Upper Critical Temperatures and Forced Ventilation Effects for High-Yielding Dairy Cows in a Subtropical Climate

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ABSTRACT

Upper limit of thermal stability and subsequent rise of thermoregulatory functions as affected by forced ventilation were examined. Rectal temperature, respiratory frequency, ear skin temperature, body weight, and milk yield were recorded biweekly July to March over 2 yr for 170 Israeli-Holstein cows (305-day milk yield 9000 kg/cow) at air temperatures 10 to 36°C. Cows were in an open shelter. One side was force ventilated over 2.5 m along the stanchions (air velocity 1.5 to 3 m/s) from 0500 to 2200 h. Control side mean air velocity was .5 m/s. Within the 10 to 24°C range, rectal temperature was not affected by air temperature or forced ventilation but increased by .02°C/kg fat-corrected milk in animals producing above 24 kg/day. Between 26 and 36°C rectal temperature increased with air temperature in both groups; rate of rise was halved by forced ventilation. In this range of air temperature, rectal temperature increased with rising milk yield, as in the lower air temperature range, in both high-producing and lower-producing cows in forced ventilation. Body weight or parity did not have significant effects. Mean ear skin temperature was higher for control animals, but its rate of increase with air temperature was similar in both groups. Forced ventilation reduced mean respiratory rate. An upper critical temperature is 25 to 26°C and is independent of milk yield or acclimatizational state of cows exposed to the natural sequence of climate.

INTRODUCTION

Body temperature usually is maintained by the thermoregulatory system within 1°C of its normal under ambient conditions that do not impose severe heat stress (10). At air temperatures above the lower critical temperature, body temperature gradually rises (1); this rise is associated with gradual deterioration of feed intake and productivity (18). Estimates of ambient temperatures at which body temperature rises result mostly from studies in which animals were exposed for short periods to constant temperatures in climatic chambers (20, 32). Prolonged exposures allow adaptations that reduce the effect of a given temperature stress (19).

In lactating dairy cattle, complete adaptation to constant temperatures is not attained within 9 wk of continuous exposure (25). Findings were similar for both dairy and beef heifers; their responses varied also with the season in which they first were brought into the climatic chamber (11, 30). It is uncertain whether results from climatic chambers are wholly applicable to the outdoor situation in which diurnal and seasonal cycles of climate prevail. The paucity of data on thermal equilibrium of lactating dairy cattle in the normal environment does not permit quantification of the relationship of body temperature to ambient temperature, particularly for high-yield cows. Such information is needed to evaluate methods of reducing heat gain or increasing heat loss to
alleviate deleterious effects of warm climates on milk production and fertility.

Recently, forced ventilation has been introduced in Israel to alleviate heat stress in dairy cows in open shelters. Our study examined effects of air temperature, forced ventilation, and lactation on the body temperature of dairy cows in a normal environment.

METHODS

The study was of 170 Israeli-Holstein cows over 2 yr in the commercial herd of kibutz Merhavia, in which mean 305-day milk production was 9000 and 220 SE kg per cow, the highest mean yield of all herds in Israel at that time. The experiment was on 120 cows that calved from May to August. Their production declined during winter with advancing lactation. To obtain information on the thermal state of high-producing cows during the cooler season, another group of 50 cows that calved during November and December was used.

Results for milk production, estrous behavior and fertility were reported separately (12) together with details of animals, management, feeding, and experimental procedures; only procedures relating specifically to this part of the study are presented here.

Animals were in an open shed with an asbestos-cement roof reaching not lower than 3 m above ground at the eaves; sides of the shed were open except for a 60-cm high wall that extended along part of the shelter sides. The east-west oriented, 80-m long, 18-m wide shelter was divided lengthwise into two equal parts by a 4-m wide elevated concrete throughput with mangers and stanchions on either side. The area within either side of the shed (6 m²/cow) was bedded with straw. Cows had access to unroofed, unbedded yards (10 m²/cow) extending on either side of the open shed. Primiparous and multiparous cows were kept together; they were assigned randomly to control and forced-ventilation sides of the shelter after being paired by number of lactations, yield, and calving date.

Forced ventilation was on the northern side of the shed by fans spaced 11 m apart at 3 m height and 2 m from the stanchion line. They created an air velocity of 1.5 to 3 m/s over a 2.5-m wide strip over the bedded area along the stanchions. Fans were set to operate from 0500 to 2200 h at air temperatures above 12°C. In the naturally ventilated southern side of the shelter, mean air velocity over the experimental period at 80 cm above ground was .5 m/s by sensitive cup anemometer.4

Rectal temperature (Tr), ear pinna skin temperature (Te), and respiratory frequency (Rf) were measured at 0530 to 0630 (before morning feeding and milking), 1130 to 1230 (before noon milking), 1630 to 1730, and 2200 to 2300 h (1 h after noon and night milkings) at about 2-wk intervals from July to March during 2 yr. These measurements were at least 2 h after a meal.

Respiratory frequency was determined by flank movements counted over two consecutive 30-s periods. The Tr and Te were measured by thermistor probes to the nearest .1°C (probes 406 and 427, respectively, monitor model 46TUC5). The Tr was measured with the probe tip inserted 12 cm into the rectum. The Te was measured with the flat thermistor probe fixed with epoxy resin inside a spring-tensioned clothes peg; the spring was loosened so that the clothes peg would maintain the thermistor only in contact with the skin, without pressing the ear tissues. This made possible rapid measurement of Te with minimal disturbance to animals. Calibration of thermistor probes was tested by their immersion to a depth of 12 cm into a thermostatic bath, the temperature of which was determined by a certified thermometer accurate to ±.02°C. All measurements were with animals standing and tethered in stanchions. Air temperatures were determined at the start and end of each measurement time by a suitable thermistor (YSI probe 405). Air temperatures were within .5°C of the temperature of a meteorological standard black globe placed .5 m above animal height. Because animals spent most daylight hours inside the shed and the ambient relative humidity ranged within 35 to 50% from 1000 to 1600 h, air temperature was a measure of environmental heat stress.

The relationship of Tr, Te, and Rf to independent variables (Ta, daily milk yield, parity, body weight, and time of day of mea-

3 Stork, Model ASD-504, Neema, Utrecht, Holland.
4 Model T16112, Casella, London, UK.
5 Yellow Springs Instruments, Yellow Springs, OH 45387.
surements) was analyzed by multiple regression procedure in which the order of inclusion of independent variables was determined by the extent of contribution of each variable in accounting for the total variance. The analysis was as a combination of regressions between animals plus within animal as well as regression within animal. The latter was by analysis of variance of deviations from means of the individual animals. In either case, the effect of the time of day was analyzed as a nonmetric factor, as diurnal variation of ambient temperature was similar in all seasons.

Characteristics of regression analyses in the two modes were similar as also were R² of the regressions. The within-animals regression corrected for differences between animals in their mean body temperatures. Hence, the two modes of analysis would be expected to yield different R² if interindividual differences in mean body temperature, unaccounted for by the independent variables, had contributed significantly to the total variance. The similarity of R² in the two regression modes suggested that differences within animal in response to a given ambient temperature change probably constituted a larger component of total variance than differences between animals in mean body temperature.

RESULTS

Rectal Temperature

The scattergram of the data (Figure 1) suggested little effect of Ta on Tr at ambient temperatures below 24°C; a gradual rise of Tr was evident at higher ambient temperatures. Regression analyses were separate for lower and the higher air temperature ranges, 10 to 24°C and 26 to 36°C. The total number of observations was 3489; 2259 were in the lower temperature range and 1230 at the higher temperature range. Less than a third of the data came from primiparous animals.

In the 10 to 24°C range of air temperature, no effect of Ta on Tr was found nor was Tr affected by forced ventilation. However, within this range of air temperature an effect of daily milk yield on Tr (P<.05) was found in either mode of regression analysis. The data for the within-animals regression analysis only are presented here (Table 1) as regressions were similar. To examine this effect further, these data were divided into two groups on daily milk yield, a low-yielding group (21.8 ± .1 kg fat-corrected milk (FCM)/day, mean and SE) and a high-yielding group (29.7 ± .1 kg FCM/day). Variation of daily milk yields is because experimental groups were initially composed of cows varying in milk production, and because milk yields of individual animals also changed during the lactation during the experimental period. Separate regressions were calculated for each group; these suggested a significant effect of daily milk yield on Tr (P<.05) in the group with higher daily milk yield only. The R² still remained low in either group and indicated that only 9% of total variance was accounted for by the regression. Using exponential or polynomial regressions did not improve the R². First order interactions were not detected.

At the higher Ta range (26 to 36°C), an effect of daily milk yield was also evident but only in the forced ventilation group at the two daily milk yields. The partial effect of Ta on Tr was statistically significant in this ambient temperature range and was not affected markedly by daily milk production. Forced ventilation reduced the effect of Ta on Tr to about half of that in the control animals and significantly reduced the mean Tr in the group with higher daily milk yield. The R² were greater in control groups than in the forced-ventilation groups, suggesting greater dependence of Tr on Ta and daily milk yield in the control animals.

The regressions of Tr on air temperature and daily milk yield include additional sources of
### Table 1. Regressions of rectal temperature (Tr, °C) deviations from means of individual cows on air temperature (Ta, °C) and milk yield (kg fat-corrected milk (FCM)/day, Y).1

<table>
<thead>
<tr>
<th>Yield group</th>
<th>Experimental group</th>
<th>Regression equation</th>
<th>$R^2$</th>
<th>Tr $\bar{X}$</th>
<th>SE</th>
<th>FCM $\bar{X}$</th>
<th>SE</th>
<th>Ta $\bar{X}$</th>
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<th>NC</th>
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<td>Air temperature range 10–24°C</td>
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<td></td>
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</tr>
<tr>
<td>All</td>
<td>All</td>
<td>$-0.33 + 0.01Y$</td>
<td>0.03</td>
<td>38.8</td>
<td>0.1</td>
<td>27.0</td>
<td>0.1</td>
<td>18.0</td>
<td>0.2</td>
<td>2259</td>
<td>145</td>
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<tr>
<td>Low$^2$</td>
<td>All</td>
<td>N.S.</td>
<td>...</td>
<td>38.7</td>
<td>0.1</td>
<td>21.8</td>
<td>0.1</td>
<td>18.1</td>
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<td>High$^3$</td>
<td>All</td>
<td>$-0.26 + 0.02Y$</td>
<td>0.09</td>
<td>38.8</td>
<td>0.1</td>
<td>29.7</td>
<td>0.1</td>
<td>18.0</td>
<td>0.1</td>
<td>1430</td>
<td>133</td>
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<tr>
<td>High</td>
<td>FV</td>
<td>$-2.40 + 0.08Ta + 0.02Y$</td>
<td>0.07</td>
<td>39.1</td>
<td>0.2</td>
<td>30.3</td>
<td>0.2</td>
<td>29.4</td>
<td>0.2</td>
<td>474</td>
<td>54</td>
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<td></td>
<td>C</td>
<td>$-4.57 + 0.17Ta$</td>
<td>0.32</td>
<td>39.4</td>
<td>0.2</td>
<td>29.7</td>
<td>0.1</td>
<td>29.9</td>
<td>0.1</td>
<td>458</td>
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<tr>
<td>Low</td>
<td>FV</td>
<td>$-2.64 + 0.09Ta + 0.02Y$</td>
<td>0.15</td>
<td>39.1</td>
<td>0.3</td>
<td>21.1</td>
<td>0.2</td>
<td>30.0</td>
<td>0.1</td>
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<td></td>
<td>C</td>
<td>$-5.65 + 0.20TA$</td>
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<td>39.2</td>
<td>0.2</td>
<td>21.0</td>
<td>0.2</td>
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1NO = Number of observations, NC = number of cows observed, NS = nonsignificant, FV = forced-ventilation cows, C = control cows.

2Milk yield below 24 kg FCM/day.

3Milk yield above 24 kg FCM/day.

Variance of which variation between animals in response to Ta would be an important component. This variation included differences in heat dissipation capacity as well as the effect of ranking order on thermoregulatory behavior. For this, regression analyses were carried out on means of groups of cows (10 to 40 animals per group) measured at different times of day over the experimental period. There were 204 such groups. Coefficients of regression were similar to those in the full analysis, but the $R^2$ were markedly higher, ranging between .54 and .70. The large increase of $R^2$ suggests a significant component of between-animal variation in response. Part of this variation probably could be reduced by proper management methods and shelter design.

#### Ear Pinna Skin Temperature

On 41 occasions ear pinna skin temperature was examined (2240 measurements, 1125 in the control and forced-ventilated groups) in the 11.8 to 31.6°C ambient temperature range. The scattergram of means of the forced-ventilation and control groups is in Figure 2. Forced ventilation slightly reduced mean Te (28.6 vs. 30.0°C, $P<.05$); it did not affect the relationship of Te to Ta in the overall Ta range (mean regression Te=21.6 + .45 Ta; $R^2 = .52$, $P<.001$, mean Te and SE 29.3 ± .4). The effect of forced ventilation was more marked in the lower Ta range (10 to 24°C) where intercepts of the regression relating Te to Ta in the pooled data were lower ($P<.05$) in the forced-ventilation group than in the control group (Te = 18.1 + .63 Ta, $R^2 = .50$ vs. Te = 22.9 + .43 Ta, $R^2 = .38$). The Te was always above Ta in this experiment, indicating peripheral vasodilation, although increased variability in Te was evident at Ta below 20°C. However, ear skin temper-
At bed temperatures equalled air temperatures at about 20°C (Ta) during the first .5 h after cows returned from milking; cows had the lower part of their body wetted by sprinklers before milking. Partial regression analysis did not reveal significant relationship between Te and milk yield.

Respiratory Frequency

On 14 occasions respiratory frequency was measured (822 observations, 395 and 427 in the control and forced-ventilation groups) in the 21 to 31°C ambient temperature range. The scattergram of means of control and forced-ventilation groups is in Figure 3.

Forced ventilation reduced Rf from a mean of 73 ± 2 in the control group to 59 ± 1 (means and SE) in the forced-ventilation group. It did not affect the relationship of Rf to Ta, which was similar in the two groups (Rf = .5 + 2.5 Ta, R² = .67, P<.01).

Separate regressions of the data measured at ambient temperatures above 25°C in the control and forced-ventilated animals also indicated similar regression coefficients in both groups. This suggests a similar effect of ambient temperature on respiratory frequency in both the control and the forced-ventilation animals. Extrapolation showed that Rf of 50 to 60 were to be attained at Ta of about 24 to 26°C.

DISCUSSION

Differences in response to a given ambient temperature change between animals as well as in an individual animal may arise from the nature of the animal shelter system. In the roofed area the thermal load is significantly less than in the sun-exposed yard; ventilation also presumably reduced thermal load in the ventilated strip under the roofed area vs. the unventilated part of the same area. The location of an animal, and hence, the thermal load it is exposed to, is determined largely by its ranking order and by changes in position of the dominant animals. Because animals were stanchioned only to measure their reactions, their responses would be affected by the thermal load to which they were exposed earlier. As location of animals was not constant, this might have introduced variation into the response to ambient temperature, which was partly responsible for the relatively low R² (Table 1).

We failed to detect effects of parity and body weight on dependent variables or in modifying the response to the other independent variable (Ta, daily milk yield, body weight). The effect of body weight also was not significant. Therefore, only effects of Ta and of daily milk yield were presented.

The effect of milk production on body temperature was similar to observations that during thermal equilibrium, rectal temperature is independent of air temperature but related to energy metabolism in man (13), dog (33), and rat (31). Metabolic rate and Tr also were interrelated during their circadian changes at thermoneutral ambient temperatures in the rat (15) and in the domestic fowl (Berman and Meltzer, unpublished data). It seems, therefore, that a relationship between Tr and metabolic rate can be expected under thermal comfort conditions.

The upper critical temperatures can be inferred from thermoregulatory functions like skin and respiratory water loss and from body temperature. In a study on lactating cows, skin evaporative loss increased at air temperatures above 20°C (4). In the present experiment, respiratory frequency started to rise above 50 to 60 Rf at ambient temperatures higher than 25°C, as also in earlier experiments on rapidly growing dairy heifers and high-producing dairy cows (2, 6); body temperature also started rising above base at air temperatures

Figure 3. Scattergram of means of respiratory frequency of experimental groups as measured at 0530 to 0630, 1130 to 1230, 1530 to 1630, and 2200 to 2300 h during the experimental period.

- Forced-ventilation animals; ○ control animals.
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higher than 25 to 26°C. A similar threshold air temperature for body temperature was suggested from studies on dairy heifers (3) and high-yielding cows in a hot desert (6). We recalculated data published from Missouri on Holstein cows yielding 10 to 25 kg FCM/day at constant ambient temperatures increased at 2-wk intervals (21, 22, 24), and we found that body temperatures increased, as in our observations, only at air temperatures above 26°C. The regression relating the two measures at air temperatures above 26°C was similar to that in our control cows.

Studies on the relationship between conception rate or milk yield and temperature-humidity index suggested that both conception rate and milk yield decreased at air temperatures above 25°C in any particular temperature and humidity combination (16, 26). Increases of body temperature occurring above this air temperature are associated with lower feed intake, daily milk yield (17, 18), and lower metabolic rate (3).

Higher daily milk yields are associated with higher metabolic heat production. The impact of this on Tr at the lower ambient temperature range was discussed earlier. At higher Ta, increases of Tr in the higher Tr range could act as a factor limiting milk production. Acclimatization to heat, which increases heat loss capacity, would allow for attainment of higher milk yields at a given Tr or for lower Tr at a given Ta. That Tr increased at Ta above 24 to 26°C irrespective of milk yield suggests that animals with a potential for high production respond to acclimatization by increasing milk production rather than by reducing body temperature. From data, 25 to 26°C is the upper critical ambient temperature for high-producing dairy cows, irrespective of previous acclimatization or of their milk production.

This estimate for the upper critical temperature should be considered in relation to estimates for lower critical temperature in dairy cattle. For cows producing 30 kg FCM/day it was estimated, on the basis of calorimetric data, as −16°C to −37°C (14, 27). Non-evaporative heat loss declines as ambient temperatures rise above the lower critical ambient temperature; animals thus become increasingly dependent upon peripheral vasodilation and water evaporation to enhance heat loss and to prevent rise of body temperature. Peripheral vasodilation is unlikely to be a major factor increasing heat dissipation in cattle because of their large body mass. The maximal rates of total water evaporation are 1.5 kg/h (4), which is equivalent to 18 Mcal/day. This rate of heat loss is close to the heat production of a dry nonpregnant 600 kg cow but only about half that of a cow yielding 30 kg/day. This is the probable basis for the lesser sensitivity of dry cows to high ambient temperatures. The mentioned estimates of lower critical ambient temperatures are hard to reconcile with known high milk production in some hot climates, as they imply high evaporative cooling rates for which there is no evidence. It is also difficult to conceive a 40 to 60°C wide thermoneutral temperature zone, as implied by these estimates of lower critical temperature and the upper critical temperature.

Adaptive changes of insulation and metabolic rate could shift the lower critical temperature higher if the extrapolated ambient temperature for zero metabolic rate remains more or less constant. Adaptive changes of tissue and hair heat conductance are reflected in the slope relating nonevaporative heat loss to air temperature. This slope was calculated from available published data. The −0.07 to −0.09 Mcal/m² 24 h °C was similar for mature steers of British breeds (9), crossbred beef heifers in Canada (29), and lactating Holstein and dry Guernsey cows in Missouri (8, 23). Slopes twice as large were found in the subtropical climate of Israel in Israeli-Holstein lactating cows in winter; there was a further 30% increase in summer (6) probably associated with the seasonal decrease of coat depth from 6 to 2 mm (7).

Reductions from winter to summer of metabolic rate of about 20%, unassociated with lower productivity, were observed in Israeli-Holstein lactating cows and mature heifers exposed to a near natural subtropical climate (3, 5, 6).

It seems that metabolic and insulative adaptations to the local climate and their seasonal changes are sufficient to maintain normal productivity even in warmer climates. Such presumption is supported by studies of energy exchange in veal calves (29) and beef cattle (28) and growth rate in mature heifers (11, 30).

In the forced-ventilation animals rate of increase of Tr in the 26 to 36°C air temperature
range was about half that in the control animals. As a result, lower Tr and Rf were maintained in the forced-ventilation animals in this ambient temperature range. It is significant that forced ventilation also reduced $R^2$ as compared to those in control animals. Forced ventilation was an efficient means of reducing the stressing effect of ambient temperature as expressed in both Tr and in reproductive performance (12). Forced ventilation over a 2.5-m wide strip in the shelter allowed for thermoregulatory behavior, because the animals could move in and out of the ventilated area.

Our results suggest that 25 to 26°C is the upper limit of ambient temperatures at which Holstein cattle may maintain stability of body temperature. It is significant that this critical temperature was apparently not modified by acclimatization or by milk production. It seems, therefore, that acclimatization changes heat dissipation capacity up to this threshold ambient temperature. The increase of body temperature beyond this ambient temperature limits reproductive performance and milk yield. It seems that 25°C is the upper limit of ambient temperatures beyond which husbandry procedures should intervene to prevent or reduce the rise of body temperature. Forced ventilation seems an effective procedure for this purpose up to ambient temperatures near body temperatures. Additional methods, more powerful in dissipating metabolic heat production and low in their energy costs, are being examined currently.

REFERENCES


