J. Dairy Sci. 100:10367–10380
https://doi.org/10.3168/jds.2017-13676

A 100-Year Review: Stress physiology including heat stress[1]

R. J. Collier,[2] B. J. Renquist, and Y. Xiao
School of Animal and Comparative Biomedical Sciences, University of Arizona, Tucson 85719

ABSTRACT

Stress is an external event or condition that places a strain on a biological system. The animal response to a stress involves the expenditure of energy to remove or reduce the impact of the stress. This increases maintenance requirements of the animal and results in loss of production. The biological response to stress is divided into acute and chronic phases, with the acute phase lasting hours to a few days and the chronic phase lasting several days to weeks. The acute response is driven by homeostatic regulators of the nervous and endocrine systems and the chronic phase by homeorhetic regulators of the endocrine system. Both responses involve alterations in energy balance and metabolism. Thermal environment affects all animals and therefore represents the largest single stressor in animal production. Other types of stressors include housing conditions, overcrowding, social rank, disease, and toxic compounds. "Acclimation" to a stress is a phenotypic response developed by the animal to an individual stressor within the environment. However, under natural conditions, it is rare for only one environmental variable to change over time. "Acclimatization" is the process by which an animal adapts to several stressors within its natural environment. Acclimation is a homeorhetic process that takes several weeks to occur and occurs via homeorhetic, not homeostatic, mechanisms. It is a phenotypic change that disappears when the stress is removed. When the stress is severe and not relieved by acclimatization or management changes, the animal is considered chronically stressed and is susceptible to increased incidence of disease and poor health. Milk yield and reproduction are extremely sensitive to stress because of the high energy and protein demands of lactation and the complexity of the reproductive process and multiple organs that are involved. Improvements in protection of animals against stress require improved education of producers to recognize stress and methods for estimating degree of stress on animals.

Received August 11, 2017.
Accepted August 22, 2017.
[1]This review is part of a special issue of the *Journal of Dairy Science* commissioned to celebrate 100 years of publishing (1917–2017).
[2]Corresponding author: rcollier@ag.arizona.edu

Key words: acclimation, homeorhesis, strain, stress

INTRODUCTION

Hans Selye (1936) first introduced the concept of stress as 'the non-specific response of the body to any demand," and many attempts have been made to refine its meaning (Friend, 1991; Appendix Table A1). However, the definition remains ambiguous and the word is used differently in different contexts. As pointed out by Schulte (2014), the variability in the definition of stress may stem from the fact that stress research has developed relatively independently across several fields of biology, with substantial gulfs between those interested in stress from a biomedical perspective and those interested in the effects of stressors in natural populations (Bijlsma and Loeschcke, 2005; Boonstra, 2013).

For the purpose of consistency, we will define stress as an "external event or condition." We will further define a stressor as the component of the environment that places a strain on a biological system. Examples of stressors are shown in Table 1 and include thermal environment, management, social interaction, environmental contaminants, and disease, to name a few. Stress is a threat to homeostasis because it always increases the maintenance requirements of domestic animals. Because energy demands alter animal production, we are restricting this review to "external challenges that require a change in maintenance output to meet the challenge." One of the earliest estimates of maintenance energy requirements in cattle was published by Washburn (1938). Brody (1956) reviewed the effects of thermal environment on basal metabolism. The increase in maintenance requirement by stress is of real concern to production animal systems because it increases costs, reduces efficiency, and leads to lower profitability of an animal enterprise. The reason a stress increases maintenance cost is because energy must be expended to return the animal to homeostasis of body function. This energy must come from net energy for production because it is not physically possible to remove it from net energy for maintenance. The environmental temperature below which the body produces extra heat to meet the thermostatic heat requirement is termed the "lower critical temperature" and was first estimated

Table 1. Partial list of types of stressors and biological responses to them[1]

Stressor	Symptom	Physiological system activated or inhibited
Heat	Elevated body temperature	Heat loss mechanisms increased; decreased phagic drive
Cold	Reduced body temperature	Heat gain mechanisms enhanced; heat loss mechanisms reduced; feed intake enhanced
Infection	Elevated body temperature	Immune system activated; decreased phagic drive; hypothalamic body temperature setpoint altered
Poor housing	Increased lameness	Hypothalamic-pituitary-adrenal axis activated; reduced phagic drive
Poor nutrition	Deficiency symptom varies with nutrient	Mobilization of nutrient reserves; activation of pituitary-adrenal axis; altered behavior
Environmental	Hepatotoxicity	Liver function reduced; multiple organ damage; hypothalamic-pituitary-adrenal axis activated
Social	Altered behavior	Feed intake reduced; hypothalamic-pituitary-adrenal axis activated

[1]References: Bauman and Currie, 1980; Collier et al., 1982b; Friend, 1991; Coulombe, 1993; Bauman (2000); Collier and Gebremedhin, 2015; Chebel et al., 2016.

by Kleiber (1961) and confirmed by Hamada (1971). The environmental temperature above which the body starts storing heat and losing milk yield was established by Berman et al. (1963, 1985). For other stressors, we do not yet have specific end points by which to measure the relationship between the stress and loss in productivity of cattle. A key opportunity for the future will be to improve our ability to identify and measure levels of various stressors and their impact on animals in order to develop strategies to reduce the effects of those stressors on dairy animals (Appendix Table A1).

STRESS RESPONSE

Animals mount a response to a stress that involves behavioral, metabolic, and physiological changes at multiple levels of vertebrate organization from subcellular to the whole animal (Selye, 1936; Collier and Gebremedhin, 2015). The stress response is divided into 2 phases: acute and chronic (Friend, 1991). Acute stress responses last from a few minutes after the beginning of the stress to a few days (Horowitz, 2001). Activation of the acute response to stress is initiated by various receptors that respond to changes in the environment (Collier and Gebremedhin, 2015; Figure 1). The afferent pathways for the stress transmit this information to the central nervous system, including the thalamus and hypothalamus, where setpoints are controlled, and to the cortex for perception (Figure 1). These centers then activate various efferent pathways to effect a response to the environment (Figure 1). The acute response is driven by the autonomic nervous system promoting release of catecholamines and glucocorticoids, which alter metabolism and activate transcription factors involved in the acute response. The chronic response to stress is driven by the endocrine system and is associated with altered receptor populations, changing tissue sensitivity to homeostatic signals and resulting in a new physiologic state (Bligh, 1976; Bauman and Currie, 1980). Selye (1946) coined the term "heterostasis" to describe the process of achieving a new equilibrium state following exposure to a stressor (Fink, 2009). The term "rheostasis" was introduced to emphasize that the setpoints for homeostatic regulation may vary across environments or seasons (Mrosovsky, 1990), and the term "enantiostasis" was coined to refer to a situation in which multiple physiological variables are varied to maintain the overall functionality of a system (Mangum and Towle, 1977). These concepts emphasize the idea that maintaining functional homeostasis may require dynamic changes in a variety of parameters. Acclimation to a stress is a phenotypic response developed by the animal to an individual stressor within the environment (Fregley, 1996). However, under natural conditions, it is rare for only one environmental variable to change over time. Acclimatization is the process by which an animal adapts to several stressors within its natural environment (Bligh, 1976). Acclimation and acclimatization are not therefore evolutionary adaptations or natural selection, which are defined as changes allowing for preferential selection of an animal's phenotype and are based on a genetic component passed to the next generation. The altered phenotype of acclimated animals will return to normal if environmental stressors are removed, which is not true for animals that are genetically adapted to their environment (Collier et al., 2004). Acclimatization is a process that takes several weeks to occur, and close examination of this