

**HYDRATION AND BLOOD VOLUME EFFECTS ON HUMAN
THERMOREGULATION IN THE HEAT: SPACE APPLICATIONS**

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ABSTRACT

Astronauts exposed to prolonged weightlessness will experience deconditioning, dehydration and hypovolemia which all adversely affect thermoregulation. These thermoregulatory problems can be minimized by several countermeasures that manipulate body water and vascular volumes. USARIEM scientists have extensively studied dehydration effects and several possible countermeasures including hyperhydration, plasma and erythrocyte volume expansion. This paper reviews USARIEM research into these areas.

INTRODUCTION

Space physiologists have an interest in thermoregulation because astronauts must perform strenuous exercise (~250 watts during space shuttle extravehicular activities (EVA) and probably higher during space station construction) that could be limited by thermal strain (5). This may be a particular problem during space station construction and habitation, because prolonged weightlessness will cause deconditioning, reduced blood volume and dehydration. All of these factors will adversely affect the astronaut's ability to thermoregulate during exercise-heat stress. In addition, EVA missions during space station construction might require astronauts to exercise at barometric pressures reduced to equivalent altitudes of 914 to 1524 meters. These lowered barometric pressures could also adversely influence thermoregulation.

This paper reviews USARIEM (and other selected) research concerning hydration and blood volume effects on human thermoregulation. This review has direct application for development of approaches to maintain thermoregulatory and exercise capabilities during prolonged human presence in space.

TEMPERATURE REGULATION

Physical exercise will routinely increase body metabolism by 3-10 times the resting rate to provide energy for skeletal muscle contraction, and most (70% and 100%) of the metabolic rate results in heat which must be dissipated to restore body heat balance. Depending on environmental temperature, the relative contributions of evaporative and dry (radiative and conductive) heat exchange to the total heat loss vary. The hotter the environment the greater the dependence on evaporative heat loss, and thus on sweating. Therefore, in hot environments, a considerable amount of body water can be lost through

sweat gland secretion to enable evaporative cooling of the body.

During exercise in the heat, thermoregulatory responses are primarily influenced by a person's heat acclimation state, aerobic fitness and hydration level. Heat acclimated persons, who are aerobically fit and fully hydrated, will have less heat storage and optimal performance. Hydration level is particularly important during exercise in the heat because a body water deficit will neutralize the thermoregulatory advantages of heat acclimation and high aerobic fitness (1,28).

DEHYDRATION

During physical exercise in the heat, it is a problem to closely match the volume of fluid intake to the volume of sweat output. This is a difficult problem to solve because thirst does not provide a good index of body water requirements (4,13). It is not uncommon for individuals to "voluntarily" dehydrate by 2-8% of their body weight during exercise-heat stress, despite the availability of adequate amounts of fluid to rehydrate.

Sweat loss results in a reduction of total body water if an adequate amount of fluid is not consumed. As a consequence of free-fluid exchange, dehydration will affect each fluid space within the body. At low volumes of body water loss, the water deficit primarily comes from the extracellular space; however, as the body water loss increases, a proportionately greater percentage of the water deficit comes from the intracellular space (3). Regardless, dehydration from sweat loss will result in an increased plasma osmolality with a decreased blood volume (22).

Generally, loss of body water impairs aerobic exercise performance in the heat; and the warmer the environment, the greater the adverse effect of dehydration (22). In comparison to euhydration, a water deficit of as little as 1% of body weight increases core temperature during exercise in both comfortable and hot environments, and the greater the water deficit, the greater is the elevation of core temperature during exercise (15,30). Dehydration impairs both dry and evaporative heat loss (22). In addition, dehydration causes exhaustion from heat strain to occur at lower core temperatures during exercise-heat stress (31).

Dehydration may be associated with either reduced or unchanged sweating rates at a given metabolic rate in the heat. However, even when dehydration is associated with no change in sweating rate, core temperature is usually elevated, so that sweating rate for a given core temperature during dehydration is still lower. The physiological mechanisms mediating the reduced sweating rate during dehydration are not clearly defined, but both the separate and combined effects of plasma hyperosmolality and hypovolemia play a part (7,8,25).

Dehydration affects cardiovascular responses to exercise-heat stress. During submaximal exercise with moderate to severe thermal strain (15,18), dehydration increases

heart rate and decreases stroke volume and cardiac output relative to euhydration. Dehydration also reduces cutaneous blood flow for a given core temperature (6,7,18), and therefore the potential for dry heat exchange. Likewise, hyperosmolality, in the absence of hypovolemia, can also reduce the cutaneous blood flow response during exercise-heat stress.

In addition to the effects of dehydration on thermoregulatory responses, USARIEM scientists have examined the effects of dehydration on hormonal (9,10), muscle glycogen (19), immunological (29), gastric emptying (20) and vascular volume (24) responses during exercise-heat exposure. USARIEM scientists continue to have an active program studying dehydration effects in hot environments.

HYPERHYDRATION / HYPERVOLEMIA

If dehydration reduces performance during exercise-heat stress, can excess body fluids improve performance beyond the levels achieved when euhydrated? Moroff and Bass (17) examined the influence of excessive fluid ingestion on thermoregulatory responses during exercise in the heat. They reported that hyperhydration decreases core temperature, while increasing sweating rates above control levels. During the control experiments, however, their subjects were slightly (greater than 1%) dehydrated. Therefore, these results may demonstrate the effects of dehydration rather than hyperhydration. In addition, Nielsen and colleagues (21) reported lower core temperatures during exercise in subjects who were hyperhydrated with 1.5 liters of water; however, they did not employ a euhydration control experiment. In contrast, Grucza and colleagues (12) reported that water hyperhydration will reduce core temperature responses during exercise in a temperate environment.

Several well controlled studies have not observed any thermoregulatory benefits from water hyperhydration. Greenleaf and Castle (11) reported that excessive water ingestion did not alter core temperature or sweating rate from control levels during exercise in the heat. Nadel et al. (18) hyperhydrated subjects by administering antidiuretic hormone and water. They did not find any significant improvements in thermoregulation from hyperhydration.

Recently, Lyons et al. (14) reported that glycerol-induced hyperhydration had a marked thermoregulatory advantage during an exercise-heat stress. They reported increases in sweating rate and substantial reductions in core temperature during the glycerol-induced hyperhydration compared to hyperhydration with water. Subsequent studies from their laboratory have reported no thermoregulatory improvements with glycerol hyperhydration (16). USARIEM has recently initiated a comprehensive research program on glycerol hyperhydration and temperature regulation.

If hyperhydration does improve performance during exercise-heat stress, these improvements will most likely be mediated by hypervolemia. Several studies on the

effects of artificially expanded plasma volume have indicated no differences in core temperature (6,27) in comparison with normovolemic control levels during exercise-heat stress. Generally, these studies found that plasma volume expansion lowered heart rate responses during exercise in the heat. In contrast, both Fortney et al. (8) and Deschamps et al. (2) reported that artificially expanded plasma volume lowered core temperature below control levels during exercise, despite no difference in the sweating rate response.

BLOOD INFUSION

Two studies examined the effects of acute polycythemia (via erythrocyte infusion) on thermoregulation during exercise in the heat (23,26). In the first study (23) nine male soldiers, who were not heat acclimated, were infused with either 600 ml of a saline solution containing a ~50% hematocrit (n=6, infusion) or 600 ml of saline only (n=3, control). Subjects attempted a heat-stress test while euhydrated at approximately 2 wk pre- and 48 h post-infusion. The heat stress test consisted of a 120-min exposure (two repeats of 15 min rest and 45 min treadmill walking) in a hot (35°C, 45% rh) environment. The erythrocyte infusion subjects tended to store less body heat during the post-infusion heat-stress test. For the control group, a tendency for a greater body heat storage was evident during the post-infusion heat-stress test (compared to pre-infusion).

The avenues of heat exchange responsible for the reduced body heat storage after erythrocyte infusion were inconclusive. For the erythrocyte infusion group, steady-state values for evaporative as well as radiative and convective heat exchange were not altered from pre- to post-infusion. However, the sweating onset time was reduced (50%) and sweating sensitivity was increased (78%) post-infusion (25). These thermoregulatory advantages occurred despite the fact that erythrocyte infusion reduced plasma volume so that total blood volume was the same as during the pre-infusion measurements.

This initial study (23) raised questions concerning the use of acute polycythemia as an ergogenic aid during exercise in the heat. First, would the small thermoregulatory advantage conferred by acute polycythemia still be present in heat acclimated subjects? Heat acclimation enables an individual to perform exercise in the heat with reduced heat storage, and may elicit optimal thermoregulatory adaptations that acute polycythemia cannot improve upon. Second, would acute polycythemia provide a thermoregulatory advantage or disadvantage in dehydrated subjects during exercise in the heat? Dehydration reduces plasma volume (22), and this reduction may be accentuated by the decreased plasma volume in response to acute polycythemia which could provide a thermoregulatory disadvantage during subsequent exercise in the heat. Therefore, acute polycythemia could potentially reduce exercise performance (below pre-infusion levels) for hypohydrated subjects.

In the second study (26), five heat-acclimated men attempted four heat-stress tests; two pre- and two post-infusion with autologous erythrocytes (product of two blood units) in saline solution (~50% hematocrit). Both pre- and post-infusion subjects attempted one

heat-stress test while euhydrated, and one heat-stress test while hypohydrated (-5% of body weight). The protocol for the heat-stress tests was the same as in the previous investigation. During exercise, the subjects stored less body heat after erythrocyte infusion during both euhydration and hypohydration heat-stress tests. In addition, the subjects demonstrated an improved sweating response to exercise-heat stress after erythrocyte infusion. Both total body sweating and steady-state local sweating were greater post-infusion, and onset time for sweating tended to be more rapid. The sweating sensitivity was increased (~68%) after infusion (25). Unlike the previous study, erythrocyte infusion resulted in a slightly expanded plasma volume during rest and exercise in the heat-acclimated subjects. The slightly expanded plasma volume combined with the additional erythrocytes to increase total blood volume during both rest and exercise. Finally, the investigators found a reduced plasma hyperosmolality during the post-infusion hypohydration experiments. Future research projects will examine the potential for erythropoietin administration to induce polycythemia and modify exercise-heat performance.

DISCLAIMER

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PREDICTION MODELING OF PHYSIOLOGICAL RESPONSES AND HUMAN PERFORMANCE IN THE HEAT WITH APPLICATION TO SPACE OPERATIONS**Kent B. Pandolf, Leander A. Stroschein, Richard R. Gonzalez and Michael N. Sawka****Environmental Physiology and Medicine Directorate****U.S. Army Research Institute of Environmental Medicine (USARIEM)****Natick, Massachusetts 01760-5007****ABSTRACT**

This Institute has developed a comprehensive USARIEM Heat Strain Model for predicting physiological responses and soldier performance in the heat which has been programmed for use by hand-held calculators, personal computers, and incorporated into the development of a heat strain decision aid. This model deals directly with five major inputs: (a) the clothing worn, (b) the physical work intensity, (c) the state of heat acclimation, (d) the ambient environment (air temperature, relative humidity, wind speed, and solar load), and (e) the accepted heat casualty level. In addition to predicting rectal temperature, heart rate and sweat loss given the above inputs, our model predicts the expected physical work/rest cycle, the maximum safe physical work time, the estimated recovery time from maximal physical work, and the drinking water requirements associated with each of these situations. This model provides heat injury risk management guidance based on thermal strain predictions from the user specified environmental conditions, soldier characteristics, clothing worn, and the physical work intensity. If heat transfer values for space operations' clothing are known, NASA can use this prediction model to help avoid undue heat strain in astronauts during space flight.

INTRODUCTION

Since the early 1970s, our Institute has established the data base and developed a series of predictive equations for deep body temperature, heart rate and sweat loss responses of clothed soldiers performing physical work in the heat. Individual predictive equations for rectal temperature (4), heart rate (5), and sweat loss (16) as a function of the physical work intensity, environmental conditions and particular clothing ensemble have been published in the open literature. In addition, important modifying factors such as metabolic rate (2,11), state of heat acclimation (6), state of hydration (14,15), and solar load (1) have been studied and appropriate predictive equations developed.

Currently, we have developed a comprehensive USARIEM Heat Strain Model which has been programmed for use by hand-held calculators, personal computers, and incorporated into the development of a heat strain decision aid. The mathematical basis employed in the development of the various individual predictive equations and the predictive capabilities of our heat strain model have been published previously (12,13). Our model deals directly with five major assessment factors and associated inputs: (a) U.S. Army clothing systems as selected from a clothing menu; (b) physical work intensity entered at three fixed values (i.e., light, moderate, or heavy), or directly entered if a value