Estimates of heat stress relief needs for Holstein dairy cows[1]

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ABSTRACT: Estimates of environmental heat stress are required for heat stress relief measures in cattle. Heat stress is commonly assessed by the temperature-humidity index (THI), the sum of dry and wet bulb temperatures. The THI does not include an interaction between temperature and humidity, although evaporative heat loss increases with rising air temperature. Coat, air velocity, and radiation effects also are not accounted for in the THI. The Holstein dairy cow is the primary target of heat stress relief, followed by feedlot cattle. Heat stress may be estimated for a variety of conditions by thermal balance models. The models consist of animal-specific data (BW, metabolic heat production, tissue and coat insulation, skin water loss, coat depth, and minimal and maximal tidal volumes) and of general heat exchange equations. A thermal balance simulation model was modified to adapt it for Holstein cows by using Holstein data for the animal characteristics in the model, and was validated by comparing its outputs to experimental data. Model outputs include radiant, convective, skin evaporative, respiratory heat loss and rate of change of body temperature. Effects of milk production (35 and 45 kg/d), hair coat depth (3 and 6 mm), air temperature (20 to 45°C), air velocity (0.2 to 2.0 m/s), air humidity (0.8 to 3.9 kPa), and exposed body surface (100, 75, and 50%) on thermal balance outputs were examined. Environmental conditions at which respiratory heat loss attained approximately 50% of its maximal value were defined as thresholds for intermediate heat stress. Air velocity increased and humidity significantly decreased threshold temperatures, particularly at higher coat depth. The effect of air velocity was amplified at high humidity. Increasing milk production from 35 to 45 kg/d decreased threshold temperature by 5°C. In the lying cow, the lower air velocity in the proximity of body surface and the smaller exposed surface markedly decrease threshold temperature. The large variation in thresholds due to environmental and animal factors justifies the use of thermal balance-based indices for estimating heat stress. Such an approach may make possible estimates of threshold temperatures at which heat stress relief is required for widely different cattle types and environmental situations.

Key Words: Cattle, Climate, Index, Stress, Temperature

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Introduction

No clear criteria exist as to conditions in which heat stress relief is needed. The temperature humidity index (**THI**) is used for assessing thermal stress. It estimates human thermal comfort sensation at different ambient temperatures and air humidity, at low air velocity (Thom, 1958). Values of THI were categorized into four hazard levels for cattle by the Livestock Conservation Institute, but supporting experimental evidence was not clear (Whittier, 1993). Cattle responses were related to THI (Hahn, 1983; West, 2003). Responses may, however, also be affected by air velocity, radiation, and factors such as the posture and density of animals, their heat production, and coat insulation (Berman, 2004). Thermal balance simulation models for cattle (McGovern and Bruce, 2000; Turnpenny et al., 2000) may allow for heat stress estimation in a variety of environments. These models are based on research of cattle thermoregulation, radiant, convective, and evaporative heat loss from skin and respiratory tract. They consist of functions derived from cattle thermoregulation and heat exchange physics. Animal and environment characteristics serve as input, and animal responses are produced as output. Application of such models is limited as each simulation estimates one set of input data, and outputs apply only to a particular set of conditions. It was presumed that this may be overcome by repeated simulations, in which input variables (heat production, coat depth, air temperature, humidity, and velocity) are

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modified in a balanced design. A data set of input variables and predicted animal responses may be produced. An analysis of this data set may yield approximations of the predicted animal responses over a range of input variables (e.g., air temperature, humidity and velocity) without having to repeat simulation model runs for each set of environmental conditions. These estimates may be reliable enough to be used as an aid in decision making in dairy cattle heat stress management.

Materials and Methods

Holstein dairy cows and feedlot cattle would likely benefit the most from heat stress relief. The Holstein dairy cow probably is the primary target for a heat stress index-based heat stress relief management. Thermal balance models view the animal as a heat exchange system. In this study, a thermal balance model was used (McGovern and Bruce, 2000) that consists of 153 elements that detail the thermal environment, animal characteristics, respiratory functions, heat production and distribution in the body, the distribution of heat loss via combined heat loss through coat, evaporative skin heat loss and respiratory heat loss, and eventual rates of change of body temperature. In this model, when heat loss is limited by ambient conditions, evaporative skin loss is initially increased, followed by heat loss from the respiratory system, and if the resultant value is less than total heat input, the remaining heat is stored in the body as an increase in temperature. Seven of the animal parameters in the model were not specific for Holstein cows, and incorporating them overestimated total skin and respiratory heat loss. These parameters were replaced by data derived from studies of Holstein cows carried out in temperate and warmer climates, as detailed in the following section, to better simulate the thermal balance of a Holstein cow. These changes in animal parameters shift the ambient temperatures at which skin and respiratory heat loss is recruited and that at which body temperature starts rising. They do not otherwise modify model structure or its mode of working. The model was otherwise left as originally described (McGovern and Bruce, 2000). The modified model was subsequently validated to verify that it adequately represented responses of Holstein cows.

Metabolic heat production was calculated according to NRC (2001): maintenance heat production as 0.080 Mcal/kg $BW^{0.75}$; milk NE_L concentration = 0.36 + [0.0969 × (fat%)]; and efficiency of dietary ME for milk energy production as 64%. Body surface area was estimated by $0.14 \cdot BW^{0.57}$ (Brody, 1945) instead of the $0.09 \cdot BW^{0.67}$ equation (Mitchell, 1928) for reasons detailed in another study (Berman, 2003). Tissue insulation was calculated from data specific for Holstein cattle (Berman, 2004). Hair coat insulation was estimated according to available information on Holstein cows as $0.30 m^2/(d \cdot Mcal)$ for each 1 mm of coat depth and a 3-mm coat depth for Holstein cows in the summer (Berman, 2004). Maximal skin evaporative heat loss was estimated as 220 $g \cdot m^2/h$ according to data measured in shaded lactating Holstein cows in a hot desert environment (Berman and Morag, 1971). In the model, tidal volume was estimated from BW by an equation (Hales and Findlay, 1968) derived from respiratory data of calves weighing 110 to 280 kg. Extrapolating to animals weighing 500 to 700 kg produced data that overestimated tidal volume by 49% relative to the tidal volume measured in mature Holstein cattle data (Hall and Brody, 1933; Kibler, 1964; Berman, 1967). This overestimation of tidal volumes led to overestimations of respiratory heat loss, as mentioned in the description of the model (McGovern and Bruce, 2000). The equation for maximal tidal volume estimation in the model was replaced by that based on the mean of the aforementioned studies of Holstein cows:

$$V_t = 0.4 + 0.0064 \times BW \quad [1]$$

where V_t = tidal volume (L/breath).

Maximal and minimal tidal volumes were set as 4.3 and 1.9 L/breath, respectively. In the model equations for vapor content in the expired air, it was presumed that air is exhaled at body temperature. This presumption is of doubtful validity as a number of studies have indicated that expired air temperature is significantly lower than body temperature. It was replaced by an empirical equation computed from a large experimental data base on Holstein cows (Stevens, 1981):

$$Tex = 17 + 0.3 \times Td + e^{(0.01611 \times RH + 0.0387 \times Td)} \quad [2]$$

where Tex = exhaled air temperature, °C; Td = ambient air temperature, °C; and RH = relative humidity, %.

The overall soundness of the model has been shown in its original publication (McGovern and Bruce, 2000). The modified model was further validated by comparing the data it produced with data of experiments carried out on Holstein cows kept in the shade. Respiratory frequencies in field studies on Holstein cows (Berman, 1971) were highly correlated (r = 0.996) with those predicted by the equations derived by Stevens (1981) for estimates of respiratory water loss. These alterations produced respiratory heat loss values more realistic than the original values set in the model. Changes in rectal temperature estimated by the modified model were closely related (r = 0.89) to those measured in shaded Holstein cows in field studies (Berman, 1968; Berman and Morag, 1971; Berman et al., 1985; Igono et al, 1987; Her et al., 1988). The rapid rise in respiratory frequency and rectal temperature to levels indicative of stress during a summer day (Berman and Morag, 1971) occurred at ambient conditions as predicted by the model. Respiratory frequency and rectal temperatures determined in shaded cows with concomitant records of air temperature, humidity, and air velocity (Roman-Ponce et al., 1977), corresponded well (r = 0.85) to those expected from the equations presented here.

The increase in respiratory heat loss, which is associated with rising air temperatures, was curvilinear, as found in cows exposed to constant as well as to cycling temperatures in climate chamber studies (Kibler and Brody, 1950; Brown-Brandl et al., 2003). Predicted evaporative heat loss increases and combined radiant-convective heat loss decreases with rising air temperature, and they intersect at approximately 25 to 27°C, similar to the results with Holstein cows (Kibler and Brody, 1950). These findings suggest that the modified model may be used to estimate responses of shaded Holstein dairy cows exposed to warm environments.

Simulations of thermal balance were run for the following environmental situations: air temperatures from 20 to 45°C at 5°C intervals; water vapor pressure (**Pw**) of 0.8, 1.6, 2.4, 3.1, 3.5, and 3.9 kPa (equivalent to absolute humidity of 5, 10, 15, 20, 22.5, and 25 g of water/kg of dry air); and air velocities of 0.2, 0.6, 1.0, 1.5, and 2.0 m/s. In climate chambers, radiant temperature equals air temperature, but in cattle sheds, it depends on solar radiation, shade area per cow, and height of roof and its radiant characteristics (Kelly et al., 1950). Radiant temperature was assumed to be 3°C above air temperature, as estimated to prevail from black globe temperature (**BGT**) data measured in open shelters (A. Berman, unpublished data). The difference between air temperature and radiant temperature depends on the intensity of solar radiation, cloudiness, air velocity, roof height, roof thermal characteristics, shade area, and mean ground temperature. A difference of 3°C between air and radiant temperature represents a high and reflective roof, large shade area per cow (approximately 10 m^2/cow), and moderate air velocity typical of open dairy sheds, such as those used in Israel. The simulations, 1,408 in all, were carried out for a 600-kg cow producing 35 or 45 kg of milk with 3.5% fat per day, a metabolic heat production of 19 and 23 Mcal/d, respectively, and a coat thickness of 3 and 6 mm. These simulations also were carried out assuming that body surface area is 75 and 50% of that calculated for a 600-kg BW cow, to simulate a variably exposed body surface as present in lying or huddling cows.

The thermal balance model outputs included animal responses of total heat production, respiratory heat loss, skin evaporative, convective, and radiant heat losses, tissue insulation, and rate of change in body temperature. The relations between model inputs (air temperature, humidity and air velocity) and model outputs, that is, the predicted responses, were estimated by the GLM procedure of SAS (SAS Inst., Inc., Cary, NC). Quadratic terms were used wherever required by consideration of thermoregulatory or heat exchange functions. Regression models were decreased to significant ($P < 0.01$) terms. The relative contribution of environment factors on responses was estimated by the R^2 selection method in the REG procedure in SAS. In this particular data set, the R^2 estimates the extent to which the regressions explain the responses predicted by the simulations. The purpose of these analyses was to produce relatively simple equations that may be used to approximate the predictions of the simulation model.

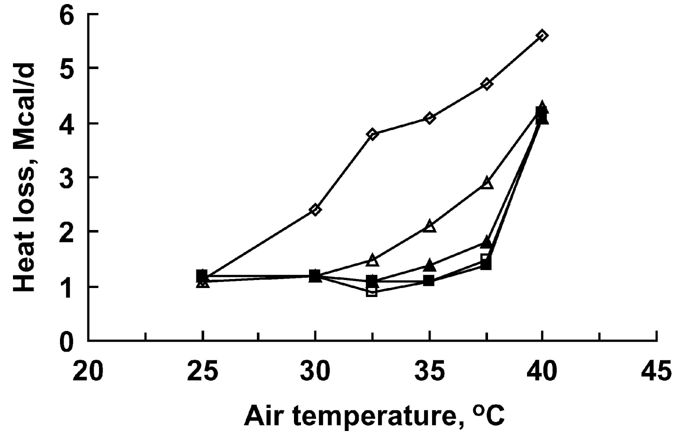

Figure 1. Respiratory heat loss (HER, Mcal/d) estimated for a cow with coat depth of 3 mm, producing 35 kg/d of 3.5% fat milk, at air temperature 25 to 40°C and vapor pressure of 2.6 kPa and air velocity of 0.2 (◇), 0.6 (△), 1.0 (▲), 1.5 (□), and 2 (■) m/s.

Results

Skin and Respiratory Water Loss

Water evaporates from both skin and the respiratory tract. Skin water loss (**HES**, Mcal/d) begins at initial phases of heat stress, followed by recruitment of respiratory heat loss (**HER**, Mcal/d). The surface of the animal is exposed to air velocity as well as to ambient air humidity. The HES increases with increasing ambient temperatures to a ceiling value determined by the maximum skin water loss rate typical for the animal, set as 220 g/(m^2·h) in these simulations. At lower ambient temperatures, greater air velocities increase convective heat loss, and thereby decrease demand for evaporative heat loss. The greater evaporation rates required at higher ambient temperatures are decreased when air velocity on the body surface is low. At air velocities of 0.6 and 0.2 m/s, skin water loss is decreased to 88 and 60% of the maximal value, respectively. The estimated HES depend on the humidity and velocity of air, the effects of which increase at higher ambient temperature.

The HER takes place at the interface between inhaled air and the surface of the respiratory tract over which air flows. It is shielded from air movement outside the body, and is affected by velocity and volume of air flow in the respiratory pathways (i.e., respiratory frequency and tidal volume, respectively). Higher air velocity increases skin convective heat loss, decreases the demand for evaporative heat loss, and may indirectly decrease HER.

At the lowest air velocity, 0.2 m/s, HER was initiated when ambient temperatures rose above 25°C (Figure 1). Increasing air velocity to 0.6 m/s increased this

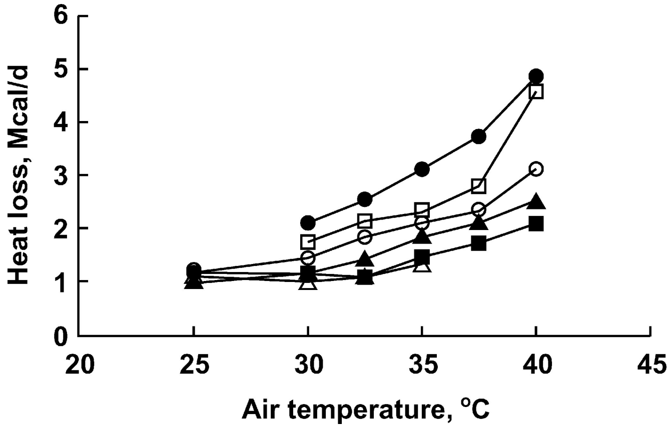

Figure 2. Respiratory heat loss (HER, Mcal/d) estimated for a cow with coat depth of 3 mm, producing 35 kg/d of 3.5% fat milk, at air temperature 25 to 40°C and air velocity 1 m/s and vapor pressure of 0.8 (△), 1.6 (■), 2.4 (▲), 3.2 (○), 3.5 (□), and 3.9 (●) kPa.

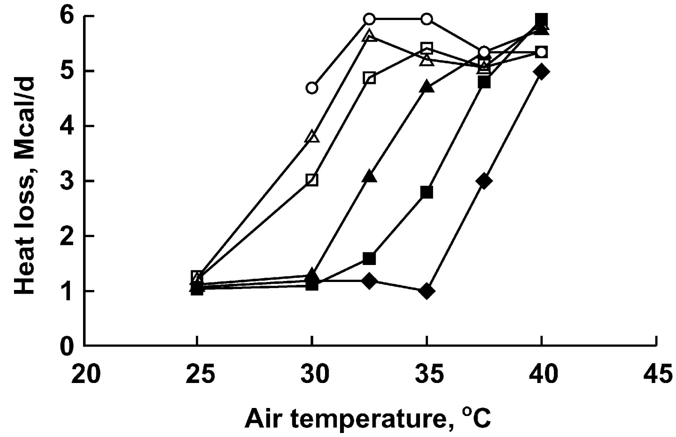

Figure 3. Respiratory heat loss (HER, Mcal/d) estimated for a cow with coat depth of 3 mm, producing 35 kg/d of 3.5% fat milk, at air temperature 25 to 40°C and air velocity 0.2 m/s and vapor pressure of 0.8 (◆), 1.6 (■), 2.4 (▲), 3.2 (□), 3.5 (△), and 3.9 (○) kPa.

threshold by approximately 5°C. Higher air velocities, of 1, 1.5, and 2 m/s, did not differ in their effects on respiratory heat loss, which increased exponentially at ambient temperatures above 35°C. Air humidity modified the rate of HER increase with increasing air temperature (Figure 2). Based on these results, the relationship of HER to air velocity and humidity was expressed by two regression equations:
For air velocities less than 1 m/s:

$$\text{HER} = 20.3 - 1.36 \times \text{Td} + 0.024 \times \text{Td}^2 + 65.1 \times \text{V} - 17.0 \times \text{Pw} + 1.0 \times \text{Td} \times \text{Pw} - 0.01 \times \text{Td}^2 \times \text{Pw}\ (R^2 = 0.832) \quad [3]$$

where HER = respiratory heat loss, Mcal/d; Td = air temperature, °C; V = air velocity, m/s; and Pw = vapor pressure, kPa.
For air velocities of 1 m/s and greater and air temperatures greater than 25°C:

$$\text{HER} = 67.8 - 4.0 \times \text{Td} + 0.06 \times \text{Td}^2 - 1.0 \times \text{Pw} + 0.03 \times \text{Td} \times \text{Pw}\ (R^2 = 0.813) \quad [4]$$

The increase in respiratory heat loss with air temperature was exponential and was affected by air humidity as well as by air velocity. Respiratory heat loss means ranged between 1 and 6 Mcal/d, and in extreme conditions, individual values of up to 8 Mcal/d were found. The distribution of these values depends on air temperature, humidity, and air velocity.

Threshold Conditions for Rise in HER

The HER represents an integrated response of the thermoregulatory system to heat stress. The ambient conditions at which HER increases may serve as an index of environmental heat stress. The air temperature at which HER increases is, however, difficult to define, owing to the exponential nature of the response of HER to Td. Intermediate rates of HER, present between minimal and maximal HER rates (e.g., Figure 3), represent ambient conditions in which displacements in respiratory heat loss per unit change in air temperature are the greatest. Intermediate HER values may therefore serve as a sensitive parameter for assessing the effect of ambient conditions on respiratory heat loss. They ranged between 2.5 and 4 Mcal/d and averaged 3.25 × 1 (SEM) Mcal/d. Their mean value is close to mid-maximal respiratory heat loss, approximately 53% of it. These intermediate values occurred at different air temperature, air velocity, and humidity conditions. The latter represents ambient conditions that induce onset of thermal stress. A data set was formed of simulations in which intermediate HER values were present. It served to examine the effects of air velocity and air humidity on the air temperature at which the intermediate values occurred. These relationships were examined in data subsets representing different categories of milk production, coat thickness, and exposed surface area.

The data of simulations carried out for the aforementioned conditions for a cow yielding 35 kg of 3.5% fat milk, with a maximal skin evaporative capacity of 220 g/(m^2·h), and a 3-mm-deep coat, produced the following equation:

$$\text{Td} = 38.7 + 7.9 \times \text{V} - 3.8 \times \text{V}^2 - 3.2 \times \text{Pw} + 1.7 \times \text{V} \times \text{Pw}\ (R^2 = 0.883) \quad [5]$$

where Td = air temperature (°C) at which intermediate HER occur. All terms in the regression were significant ($P < 0.01$).

The air temperature at which intermediate HER occurs increases with air velocity, decreases with air humidity, and the effect of humidity is decreased by increasing air velocity. It may serve as a threshold that represents the onset of thermal stress. The threshold indicates a need for heat stress relief means to prevent deterioration of the animal's condition. The threshold temperature, Td, was calculated at low and high humidity (1 and 3.4 kPa, respectively) and 0.2 to 2 m/s air velocity. Increasing air velocity increased Td (i.e., the ambient temperature at which mid-maximal respiratory response is attained), with a plateau reached at approximately 1.5 m/s. At 0.2 m/s, air velocity Td values were 37 and 30°C for the low and high humidity, respectively. The difference between the two humidity levels decreased with increasing air velocity, to become zero at approximately 2 m/s.

For a similar cow, but one yielding 45 kg of 3.5% fat, the following equation was obtained:

$$Td = 33.7 + 7.9 \times V - 3.8 \times V^2 - 3.3 \times Pw + 1.6 \times V \times Pw \; (R^2 = 0.829) \qquad [6]$$

The higher milk production decreased the intercept, but did not alter air velocity or humidity effects on the air temperature at which intermediate respiratory heat loss occurred. For an otherwise similar cow, but carrying a 6-mm coat and producing 35 kg of 3.5% fat milk, the equation was:

$$Td = 37.0 + 10.2 \times V - 4.3 \times V^2 - 3.7 \times Pw + 1.7 \times V \times Pw \; (R^2 = 0.833) \qquad [7]$$

Increasing the depth of the coat (increasing external insulation) decreased the intercept and increased the air velocity effect on the air temperature at which intermediate values of respiratory heat loss are reached. It did not alter the coefficient representing the effect of air humidity on respiratory heat loss.

The effect of coat thickness and humidity was examined by using Eq. [5] and [7] to estimate Td at low and high vapor pressure (1 and 3.4 kPa) and air velocity (0.2 to 2 m/s). The high humidity lowered Td, but its effect decreased with increasing air velocity: 7.5°C at 0.2 m/s and zero at 2 m/s. The effect of the greater coat thickness depended on both air velocity and humidity. At low humidity and 0.2 m/s air velocity, Td was 1°C lower for a 6-mm-thick coat than for the 3-mm-thick coat. The difference declined with rising air velocity, to become zero at approximately 1.2 m/s. At a high humidity and 0.2 m/s air velocity, Td were decreased to 30 and 27.5°C for the 3- and 6-mm-thick coats, respectively; the difference between the two decreased to zero at approximately 2 m/s air velocity.

The effect of decreasing the exposed body surface area to 75 or to 50% also was examined for a cow carrying a 3-mm coat and producing 35 kg of 3.5% fat milk. These simulate recumbent postures and huddling situations, in which the exposed surface area is decreased to a varying extent. If the body surface area exposed to moving air is decreased to 75% (and a dry, insulating resting surface may be assumed to reach skin temperature), the equation was:

$$Td = 29.0 + 13.7 \times V - 6.86 \times V^2 - 2.6 \times Pw + 1.5 \times V \times Pw \; (R^2 = 0.740) \qquad [8]$$

If the exposed body surface area is decreased to 50% the equation becomes:

$$Td = 17.7 + 9.4 \times V - 2.90 \times V^2 - 3.3 \times Pw \; (R^2 = 0.840) \qquad [9]$$

Decreasing the exposed body surface area had the most marked effect on the intercept, followed by an increase in the coefficients for the air velocity effect on respiratory response. The coefficient expressing the effect of air humidity was modified to a minor degree only.

These previously defined equations were used to estimate the air temperatures at which respiratory heat loss reaches mid-maximal values at different milk production levels, coat depths, and air humidity and velocity (Table 1). The estimates may be viewed as effective temperatures, corrected for the effects of air velocity, air humidity, milk yield, and hair coat depth. Increasing milk production from 35 to 45 kg/d had practically no effect on the coefficients for the effects of air velocity and air humidity (and their interaction); it only decreased the value of the intercept. Increasing coat depth from 3 to 6 mm mostly affected the coefficients for air velocity effects. These results suggest that milk production (i.e., metabolic heat production) has an additive effect on these estimates, whereas that of coat depth is multiplicative. The estimates produced by these equations for air velocities of 0.2 and 1.5 m/s are based on the assumption that the entire body surface is exposed to air movement at such velocities. In reality, the situation is more complex. Air movement is directional, so that an animal exposed to an air velocity of 1.5 m/s on one of its body sides will experience air movement at a much lower velocity (e.g., 0.2 on the other side of its body). To estimate this, the estimates were also calculated for an air velocity of 0.85 m/s, the mean of 1.5 and 0.2 m/s.

The predicted thresholds presented in this table encompass a wide range of air velocity, air humidity, and exposed body surface area effects, representative of different climates, management systems, and animal behavior situations. These effects may be compared for a cow yielding 35 kg/d of 3.5% fat milk. The data point to the posture effect as most powerful in modifying the threshold temperature. The recumbent cow (75 and 50% exposed surface area) has markedly lower threshold temperatures than the standing cow, and is therefore the most sensitive to heat stress. Next to recumbence is the effect of coat depth. Air velocity increased and air humidity decreased threshold temperatures.

Table 1. Air temperature (°C) at which threshold respiratory response (53% of maximal respiratory heat loss) is attained by a 600-kg BW Holstein cow, calculated by Eq. [3] to [9] according to the terms specified in model

Item		Terms in model				
Milk, kg/d		35	35	45	35	35
Coat depth, mm		3	6	3	3	3
Exposed SA, %[a]		100	100	100	75	50
Air velocity, m/s	Pw[b]	Predicted threshold air temperatures, °C				
0.2	1	37	36	32	29	16
0.2	3.4	30	27.5	25	24	8
1.5	1	41	42	36	34	22
1.5	3.4	40	39	34	33	14
0.85	1	39	37	36	34	20
0.85	3.4	36	31	31	31	11

[a]Body surface area, m^2.
[b]Water vapor pressure, kPa.

These effects were amplified by coat depth. Increasing humidity from 1 to 3.4 kPa decreased the threshold temperature (at 0.2 m/s air velocity) by 7 and 8.5°C when coat depth was 3 and 6 mm, respectively. Increasing air velocity from 0.2 to 1.5 m/s (at 1 kPa) increased threshold temperature by 4 and 6°C when coat depth was 3 and 6 mm, respectively. The effect of air velocity on threshold temperature was amplified by high humidity. Increasing air velocity from 0.2 to 1.5 m/s increased threshold temperature (for a cow producing 35 kg/d milk with a 3-mm-thick coat) by 4 and 10°C at ambient humidity of 1 and 3.4 kPa, respectively. Increasing milk production from 35 to 45 kg/d decreased threshold temperatures by 5°C, with little if any change in coefficients for humidity or air velocity effects.

Discussion

The systems rating thermal environments are based on the relationships between components of the thermal environment and the responses of animals. These relations are expressed in an effective temperature measure. The effective temperature concept for humans, apparently first developed by Houghton and Yaglou in 1923, is based on the warmth sensed at combinations of Td, wet bulb temperature (**Tw**), and air velocity (Belding, 1970). Human environment research later used systems that combined mean radiant and air temperatures, air velocity, human insulation, physical activity, heat exchange, and evaporative cooling for a comprehensive assessment of thermal stress (Budd, 2001).

The simpler index for the indoor environment based on the sum of Td and Tw, the THI (Thom, 1958), has been used to estimate thermal stress in cattle (Ingraham et al., 1976; West, 2003). The Td and Tw are given equal weight in the THI equation. The relative weights of Td and Tw differ, however, for responses of dairy cows (respiratory rate, rectal temperature, and milk yield decrease) to temperature and humidity stress in an indoor environment; interactions prevail between Td and Tw effects on these responses, and the effects of Td and Tw were in no case equal to each other as in the THI index (Johnson et al., 1962; Kibler, 1964). Nonevaporative heat loss decreases with rising ambient temperatures, whereas evaporative heat loss progressively increases. This indicates that the weight of humidity as a heat stress factor is underestimated by the THI index. The correlations between THI and responses of cattle (Ingraham et al., 1976; Buffington et al., 1981; West, 2003) may thus underestimate the effects of humidity. The Td does not represent the thermal radiation and air movement present in the outdoor environment. These may be accounted for by replacing air temperature with black globe temperature (Buffington et al., 1981), to produce the black globe temperature humidity index, which integrates the effects of air temperature, thermal radiation, and air velocity.

An alternative to THI may be to estimate the effect of thermal balance components on deviations of an animal response from that at reference conditions (Belding, 1970). Such a study on lactating dairy cattle (Baeta et al., 1987) yielded intriguing results when compared with other studies (Kibler and Brody, 1953; Thompson et al., 1954; Cargill et al., 1962; Berman et al., 1985). These discrepancies may be due to a partial (3 d long) acclimation to experimental conditions, as acclimation of dairy cattle requires continuous exposure for at least 9 wk (Kibler et al., 1965). Thus, effective temperatures determined from whole-animal studies apply mostly to animals and conditions similar to those in which they were estimated.

Animal-related characteristics (e.g., metabolic heat production, skin and respiratory heat loss, and behavior patterns) vary among animals and among groups in a herd. Management-related variables include animal density, radiant heat, feeding system, and heat stress relief methods. The environment surrounding the animal's surface may differ significantly from that measured by standard meteorological procedures. Air velocities less than 0.2 m/s were found close to the animal's surface away from the wind, whereas velocities of 1.5 to 2 m/s were measured close to the surface facing the wind. In open sheds, animals may obstruct free flow of air to each other, so that air velocity between animals may be much lower than that measured at 1 m above the animals, particularly so in stalled animals (my unpublished observations). Estimates here indicate that such differences in air velocity, coat depth, and milk yield have marked effects on threshold temperatures, especially at higher humidity. This study indicated that high humidity lowers threshold temperatures, and also that the effect of humidity is decreased by increasing air velocity to become practically zero at 1.5 to 2 m/s. A heat stress index that does not account for such differences may be of lower value for a rational use of heat stress relief measures. An ability to estimate heat stress for animals of different characteristics or to estimate the change in thermal stress attained by alteration of specific thermal environment components may improve dairy cattle management in warm and hot climates.

Thermal balance models, based on a great deal of experimental evidence (McGovern and Bruce, 2000; Turnpenny et al., 2000), may be used to explore the effect of environmental modifications as well as responses of cattle that differ in characteristics. The outputs obtained from such a simulation model (McGovern and Bruce, 2000), modified to suit the heat-acclimatized Holstein cow, served as the data set to produce equations that may be used to predict onset of thermal stress.

Respiratory frequency increases in response to heat stress. The mid-maximal respiratory response is suggested here as an indication of need for heat stress relief. In cattle exposed to a fluctuating air temperature, the rise in respiratory response precedes that in rectal temperature (Berman and Morag, 1971; Brown-Brandl et al., 2003). In the mature cow, the mid-maximal respiratory response represents a respiratory frequency of approximately 70 to 80 breaths/min (Stevens, 1981). This value was adopted as it is an immediate response to heat, probably associated with the standing position. The percentage of cows in the standing position increases linearly as temperatures increase (Shultz, 1984). Adopting the respiratory response measure makes it possible to initiate heat stress relief before a significant increase in body temperature and the associated interference with normal body function.

The thermal stress imposed by higher ambient temperatures may, however, be relieved by forced ventilation and by using evaporation of water. Forced ventilation normally is the first to be used at the lower range of heat stressing conditions (Berman et al., 1985). The data presented here may serve to indicate the ambient conditions (temperature and humidity) at which forced ventilation may improve the thermal state of cows relative to their production level. Cows may be cooled by sequentially wetting the hair coat and evaporating the water contained in it by forced ventilation (Flamenbaum et al., 1986). Air movement over the animal's surface may make evaporation from a wet coat practically independent of surrounding air humidity. The operation of such systems may be controlled by the equations presented here. They may be used to suggest ambient conditions at which forced ventilation combined with water evaporation may be used. These also may rationalize power and water use for heat stress relief. The importance of posture was indicated, implying that recumbent animals may develop heat stress at lower ambient temperatures than standing animals. The recumbent posture, typically adopted during night periods, shifts the thresholds to cooler ambient conditions. Results of this study also highlight the importance of milk production level and of air velocity in modifying thresholds of heat stress relief.

Dairy and feedlot cattle are the primary targets for heat stress relief. A capacity for assessment of thermal stress over a wide range of conditions is crucial for cost-benefit evaluation of thermal stress relief measures. The latter is presently assessed by a temperature and humidity index that does not include air velocity, radiant heat, metabolic heat production, hair coat, skin water loss, and posture effects. Replacing a heat stress index based on air temperature and humidity by one based on equations including animal and environmental elements markedly widens its scope.

Taken as a whole, results of this study suggest that simulations may be used to produce estimates of thresholds for onset of mid-maximal respiratory response as function of air velocity, humidity, and temperature for cows varying in milk production and hair coat depth. These thresholds represent an intermediate heat stress state that requires intervention of heat stress relief measures. The equations presented may be used to estimate the days and the periods of the day in which heat stress relief measures are needed to prevent deterioration of the thermal balance of dairy cattle. They may serve for actuation of heat stress relief means by automated systems if adequate climate sensing elements are present. Alternatively, prevalence of respiratory frequencies of 70 to 80 breaths/min may be considered as indicating need for heat stress relief measures.

Implications

Dairy and feedlot cattle are the primary targets for heat stress relief. Rationalization of heat stress relief means requires estimates of thermal stress. Thermal stress is presently assessed by a temperature and humidity index that does not include air velocity, radiant heat, metabolic heat production, and posture effects. A thermal balance simulation model for cattle was modified for Holstein cows. The model heat balance accounted for effects of body weight, exposed body surface, milk production, hair coat, sweating, radiant heat, air velocity, humidity, and temperature. Outputs of simulations were used to produce estimates of thresholds for onset of 50% of maximal respiratory response as function of air velocity, humidity, and temperature for cows varying in milk production and hair coat depth.

These thresholds represent an intermediate heat stress state that requires intervention of heat stress relief measures.

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