Dynamic Responses of Cattle to Thermal Heat Loads

G. L. Hahn

USDA, ARS, U.S. Meat Animal Research Center, Clay Center, NE

ABSTRACT: The focal point of this limited review is bioenergetic research conducted in the Biological Engineering Research Unit at the U.S. Meat Animal Research Center (MARC), using recently developed instrumentation and analytical techniques. The dynamics of observed thermoregulatory responses in cattle to thermal heat load challenges are explored, with an emphasis on physiological and behavioral parameters of body temperature, respiration rate, and feed intake. Observations of body temperature, especially tympanic temperature, have shown hot environments to cause phase shifts, increased amplitude, and increased means for diurnal rhythms. Fractal analysis of body temperature records obtained at 2- to 10-min intervals has been found to be robust for objectively differentiating among responses of cattle in cool to hot environments, and it indicates a stress threshold of approximately 25°C (coincident with declining feed intake). Other analyses determined a 21°C threshold for increased respiration rate. The reported observations and analyses provide further understanding of how and why the animals respond to environmental challenges, an understanding that is necessary for refining performance models and developing energetic and thermoregulatory models. The dynamic responses are discussed in the context of establishing criteria for proactive environmental management for cattle during hot weather, using heat waves as an example.

Key Words: Thermal Energy, Stress, Thermoregulation, Animal Husbandry

©1999 American Society of Animal Science and American Dairy Science Association. All rights reserved.

Introduction

Hot weather can strongly affect animal bioenergetics, with adverse effects on the performance and well-being of livestock. Reduced feed intake, growth or milk production, efficiency, and reproduction are recognized results (Hahn, 1985). Although brief exposures may have little effect, vulnerability is a concern for unacclimated animals, feedlot cattle near market weight, and high-producing dairy cows, particularly during sustained hot weather, or acute heat loads imposed by heat waves (e.g., beef cattle: Hahn and Mader, 1997; dairy cows: Oliver et al., 1979). Global warming has the potential to exacerbate the impact of summer weather on vulnerable animals (Hahn, 1995b). Livestock managers need information about how and why their animals respond to environmental challenges to make improved decisions on strategies and tactics to reduce losses during hot weather.

For strategic decisions, response functions reflect how animals react over an extended period using their adaptive and compensatory capabilities (Hahn, 1995a; see also Hahn et al., 1974; NRC, 1981; Hahn, 1982); such functions can be used to evaluate long-term animal performance losses as a basis for strategic selection of appropriate environmental modification methods. Based on these evaluations, ambient temperature guidelines relevant to performance aspects have been developed for specific categories of animals (Figure 1). In contrast, tactical decisions deal with day-to-day environmental management (e.g., the use of fans, sprinklers, or altered timing of handling) and are influenced more by the dynamics of environmental challenges and animal responses. In both situations, threshold limits help define the ability of animals to cope with the environment.

Extensive reviews are available on physiological and other rhythms occurring in animals (e.g., Aschoff, 1981; Rapp, 1987; Feldman, 1989; Haken and Koeppchen, 1991). Hahn (1989) reviewed body temperature responses of farm animals to environmental influences. The current report addresses the dynamic aspects of thermoregulatory and related responses of cattle to thermal heat load challenges, primarily based on research conducted at the U.S. Meat Animal
CATTLE RESPONSES TO HEAT

Figure 1. Critical ambient temperatures and temperature zones for optimal performance and nominal performance losses in cattle. Variations in health and general physical conditions, acclimation to seasonal conditions, adequacy of feed and water, freedom from parasites and other pests, and thermal factors other than temperature can alter the response of individual animals. Wetted skin and pelage or air velocities above 0.3 m/s shift all temperatures upward; elevated humidity or exposure to solar radiation shift all temperatures downward (Hahn, 1985).

Research Center (MARC). The dynamic responses are discussed in the context of establishing criteria for proactive environmental management of cattle during hot weather.

Background

Animals are dynamic and adaptable and are able to maintain life and productive performance in a relatively broad range of environments. Coping with environmental stressors involves behavioral, physiological, and immunological functions, which are mobilized at different stressor levels to minimize adverse consequences. Performance (production, reproduction, efficiency), health, and (or) well-being can be compromised when adverse environmental stressors exceed threshold limits for coping and compensatory mechanisms. Genetic diversity within a population can also influence the level of response and the degree of adaptability, so that what is stressful for some may not be stressful for others. Life stage, conditioning, and nutritional and health status also influence the level of vulnerability to environmental stressors.

Figure 2 provides an updated schematic representation of these points, recognizing that exceeding threshold limits is a crucial element for assessing the influence of environment (magnitude [intensity and duration] and recovery aspects) on animal performance, health, and well-being.

In 1982, research was initiated at MARC to evaluate the dynamics of bioenergetic responses of livestock to environmental challenges, using the elements of Figure 2 as a “roadmap.” The MARC Environmental Laboratory provided controlled environmental conditions, either constant or repeated cyclic temperatures with a constant dew point. Initial studies concentrated on body temperature of cattle during 7- to 14-d treatment periods, using portable data loggers to obtain continuous records (Hahn et al., 1990). These observations led to selection of tympanic temperature as the primary measure. Tympanic temperature had previously been shown to be a relatively sensitive measure for assessing thermoregulatory responses, obtainable by noninvasive sensors secured in the ear canal (Guidry and McDowell, 1965; Wiersma and Stott, 1983). It also serves as an index of hypothalamic temperature (Benzingter, 1959, 1964; Baker et al., 1972; Brinnel and Cabanac, 1989), which plays a vital role in regulating endocrine and immunologic functions and is generally considered to have a central role in

regulating feed intake (Cossins and Bowler, 1987; Luiten et al., 1987). Subsequent studies included concurrent measures of tympanic temperature and feed intake (by means of weighing load cell feeders [Nienaber et al., 1990]), supplemented in limited cases by measures of respiration rate and immune response.

Observations on the Dynamics of Body Temperature

Analysis of tympanic temperature records from growing, ad libitum-fed Bos taurus crossbred cattle during the initial studies were summarized by Hahn (1989):

1. The diurnal rhythm is usually monophasic with the maximum in late evening and the minimum in late morning for animals in cool-to-moderate thermal conditions (constant or cyclic).
2. There are thresholds for thermal conditions, variable among individual animals, above which body temperature becomes driven by ambient conditions and rhythms are disrupted (phase shifts, increased amplitudes, increased means).
3. Physiological acclimation to excessive heat loads is reflected in the diurnal tympanic temperature rhythm; acclimation rates of body temperature are on the order of .1 to .4°C per day.

Figure 3 illustrates some of these points, as well as additional items discussed by Hahn et al. (1990). First, oscillations in tympanic temperature for cattle in thermoneutral environments, typically on the order of .1 to .3°C, are superimposed on the underlying diurnal rhythm, which typically has an amplitude of about .5 to 1.2°C, dependent on the diurnal range of ambient conditions. Some of the decreases in tympanic temperature during the short-term oscillations were observed to be strongly associated with initiation of feeding-related activities in cool thermal conditions, with a weaker association for heat-stressed animals. Second, there are two stages of coping with the acute phase of hot conditions: first, by increased heat dissipation (primarily through evaporative heat loss) and, second, by reduced feed intake to lower metabolic heat production. Typically, 3 to 4 d are required for the animal to attain a level of heat balance that permits acclimation to begin (in terms of decreasing body temperature). As tympanic temperature declines, feed intake increases (but not necessarily to the same level as in cooler conditions) until a new set-point temperature is established under the chronic phase of exposure (usually 8 to 10 d after initial exposure). Entrainment of body temperature by the diurnal cycle of ambient temperatures is apparent, with a 3- to 4-h time lag.

Appropriate analyses of dynamic observations to objectively reflect the recorded information is always a

![Figure 2. A schematic representation of animal responses to potential environmental stressors that can influence performance, health, and well-being (adapted from Hahn and Morrow-Tesch, 1993).](image-url)
Figure 3. Tympanic temperatures recorded at 320-s intervals from a steer during a sequential exposure to cool (10 ± 7°C) and hot (30 ± 7°C) sinusoidally diurnal controlled environments (Hahn et al., 1990). Ticks above the time scale show noon of each day. Daily feed intakes are included. Maximum and minimum air temperatures were at 1330 and 0130, respectively; lights were on at 0500 and off at 1900 daily.

For analyzing biological data sets similar to those of Figure 3, Parkhurst and Hahn (1987, 1989) considered data-dependent system (DDS) time series analysis, phase diagrams, spectral analysis, and Green's function analysis. These techniques permit evaluation of various aspects of dynamic responses. For example, DDS analyses of tympanic temperature records indicated a strong influence of the preceding 2-h (for 10 ± 7°C) to 4-h (for 28 ± 7°C) ambient conditions on current tympanic temperature (Parkhurst and Hahn, 1987). Further examination of the dynamics of those data sets using Green's function showed an exponential decay lasting 6 to 12 h for tympanic temperature perturbations in the 10 ± 7°C environment, but a damped sinusoidal wave response lasting 3 d or more for animals in the 28 ± 7°C conditions (Parkhurst and Hahn, 1987). Although helpful in detecting treatment differences and illustrating the dynamics of the thermoregulatory control system, questions remained about the robustness of the DDS procedure for modeling data with deterministic periodicity and trends (Parkhurst and Hahn, 1989). Observing many tympanic temperature data sets similar to those of Figure 3 also suggested that...
differences in responses to stressor severity and duration might be useful in classifying those responses. Subsequent testing for chaos (Parkhurst and Hahn, 1989) led to fractal analysis as a sound, robust, and rational method for objectively differentiating among thermoregulatory responses of animals in cool to hot conditions (Hahn et al., 1992; Korthals et al., 1997). The fractal dimension provides an objective measure of the underlying dynamics ("roughness") associated with thermoregulatory control, information not available from traditional statistics, such as a fitted function or mean value with a measure of variance. Korthals et al. (1997) discuss the methodology in detail; Hahn et al. (1992) and Korthals et al. (1997) also provide data acquisition criteria and practical aspects of fractal applications to thermoregulatory data sets. Kaandorp (1994) reported the usefulness of the fractal approach to mathematical modeling for many biological situations, and West and Deering (1995) suggest a fractal approach "may provide a new basis for understanding physiology."

Fractal dimensions (D-values) were computed for several tympanic temperature data sets. The D-values for 12- to 14-d exposures of cattle to controlled temperatures, averaged for three animals in 1988 (recording interval of 320 s), were 1.77 for animals at 10 ± 7°C, 1.70 at 26 ± 7, 1.53 at 28 ± 7, 1.47 at 30 ± 7, and 1.28 at 34 ± 7°C (Hahn et al., 1992). Fractal dimensions for different animals were similar under the same controlled temperature. Mean D-values for another data set (six animals during a 7-d exposure to four environmental conditions) shown in Table 1 and other data sets have repeatedly demonstrated differentiation between D-values computed for cattle in nonstressing and heat-stressing environments. The higher fractal dimension values at less-stressing environments reflect the lower level of challenge to the animal's thermoregulatory control system and have been suggested as the basis for a thermal stress classification scheme (Table 2). Objective classification of stressors using the fractal dimension also provides the basis for examining stress thresholds. Using the 1988 data set discussed above as an example, a plot of the D-values as a function of the mean environmental temperature (Figure 4) shows a threshold for reduced fractal dimension at about 25°C for growing cattle allowed to consume their diets on an ad libitum basis. This indicates that, for our experimental animals and in thermal environments without large radiant heat loads, a stress threshold for reduced performance is approximately 25°C.

**Table 1.** Fractal dimensions (D) of the tympanic temperatures of individual steers during late stages of exposure to nonstressing and stressing environments (1990 data recorded at 15-s intervals and sampled at 10-min intervals; D-values are averages of 7 d ± SD) (Hahn et al., 1992)

<table>
<thead>
<tr>
<th>Environmental temperature, °C</th>
<th>Steer 1</th>
<th>Steer 2</th>
<th>Steer 3</th>
<th>Steer 4</th>
<th>Steer 5</th>
<th>Steer 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 ± 7</td>
<td>1.733</td>
<td>1.733</td>
<td>1.755</td>
<td>1.815</td>
<td>1.813</td>
<td>1.781</td>
</tr>
<tr>
<td></td>
<td>(± .132)</td>
<td>(± .109)</td>
<td>(± .093)</td>
<td>(± .151)</td>
<td>(± .086)</td>
<td>(± .050)</td>
</tr>
<tr>
<td>30 ± 7</td>
<td>1.344</td>
<td>1.628</td>
<td>—</td>
<td>—</td>
<td>1.647</td>
<td>1.587</td>
</tr>
<tr>
<td></td>
<td>(± .090)</td>
<td>(± .133)</td>
<td></td>
<td></td>
<td>(± .110)</td>
<td>(± .091)</td>
</tr>
<tr>
<td>32 ± 7</td>
<td>1.196</td>
<td>1.557</td>
<td>1.377</td>
<td>1.358</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>(± .054)</td>
<td>(± .134)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>34 ± 7</td>
<td>—</td>
<td>—</td>
<td>1.235</td>
<td>1.368</td>
<td>1.395</td>
<td>1.418</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(± .070)</td>
<td>(± .071)</td>
<td>(± .079)</td>
<td>(± .085)</td>
</tr>
</tbody>
</table>

**Observations on the Dynamics of Respiration Rate**

Respiration rate (RR) has long served as a gross indicator of heat load in animals during hot weather, increasing when animals need to maintain...
homeothermy by dissipating excess heat as more benign avenues became inadequate. Respiration rate responses of ad libitum-fed crossbred Bos taurus feeder cattle to ambient conditions were measured in the MARC Environmental Laboratory, as reported by Hahn et al. (1997). The cyclic chamber air temperatures (dry bulb, t_{dB}) nominally cycled sinusoidally from 11 to 25°C during thermoneutral periods and from 25 to 39°C during elevated temperature conditions. From the combined observations, a threshold for markedly increasing RR was identified at an air temperature of 21.3°C, with RR increasing by 4.3 breaths/min per degree C above a baseline RR of 60 breaths/min at the threshold temperature. Respiration rate lagged behind changes in t_{dB} during both thermoneutral and hot cyclic conditions, with the highest correlations obtained for a lag of 2 h between RR and t_{dB}. Figure 5 illustrates the lag for chronic exposure to the cyclic hot environment.

Observations of Thermoregulation and Feeding Behavior

As mentioned earlier, initial observations showed an apparent high degree of association between tympanic temperature and feeding activities for cattle in thermoneutral environments, but hot environments appeared to disrupt the association. The preceding section on body temperature dynamics also reported a stress threshold of 25°C, which is coincident with the threshold for feed intake decline of the same animals (Hahn et al., 1992). The association between thermoregulation and voluntary feed intake is the basis for the concept of thermostatic regulation of feed intake (Brobeck, 1955), whereby control of body temperature is ultimately linked to the hypothalamic set point when energy density of the diet is not limiting (Baile and Forbes, 1974). Eigenberg et al. (1994, 1998) also have reported further evidence that meal events are limited by body temperature spikes. An experiment was conducted with cattle to explore the fine detail of the linkages between tympanic temperature and feeding activities, using the same recording system for both tympanic temperature and weighing load cell feeder equipment in order to resolve the timing of body temperature changes with respect to feeding activities. Figure 6 shows typical results for an animal during the chronic stages of sequential exposure to cool and hot environments. Initiation of eating events in both environments was, in almost all cases, linked with peaking or descending portions of the tympanic temperature oscillations. Further, as noted by the asterisks, several peaking or decreasing tympanic temperatures were associated with “bumping” of the feeder (shown as a downward tick on the feeder baseline), indicating that the animal was actively nosing the feeder even though no eating event occurred. However, several oscillations in tympanic temperature also occurred with no associated feeding activity (eating or bumping). More frequent meals of smaller size were recorded in the hot environment,

Figure 4. Plot of fractal dimension (D, computed from tympanic temperatures of steers in cool and hot environments) as a function of environmental temperature. The intersection of lines for animals in thermoneutral and hot temperatures occurs near 25°C, indicating the threshold for onset of stress to be approximately that temperature (Hahn et al., 1992).

Figure 5. Average hourly respiration rates (RR) of eight Bos taurus steers during chronic exposures to 24-h cyclic hot environments (Hahn et al., 1997).
consistent with earlier observations. Phase shifts and increases in mean and amplitude of the underlying diurnal rhythm of tympanic temperatures in hot conditions are also consistent with earlier and concurrent records.

**Observations of the Dynamics of Immune Response**

Results of limited experiments with crossbred cattle that were sequentially exposed for 28 d to cyclic thermoneutral (10 ± 7°C), 21 d to cyclic hot (32 ± 7°C), and returned for 14 d to cyclic thermoneutral conditions showed that white blood cell numbers were markedly reduced by heat stress (Morrow-Tesch et al., 1996). The levels remained low at 12 d after return to thermoneutral conditions. Circulating levels of γδT-lymphocytes were altered by heat stress, with the temporal nature possibly influenced by physiological adaptations during different seasons of the year. However, effects of the observed decrease and subsequent expansion of γδT-lymphocytes on the immune function of heat-stressed cattle remain unresolved. Changes in circulating levels as well as numbers of γδT-lymphocytes at skin surfaces nevertheless suggest the possibility of differences in the animal’s resistance to environmental pathogens following heat stress.

Dynamic Responses as Criteria for Environmental Management

Dynamic responses have already been shown to provide a basis for evaluating stress thresholds and a potentially useful stress-classification scheme, for establishing linkages between thermoregulation and feeding behavior and for an improved understanding of the thermoregulatory control system in animals. Responses of heat-challenged cattle also emphasize the major importance of nighttime recovery (e.g., Scott et al., 1983; Hahn and Mader, 1997). The dynamic response results serve as the basis for guidelines to minimize risk to animals and to monitor animals during exposure to heat load challenges. Key questions to address are 1) how much harm is associated with a given environmental situation and 2) is there a need for intervention to reduce the risk to the animals or to the enterprise.

Hahn and Mader (1997) used the occurrence of heat waves to demonstrate the utility of dynamic responses as criteria for environmental management.
In 1995 there was an extreme heat wave event in the central United States that caused more than 400 human deaths in the Chicago, Illinois, area and resulted in severe livestock performance and death losses, with an estimated $28 million economic loss to farmers. Thermal conditions during the heat wave buildup, in terms of the temperature-humidity index (THI), are shown in Figure 7 for Rockport, Missouri, representing an area where more than 4,000 feedlot cattle died (Hahn and Mader, 1997). When the rate at which the thermal conditions increased during the heat wave buildup is compared with the rate of response of cattle during a thermal challenge (Figure 3), it is readily apparent that the 3- to 4-d lag time required for cattle to adequately balance heat dissipation capabilities with reduced metabolic heat production (through lower feed intake) can be insufficient to counter the heat wave. This can result in heat loads that exceed the threshold and lead to impaired performance and possible death (Figure 2), especially when there is little or no opportunity for nighttime recovery, such as occurred in the Rockport area.

In another instance, a double heat wave in central Nebraska (Figure 8) caused about 100 feedlot cattle deaths even though the thermal conditions were not as extreme and the animals were preconditioned to hot weather. When challenged by heat wave Episodes 1 and 2, the ad libitum-fed animals were able to cope through feedback mechanisms to adapt by reducing feed intake to maintain life, although Episode 2 put some animals at risk for survival. Episode 3, which was milder than 2, resulted in death losses, hypothesized to be a consequence of the animals’ feed intake pattern: during cool days, such as between Episode 2 and 3, feed consumption typically increases over normal levels because of the marked reduction of intake during a heat challenge. Thus, when challenged by Episode 3, the animals had a large metabolic heat load in addition to the environmental heat load, which likely surpassed their ability to dissipate heat and resulted in death losses as high as 5 to 10% in some pens.

In the heat wave examples, dynamic responses of cattle to the onset of heat, when combined with analyses of heat waves, can be used to develop specific recommendations for limiting the impact by using proactive management. First and foremost is to be alert to the impending danger to vulnerable animals when the local forecast suggests a developing heat wave. During the 1995 heat wave example, the 3 to 4 d required for cattle to balance feed intake and heat dissipation to limit body temperature rise (as shown in Figure 3) coincided with a sustained “emergency” level of the THI-based livestock weather safety index (LWSI) on the third through fifth days of the heat wave at all locations of highest death loss, accompanied by little or no opportunity for nighttime recovery. Stress-limiting measures should be considered for locations where conditions reach THI levels of 75 or above, particularly when air temperatures may remain above 23°C at night. Feedlot managers should plan for tactical actions (e.g., the use of sprinklers; altering the timing of handling and transport) to be taken as the LWSI reaches alert, danger and emergency levels, as further detailed by Hahn and Mader (1997).

Conclusions

Cattle are remarkable in their ability to mobilize coping mechanisms when challenged by environmental stressors. Within limits, they can adjust physiologically, behaviorally, and immunologically to minimize adverse consequences. Thermoregulation is a prime illustration of a dynamic process in a homeothermic animal as observed from short-term changes in body temperature, which reflect temporary imbalances in heat production and heat dissipation. Those imbalances are a result of exogenous or endogenous factors, such as the thermal environment and metabolic processes linked with feed intake. Recent developments in technology and in evaluation techniques have provided a means of in-depth investigation of cattle dynamic thermoregulatory responses to environmental challenges.

A series of thermoregulatory dynamics studies have been conducted at MARC since 1982. For cattle, dynamic responses have demonstrated both the stability and sensitivity of the thermoregulatory control system to heat challenges. Results provide an improved understanding of thermoregulation and the basis for a potentially useful stress-classification.

\[ \text{THI} = \text{t}_{\text{db}} + 0.80 \text{t}_{\text{db}} + 4.2 + 46.4 \]

where \( \text{t}_{\text{db}} \) = daily average dry bulb temperature, °C, \( \text{t}_{\text{dp}} \) = daily average dewpoint temperature, °C, and RH = relative humidity in decimal form. THI values also serve as the basis for the livestock weather safety index (LCI, 1970): normal, ≤ 74; alert, 75–78; danger, 79–83; emergency, ≥ 84. For additional discussion of the THI, and its application for assessing the impact of thermal environments on livestock, see Hahn, 1994 and 1995a,b.
Figure 7. Hourly temperature-humidity index (THI) values and wind speeds at a midcentral U.S. location in the highest-risk area of a heat wave that caused large-scale livestock deaths and performance losses (Hahn and Mader, 1997). The “Emergency” and “Recovery” thresholds are based on LCI (1970) and Hahn and Mader (1997), respectively.

Figure 8. Heat wave events at Central City, Nebraska, July and August, 1997. Episode 1 was not life-threatening for feedlot cattle and served as preconditioning for subsequent hot weather. In Episode 2, there were 4 d with THI exceeding the high-risk “Emergency” threshold, but there was ample opportunity for nighttime recovery. Episode 3 would not normally be considered life-threatening, but vulnerable animals died on August 3rd.

scheme based on fractal analysis. Results also established stress thresholds for activation of coping mechanisms (e.g., increased respiration rate and decreased feed intake) and linkages between thermoregulation and feeding behavior. Nighttime recovery during heat challenges was shown to be an important element of coping with thermal heat loads.

The results of these studies are particularly useful in the development of proactive tactical management guidelines for cattle producers. In extremely harsh situations, the penalty of animal deaths is obvious. Less obvious are penalties such as reduced feed intake and failure of immune function, which occur at less severe deviations in the environment and can result in chronic reductions in level of performance without showing pathological evidence. These can be financially more costly than animal deaths (Balling, 1982) and are essential elements of rational environmental management (Hahn, 1976, 1995a). Preparation needs to be made and operational strategies developed in anticipation of adverse situations so that appropriate action can be taken quickly and effectively to reduce negative impacts. The results of heat wave analyses provide an example for advising producers to be alert to impending danger for vulnerable animals and serve as a basis for tactical decisions to alter operations and (or) activate environmental modification equipment.

Implications

Evaluation of the dynamics of bioenergetic processes for cattle in non-stressing and stressing thermal environments as part of a long-term research program at the USMARC has strengthened our knowledge of how and why animals respond as they do to environmental challenges. This knowledge provides a basis for practical environmental management, as well as an understanding necessary to develop and refine performance, energetic and thermoregulatory models.

Literature Cited

Balling, R. C., Jr. 1982. Weight gain and mortality in feedlot cattle as influenced by weather conditions: refinement and verification of statistical models. Rep. 82-1, Center for Agricultural Meteorology and Climatology, Univ. of Nebraska, Lincoln.


LCI. 1970. Patterns of Transit Losses. Livestock Conservation, Inc., Omaha, NE.


