adin et al., 2009; do Amaral et al., 2009, 2011). Also consistent with previous studies, in the present experiment, lactose yield was reduced in HT cows compared with CL cows (Fabris et al., 2017).

It has been proposed that full involution of the mammary gland during the early dry period is critical for optimal mammary growth in the late dry period and maximal subsequent milk production, and the timing of cooling during the dry period may be key to achieve this outcome. The reduction in milk yield caused by heat stress has been linked to compromised mammary gland involution early in the dry period, as autophagy markers associated with cell turnover are reduced in HT cows relative to CL cows (Wohlgemuth et al., 2016). Further to this is the idea that heat stress delays cellular renewal, which leads to lower epithelial cell proliferation later in the dry period (Tao et al., 2011). Therefore, we hypothesized that providing prepartum evaporative cooling during the early dry period in particular would mitigate the negative effects of heat stress and improve performance after parturition. On the other hand, heat stress abatement during the late dry period (i.e., the "proliferative" period) would only slightly abate the negative effect of heat stress on mammary gland development and future milk yield. That is, switching to cooling management in the middle of the dry period would slightly reverse the negative effects of heat stress, but cooling during the growth phase will not reverse the negative effect of heat stress during involution. Initially, it appeared that 3 wk of cooling during the early or late dry period might rescue milk yield, as the HTCL and CLHT groups had milk production intermediate to those of the CL and HT groups early in lactation. That response, however, was not maintained into lactation. In contrast, Urdaz et al. (2006) and Gomes et al. (2013) observed some yield improvement with cooling during the final 3 wk of gestation. But those studies followed yield only for the first 60 to 105 d of lactation and thus the yield effect may have been similar to the initial response observed in our HTCL cows. Indeed, the aggregate yield impact was lower in those reports compared with the current study and previous work from our laboratory, further evidence that cooling must be maintained for the entire dry period to achieve the mammary effect fully. Overall, we observed no differences between HT and CLHT treatments on milk yield in the present experiment, nor any differences in yield between the HT and HTCL treatments. Therefore, when heat stress is imposed at any time during the early and late dry period or over the entire dry period, milk yield is reduced in the subsequent lactation compared with that of cows receiving prepartum evaporative cooling during the entire dry period.

CONCLUSIONS

Cows that are exposed to a THI >68 during the dry period are under heat stress. Heat stress imposed at any time during the dry period increases respiration rate and rectal temperature. Heat stress during the early dry period reduces DMI of dairy cows. The current study demonstrated that providing prepartum evaporative cooling only in the early or late dry period does not rescue milk yield in the subsequent lactation. Based on our findings, cows that are exposed to heat stress at any time during the dry period have reduced milk yield in the subsequent lactation, and dry period exposure to heat stress reduces protein and lactose yields. The present study provides valuable information about the effect of heat-stress timing during the dry period and can be used to establish an appropriate management recommendation for dairy farms located in areas that experience hot and humid environmental conditions.

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