Defining upper critical temperatures for an effective climate control to reduce heat stress

Salvador Calvet Sanz[1]

1. *Escuela Técnica Superior de Ingeniería Agronómica y del Medio Natural, Universitat Politècnica de València, Camino de Vera, s/n, 46022 Valencia, Valencia. España.*

Abstract: The definition of homeotherm animal responses to temperature has traditionally based on metabolic and thermal physiology studies. The thermoneutral zone is defined as the range of ambient temperature within which metabolic rate is at a minimum, and within which temperature regulation is achieved by non-evaporative physical processes alone. As temperature raises, the upper critical temperature is reached, which is the ambient temperature above which thermoregulatory evaporative heat loss processes of a resting thermoregulating animal are recruited. These temperatures depend on a variety of factors including animal species and breed, age, adaptation or animal status, among others. These are also influenced by environmental conditions such as relative humidity and wind velocity. Determining upper critical temperatures seems essential to establish effective climate control strategies. However, research evidences during the last decades show that animal responses to heat stress are varied, as briefly reviewed in this article. These responses include both short and long term responses depending on the magnitude and duration of the stress. Furthermore, as temperature raises a wide and complex range of behavioural, physiological and productive responses are triggered. Thus, the effects of heat stress may relate to animal welfare, health, productivity and sustainability concerns, and seem difficult to assess with critical temperatures only. Currently, major interest is devoted to develop indicators for heat stress, particularly early indicators. These indicators may vary among animal species, but are the basis for a better environmental control. In this sense, the advances of precision livestock farming are a sound basis for heat stress control. Therefore, apart from thermal indicators, animal-based information may supply very relevant information to decide about heat stress abatement strategies. This technology is more and more available for farmers, and very relevant developments are currently developed and will also be developed in the future. In summary, an information-based decision system related to animal indicators may be effective for a practical climate control in livestock farms.

Keywords: Heat stress, Precision livestock farming, Critical temperature, Welfare, Indicators, Climate control.

1. Introduction

Ambient conditions (air temperature, humidity, wind speed and concentration of pollutants) affect the animal performance, behaviour and welfare. Maintaining these conditions within target ranges is essential for the animals to express their genetic potential, and therefore it is a main objective of livestock housing systems (Clark, 1981; Wathes and Charles, 1994). On the contrary, the exposure to high temperatures causes heat stress to the animals, which has detrimental consequences on animal welfare and productivity.

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***Corresponding Author**: **Salvador Calvet Sanz**, Escuela Técnica Superior de Ingeniería Agronómica y del Medio Natural, Universitat Politècnica de València, Camino de Vera, s/n, 46022 Valencia, España Email: salcalsa@upvnet.upv.es.

Although heat stress concerns a wide range of regions, the quantification of its impacts is scarce. Heat stress has very relevant consequences, but the quantification of its impacts is not well known. St Pierre *et al.* (2003) estimated that production losses in the livestock sector in the United States could be around $2 billion per year. Therefore, the effects of heat stress on animal production constitute a relevant sustainability concern for animal production. Furthermore, the expectations of growing livestock production in developing countries (many of them under warm conditions) and the expected effects of climate change in the forthcoming years have risen attention into the effects of heat stress (Gerber *et al.*, 2013).

The study of the effects of heat stress on animals has been subject of vast research in recent decades. As a consequence, we have now better knowledge of the processes by which animals respond to this stress. We also know that heat stress and animal responses are largely influenced by factors other than temperature, for example relative humidity, wind speed or solar radiation. Also, it is known that the stressing conditions to which animals may be exposed vary both in temporal and spatial terms, and is affected by housing systems, which may create micro-environments enhancing or mitigating the effects of heat stress. Finally, adaptation of animals to heat stress plays an essential role.

Apart from the varying nature of climate, the previsions of climate change suggest a likely increase the effects of heat stress in many livestock producing areas (Hristov *et al.*, 2017). In Southern Europe, where a relevant livestock production is located, the impacts of climate change on rising temperatures are already evident (Pérez et al., 2015). Therefore, the effects of climate change in the near future will constitute a challenge for livestock production in these areas (Battisti and Naylor, 2009; Davis *et al.*, 2015).

In terms of animal performance, it is convenient to maintain animals within the thermoneutral zone (TNZ), this is, between the upper critical temperature (UCT) and lower critical temperature (LCT). However, the ranges defining the TNZ vary according to diverse factors including as animal species, breed, age and health or physiological status. The objective of this review paper is to analyse the definition of TNZ and UCT and discuss their practical use on climate control systems, with the objective of establishing effective ways to reduce the effects of heat stress on the animals, based on precision climate control.

2. The Thermoneutral zone

Farm animals are homeostatic, which means that they develop internal physiological processes to maintain a steady state. In terms of energy, farm animals are homeotherm animals which regulate body temperature by controlling the balance between the heat they produce in their metabolic reactions and the loss of heat to the environment. Heat loss by the animals is in form of sensible heat (radiation, convection or conduction) and latent heat (water evaporation). As temperature increases, the ability of animals to dissipate sensible heat reduces and the loss of latent heat becomes more important. For this reason, heat stress effects are extremely influenced by other environmental variables such as relative humidity, wind speed and solar radiation.

TNZ is defined as the range of ambient temperature within which metabolic rate is at a minimum, and within which temperature regulation is achieved by non-evaporative physical processes alone (Panagakis *et al.*, 2007). As temperature raises the UCT is reached, which is the ambient temperature above which thermoregulatory evaporative heat loss processes of a resting thermoregulating animal are recruited (Figure 1). These temperatures depend on a variety of factors including animal species and breed, age, adaptation or animal status, among others, and are influenced by other environmental conditions such as relative humidity and wind velocity.

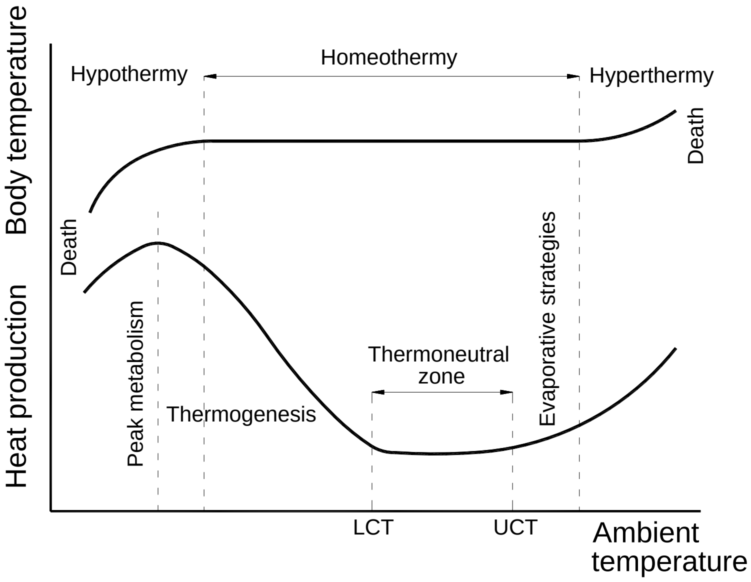

Figure 1: Effect of ambient temperature on animal metabolism and body temperature. LCT: lower critical temperature; UCT: upper critical temperature. Adapted from Esmay (1978) and Renaudeau *et al.*, (2015).

The definitions of TNZ and UCT are established according to animal physiology criteria. These definitions have remained mostly unchanged since they were defined at the middle of 20th century (Newburgh *et al.*, 1948, Hutchinson, 1954, Bligh and Johnson, 1973). However, apart from their relevant conceptual value, TNZ ranges and UCT have a practical use as recommendations for climate control. Therefore, determining TNZ ranges and UCT are of highest interest.

The definition of UCT has been controversial in literature. As UCT is the upper limit of the thermoneutral zone, it is not possible to provide a unique definition depending on its inhibitory effect on thermogenic processes associated with different activities such as digestion, growth, lactation, etc. (Webster, 1991). Therefore, the UCT can be defined as the ambient temperature when the: a) metabolic rate increases; b) evaporative heat losses increase; or c) tissue thermal insulation is minimal (Silanikove, 2000a, Blatteis *et al.*, 2001). From these definitions, the one based on the increase of evaporative heat losses is preferred because the others are difficult to measure (Silanikove, 2000a), and because it is also useful to describe the upper temperature survival limit (Blatteis *et al.*, 2001). Therefore, the UCT can be inferred from thermoregulatory functions like skin and respiratory water loss or body temperature (Berman *et al.*, 1985).

According to its definition, the use of UCT as control temperatures in animal houses under practical conditions may be questioned. As reviewed in the following section, the responses of animals to increasing exposure to heat are diverse and comprise welfare, behaviour, productive and health aspects. These responses appear at different moments as temperature rises. Therefore, this review will analyse whether more practical thermal limits than UCT can be established.

3. Animal Responses to heat stress

The responses of different animal species to heat stress have been widely reported in the literature (e.g. see Renaudeau *et al.*, 2012). In general, the metabolic adjustments related to thermoregulation under heat stress involve detrimental consequences on productivity and health. Reducing feed intake to reduce heat production is a general adaptation mechanism, together with the increased proportion of energy needed to dissipate heat. Consequently, lower nutrient intake and use efficiency explain the reduction in productivity. Direct temperature effects on animal physiology also affect the immune and reproduction systems. In this section, these responses are briefly summarized. This is a non-exhaustive revision aiming to determine the critical temperatures in terms of designing and operating climate control systems.

For broiler chickens, genetic selection has focused on increased growth rate, which involves a faster development of muscle compared to thermoregulatory organs (Havenstein *et al.,* 2003). Respiratory alkalosis occurs in broilers exposed to chronic thermal stress (Teeter et al., 1985). These authors reported that blood alkalosis results in lowered feed consumption and consequently lower growth rate. As heat stress reduces growth rate more than feed consumption, the consequence is a lower feed efficiency (Al Fataftah *et al.,* 2007). Dietary management (Teeter et al., 1985) and acclimatization to high temperatures (Arjona *et al.,* 1988; Al Fataftah *et al.,* 2007) have been described as techniques alleviating the effects of heat stress at the end of the growing period. In fact, it has been described that the mechanism to heat acclimation is a reduction in heat production related to reduced feed consumption, rather to increased heat losses (Al Fataftah *et al.,* 2007).

For laying hens, Mashaly *et al.* (2004) demonstrated that the combined effects of high temperature and relative humidity increased mortality, most probably as a consequence of the inhibition of immune responses. As reviewed by these authors, it has been demonstrated that heat stress reduces feed intake, which is associated to decreases of body weight, egg weight and shell quality. In addition, heat stress impairs the ovarian function, and as a consequence the laying rate decreases (Rozenboim *et al.,* 2007). However, the response to heat stress in laying hens depends on the intensity and the duration (Smith, 1973), and research studies differ on the level of heat stress originating these responses.

The effect of heat stress on growing pigs was reviewed by Renaudeau *et al.* (2011). These authors reported a very high variability of productive responses of growing pigs to heat stress, probably related to a variety of factors including genotype, sex, feeding or management. In their meta-analysis, they calculated the UCT as a function of body weight, separately for two criteria: average daily gain and average daily feed intake. They reported critical temperatures for average daily gain dropping from about 29ºC at 10 kg body weight to 23ºC at 90 kg. They also reported that for finishing pigs the UCT considering feed intake was higher than when considering growth rate. This means that a decrease in feed intake due to incipient heat stress may be not involving a reduce in daily gain. Huynh et al. (2005) analysed the combined effect of temperature and relative humidity in growing pigs of approximately 60 kg. These authors also reported different UCT for physiological and measurement parameters: at increasing temperatures, changes in respiratory rate are first noticed (about 22ºC), then increased heat production and reduced feed intake (about 23-25ºC) and finally rectal temperature increases (25-27ºC).

For sows, main disorders related to heat stress are seasonal infertility and gestational heat stress. Although semen quality may be affected in heat-stressed boars (Suriyasomboon *et al.,* 2004), most effects are attributed to the sow. Seasonal infertility has been demonstrated to be the combined consequence of photoperiod (mainly) and heat stress (Auvigne *et al.,* 2010). Particularly, it has been described that changes in photoperiod and thermal stress during the mating period and gestation and mobilization of body reserves during lactation affect the reproductive performance of sows (Renaudeau *et al.,* 2012). Heat stress during the first half of gestation has also been demonstrated to affect the feed intake and subcutaneous fat thickness of the offspring, probably because of altered hormone profile of foetus during subsequent growth and development (Boddicker *et al.,* 2014).

Regarding ruminants, high production dairy cows are considered the most sensitive to heat stress because of the high metabolic rate required for milk production. Increasing milk yield has been reported to reduce methane per production unit because the energy of maintenance is diluted under more productivity. However, for the same reason heat production is higher for the same body weight, which involves problems for heat dissipation. Consequences of heat stress on dairy cows are reviewed, among others, by De Rensis *et al.* (2003) and Kadzere (2002). Wolfenson *et al.*, 2000 reviewed how the reproductive function is affected by heat stress both in the short and the long term: oocyte quality and embryo development are impaired as a consequence of hormonal changes. Also, high temperatures compromise the endometrial function and alters the secretion activity. As a consequence, the risk for embryo mortality increases. For milk production (productivity and composition), Carabaño *et al.* (2015) reported a summary of effects of increasing temperatures. In summary, they found that milk fat and protein content started to decrease at lower temperatures than milk production. Similar to other animal species, adaptation may play a relevant role to alleviate the effects of heat stress (Bernabucci *et al.*, 2010; Carabaño *et al.*, 2015).

Although less information is available considering the lower economic relevance of sheep and goats, these animals are considered less susceptible to heat stress. However, at high temperatures they also suffer from heat stress. The mechanisms by which heat stress affects milk production and reproductive performance in small ruminants are essentially similar to those for cattle. The higher adaptation potential of small ruminants to heat stress, compared to cattle, relies on their relatively lower body mass and metabolic requirements, which minimise their maintenance and water requirements (Silanikove, 2000b; Marai *et al.*, 2007). Therefore, small ruminants are considered adapted to areas in which the occurrence of high temperatures or low quality foods is frequent.

In summary, we can conclude that effects of heat stress are complex in terms of causes and consequences. Acute or chronical exposure to heat stress normally have different consequences on animals. Similarly, the difference between exposing to either continuous or cyclic heat stress periods is also relevant. As proposed by St Pierre *et al.* (2003), not only the occurrence of the thermal stress, but also its intensity (expressed as THI load) and duration, as well as the possibility for recovery during the night, are relevant factors. Regarding animal responses, literature shows that productive, behavioural, welfare and physiological effects normally occur at different temperatures and depend on other factors such as previous adaptation. Considering this complexity, establishing a UCT as a target environmental control is challenging. Therefore, the options for alleviating heat stress and using precision climate control in livestock houses will be explored in the next sections.

4. Measures to reduce heat stress

Mitigation measures to reduce heat stress have been widely reported in the literature and are commonly adapted in practice (see for example Renaudeau *et al.*, 2012). The general objective of these measures is to enable ambient conditions and animal requirements to be coincident. This can be made by adapting animals to heat stress and by modifying the environmental conditions to meet the animal requirements.

Adapting animals to heat stress is an effective way to cope with heat stress in a preventive way. Adaptation includes, among others, the natural thermal plasticity, acclimation, nutrition practices and genetic selection. Some animals show a natural thermal plasticity and anticipate to seasonal changes by modifying their phenotype, for example, hair coat thickness or body fat (Collier and Gebremedhin, 2015). Some studies also reveal the importance of animal acclimation, for example, as a consequence of exposing broiler chickens exposed to thermal stress during the first days of life (Arjona *et al.*, 1988; Al Fataftah *et al.*, 2007). However, heat stress acclimation is difficult to manage in practice because it is a complex process in which homeostatic responses involving the endocrine status play an essential role (Bernabucci *et al.*, 2010).

Among the management practices, the role of nutrition has been widely studied in literature. In broilers, manipulating protein level and amino acid composition, maintaining the electrolytic and water balance and supplementing micronutrients are considered effective practices (Lin *et al.*, 2006). As reviewed by Renaudeau *et al.* (2012) similar strategies apply for the different livestock species, including feed restriction, fat supplementation or using additives.

The traditional selection of livestock animals for productivity has resulted in animals producing more heat and therefore more sensitive to heat stress. However, the genetic selection of animals tolerant to heat stress is a long-term strategy that may contribute to reduce production losses due to high temperatures. The main complications for selection are related with the complex responses of animals to heat stress. In sows, it has been demonstrated that different genetic lines differ in their tolerance to thermal stress, in terms of reproductive performance (Bloemhof *et al.*, 2008). In dairy cattle there is a reasonable amount of genetic variability in the individual responses to heat stress, but there are also antagonistic relationships between productivity and resistance to heat stress (Carabaño *et al.*, 2017). In poultry, however, genetic selection for production has played a major role on thermal sensitivity and therefore selection for tolerance to heat stress has relevant productivity concerns. However, it is likely that major genes may contribute to more resistant animals (Lin *et al.*, 2006).

Finally, the engineering solutions modifying the indoor environment of animal houses are widely used in practice. Among these, the evaporative cooling (either cooling pads or fogging/spraying systems) and increasing the air speed are common practices. For broilers and laying hens, standard solutions include the use of mechanical ventilation in a tunnel-designed building to achieve an air velocity up to 2 m/s, together with evaporative cooling pads at air inlets (Bustamante et al., 2015). On the contrary, water spraying systems have proved to be effective for dairy cows together with high volume – low speed fans (Chen et al., 2015, Collier et al., 2006). Nonetheless, cooling systems may have a limited efficiency if the ambient relative humidity is high.

Literature therefore shows that there is a wide variety of strategies to alleviate heat stress, but their practical use may be challenging in practice. As mentioned in the previous section, the definition of a UTC is complex and therefore it is difficult to establish optimal management practices as temperature rises. In some cases, for example under warm and humid conditions, it is not possible to provide the animals with an adequate environment considering technical and economical constrictions. In those situations, even with a combination of measures listed above it is not possible to maintain the animals within the TNZ and therefore productive losses, health effects and welfare issues will be expected. Particularly under those cases, the measures to mitigate heat stress have to be carefully analysed and selected. Considering these complications, the following section analyses the potential of precision livestock farming for climate control.

5. Precision livestock farming for climate control

The objective of climate control systems in livestock houses is to provide the animals with suitable, homogeneous and controllable conditions of temperature, humidity and pollutants. Ventilation should provide enough fresh air to remove excessive heat, moisture and pollutants from the building, both under natural and mechanical ventilation. If necessary, additional cooling or heating systems would be necessary to achieve target conditions. However, as mentioned before, there are two main concerns related with climate control strategies to reduce heat stress. The first is the difficulty to establish optimum temperatures and UCT for animal, whereas the second concern is the ability to respond to animal needs when UCT are exceeded.

As discussed by Fournel *et al.* (2017)~~.~~, ~~P~~precision livestock farming (PLF) can contribute to solve those concerns. PLF consists of technology and tools for online, continuous monitoring of the animals. It aims to better inform the farmers on the status of their animals and their environment and help them to take evidence-based decisions (Berckmans, 2006). In recent years, very relevant advances have been produced in PLF due to the development of sensors and computers, as well as to the collaboration between scientists and industry. Some of the advances were summarized by Halachmi and Guarino (2016) and include miking robots, individual feeding of group animals, automatic weight or behaviour analysis in broilers or fight detection in growing pigs.

Using PLF, animals responses (including behaviour, physiological and productive responses) can be used as additional criteria to establish TNZ in practice, to decide the most appropriate heat stress mitigation actions and to evaluate their efficiency. Some of the recent advances in PLF provide relevant, continuous and individual information to heat stress processes reviewed before, such as animal weight (Banhazi et al., 2011), feed intake (Halachmi et al., 2016, Andretta et al., 2016), water intake (Maselyne et al., 2016), or rectal temperature (Hoffmann et al., 2016). A comprehensive review of potential technologies used for precision environmental control can be found in Fournel *et al.* (2017). Therefore, PLF is suitable to allow a more precise understanding of the indoor environment of a livestock building, a more effective way to operate mitigation measures.

As discussed by Fournel et al. (2017), a strategy for the thermal control of animal houses based on PLF would include individual evaluation of animal responses including: (1) a more accurate estimation of heat production based on measured data and bioenergetics models; (2) an estimation of thermal comfort of animals based on measured environmental and physiological parameters; and (3) the effects of environmental quality on animal welfare.

About the second concern, once a heat stress problem is detected the proper mitigation mechanisms need to be activated. Therefore, the environmental control systems in the farms will need to integrate all animal and environmental information and be able to activate the most adequate response (or combination of responses), either for the whole building or only to a part of the animals.

6. Conclusions

Heat stress is a very relevant concern for animal production and is expected to impair animal production and welfare with increasing impact during the next decades. Adaptation to heat stress will be needed, but practical and effective strategies are required. There is a wide knowledge on animal responses to heat stress and a variety of mitigation strategies are available. However, apart from detecting heat stress conditions it is necessary to establish ways to mitigate their impacts using animal-based information. Precision livestock farming is expected to provide a better diagnosis of heat stress events and to allow evidence-based decisions to mitigate its effects. Integration of animal-based information with environmental information will be required to establish optimal climate management system in the farms.

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