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Review

Physiological adjustments to hypohydration: Impact on thermoregulation

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ABSTRACT

Sufficient body water is required to sustain thermoregulatory function, thus losses in total body water (TBW) can challenge the thermoregulatory system. A TBW deficit ≥2% body mass (hypohydration) is recognized as the threshold when thermoregulatory function becomes measurably altered. Hypohydration may occur from voluntary fluid restriction, insufficient fluid availability, or thermoregulatory sweating. The secretion and evaporation of sweat important avenues of body heat loss, and if the water lost is not replaced, hypohydration will decrease plasma volume and increase plasma osmotic pressure (hyperosmotic hypovolemia). Both osmotic and/or volume stressors delay the onset and/or reduce the sensitivity of sweating and blood flow responses. The magnitude of hypohydration, environmental heat stress, the population and circumstances of interest will determine the degree, significance and outcome of these thermoregulatory alterations and their contribution to physiological stress.

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1. Introduction

Body water is required to support cellular homeostasis and sustain thermoregulatory function. While a state of "normal" hydration can be achieved through a wide range of fluid intakes, body water balance can be challenged by circumstances involving environmental heat stress and physical labor. In this paper we review the physiological adjustments to a significant body water deficit (>2% body mass; hypohydration). Furthermore, we discuss some circumstances under which hypohydration produces the greatest physiological strain.

1.1. Body water balance

The percentage of body mass as water is commonly reported to be 60%, but varies in accordance with body composition, as lean tissue is comprised of ~72% water. Isotopic dilution, referred to as the gold standard for the determination of total body water (TBW), has a reported analytical measurement variation of 1–2% (~0.4 to 0.8 L) (Schoeller, 1996). The day-to-day variation in body mass, or TBW, represents typical physiological and behavioral body water regulation (Greenleaf, 1992) and is slightly smaller in variation than deuterium (≤1%) when fluid intake and activity are controlled (Cheuvront et al., 2004a); (Cheuvront et al., 2010a). As a consequence, daily fluctuations in body mass of ±1% cannot be reliably associated with alterations in TBW and should be considered to be typical or within the range of normal hydration (Cheuvront et al., 2013); (Ladell, 1965). In fact, it is not until a threshold of ≥2% body mass loss is achieved that hypohydration can be reliably assessed (Cheuvront and Kenefick, 2014) or alteration in

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physiological function can be reliably observed (Ladell, 1965); (Sawka et al., 2007).

Water gain occurs from consumption (liquids and food) and production (metabolic water), whereas water losses occur from respiratory, gastrointestinal, renal and skin (transcutaneous and sweat) losses. Intakes (food, fluid) are generally adequate to offset day-to-day losses (Costill et al., 1975). However, mismatches between fluid gain and loss may occur due to illness, environmental exposure, voluntary fluid restriction, lack of available water, or physical labor (work/exercise). Situations such as hiking the Grand Canyon in summer, military work in hot climates, emergency relief circumstances where water availability is limited, heat waves, competitive marathon and ultra-marathon running represent a few examples where accumulating water losses can far exceed voluntary intakes, resulting in hypohydration well beyond 2% of body mass (Cheuvront and Haymes, 2001).

1.2. Body water and thermoregulation

Humans maintain body core temperature (BCT) within narrow limits during ordinary living via behavioral and physiological regulation. Heat can be gained as a result of exposure to the environment and/or as a result of physical work. Physical work of almost any kind is extremely inefficient, as more than 75% of the energy required is released in the form of heat (Margaria et al., 1963); (Whipp and Wasserman, 1969). Behavioral thermoregulation includes conscious actions such as altering physical activity, selecting appropriate clothing, adjusting indoor thermostats, and seeking shade, sun, or shelter. Physiological temperature regulation occurs through sweating, alterations in skin flood flow, and metabolic heat production (e.g., shivering) (Sawka and Young, 2006). Heat loss occurs by a combination of evaporation, radiation, convection and conduction. These biophysical factors and their relative contribution to heat gain or loss are presented in greater detail in this special issue (Ref O. Jay manuscript). This review is exclusively focused on the physiological underpinnings of the mechanisms of heat loss.

During activity, muscle contraction produces metabolic heat that is primarily transferred from the metabolically active tissues to the blood and then the periphery. Fig. 1 schematically depicts the sensory input (BCT and skin temperature) and effector output (vasodilation, vasoconstriction, sweating) aspects of the human thermoregulatory system. Temperature sensors are located both centrally (within blood vessels, abdomen and hypothalamus) and peripherally (skin). The hypothalamus integrates and controls BCT and skin temperature signals and controls thermoregulatory responses. If the BCT signal deviates from the normal baseline, (e.g. increases), an error signal is sensed within the hypothalamus and appropriate effector responses are elicited at the periphery, such as activation of sweating and cutaneous vasodilation to increase evaporative and dry heat loss. These effector responses commence when a particular BCT threshold is exceeded and increases in a graded manner as the controlled variable (e.g. BCT) is further disturbed (increased error signal). This proportional control system is modified by thermal factors such as skin temperature, and non-thermal factors, such as hypohydration (Shibasaki et al., 2003). Skin temperature is a separate input signal and changes the sensitivity of the relationship between sweating and BCT such that at any given BCT, sweat rates are greater when the skin is warm and lower when the skin is cool. This is also the case with vasodilation; the BCT at which vasodilation is initiated will decrease as skin temperature increases (Nadel et al., 1979), thus promoting greater skin blood flow at a given level of hyperthermia.

During work in hot environments, evaporative (sweating) and dry heat loss (via vasodilation and skin blood flow) operate in tandem, with each increasing in proportion to the heat load (Stolwijk et al., 1968) in order to balance heat gain. The environment determines which avenue of heat loss predominates, but in general evaporation becomes more important as ambient temperature increases (Nielsen, 1938). When the ambient temperature is greater than, or equal to skin temperature, evaporative heat loss accounts for all of body cooling. The rate of sweat evaporation depends importantly upon air movement (convection), and the water vapor pressure gradient between the skin and the environment Gagge, AP and Gonzalez, 1996. When water vapor pressure is high, the rate of evaporation is compromised and greater sweat drippage occurs. In still or moist air, sweat that does not evaporate collects on the skin and drips from the body or clothing and provides no cooling benefit. As a result, less heat is lost, body temperature rises and a greater degree of sweating occurs (Cheuvront et al., 2004b); (Sawka et al., 1996).

Eccrine sweat glands involved in thermoregulatory sweating can be found over most of the body surface and respond primarily to sympathetic cholinergic stimulation of muscarinic receptors (Shibasaki et al., 2006). The sweat gland contains precursor secretory fluid similar in composition to plasma. However, as the fluid travels through the duct of the sweat gland, it is modified such that most of the sodium and chloride ions are reabsorbed and the resulting sweat is hypotonic relative to plasma with an osmolality typically less than half of plasma (Costill, 1977). Sweating rates depend upon the intensity of the activity and environmental conditions (Gonzalez et al., 2009); (Shapiro et al.,

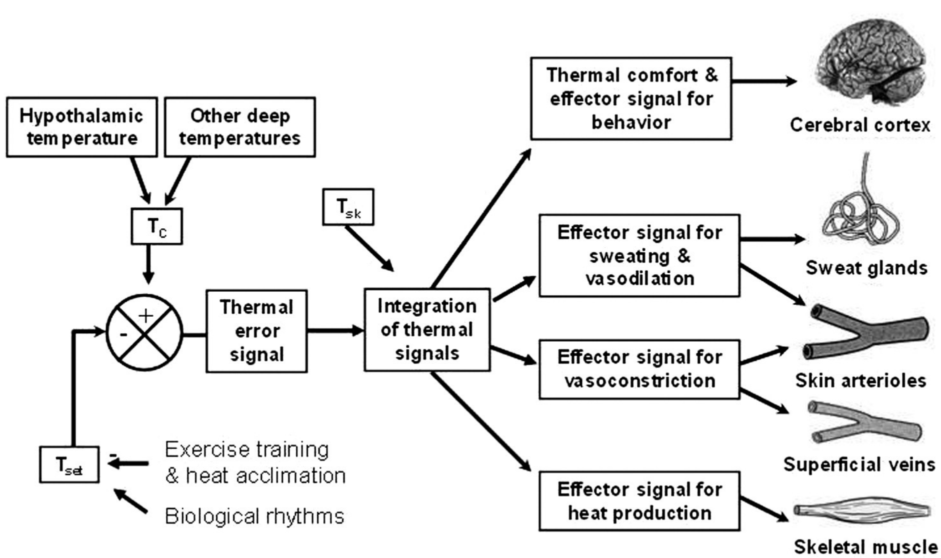

Fig. 1. Human thermoregulation. BCT = $T_{C;}$ skin temperature = T_{sk}. Adapted from Sawka et al., 1996.

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