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BODY WATER HOMEOSTASIS AND HUMAN PERFORMANCE
IN HIGH HEAT ENVIRONMENTS:
FLUID HYDRATION RECOMMENDATIONS
FOR OPERATION DESERT STORM

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Fluid Hydration Recommendations for
Operation Desert Storm**

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SUMMARY

Rapid deployment to and sustained military operations (SUSOPS) in the Persian Gulf theater during Operation Desert Storm caused many logistical concerns for military commanders. When in the desert environments of the Middle East, one potential hazard to military personnel is prolonged exposure to warm/hot temperatures. If SUSOPS continue into the warm/hot months of the spring and summer, the threat of heat stress on military personnel imposes concerns for ways to minimize heat illness and degradation in human performance. A principle concern of operational commanders should be to lessen the impact of heat stress on the effectiveness of military personnel during SUSOPS. This can be achieved by ensuring that personnel: (1) are heat acclimatized to warm/hot environments; (2) maintain strict fluid and food intake schedules; and (3) alter work/rest schedules to changes in air temperature and the intensity of workload.

Adequate hydration during SUSOPS and rehydration after field missions depends on retaining the osmotic drive for drinking. The loss of body fluids as sweat during rest and physical activity in heat will influence the ability to effectively dissipate the metabolic heat load. Sweat flow is an effective means of cooling the body through evaporation, but at the cost of losing sodium and body water. Consequently, plasma volume is reduced, which decreases the amount of blood ejected from the heart per minute. Physical performance in endurance activities will degrade and incidents of heat illness will occur as dehydration increases. The inability of the human body to consume and retain fluids at the same rate is a great limitation, particularly during prolonged heat exposure. This can be explained by the fact that water consumption causes a dilution of the blood. This, in turn, removes the salt-dependent portion of the thirst drive, and urinary water is produced. When consuming carbohydrate-electrolyte beverages containing sodium, the salt-dependent thirst drive will be prolonged for a greater period of time. Urinary water production will be minimal, allowing for a greater hydration and body water storage. The rate of decline and replenishment of plasma volume during and after SUSOPS is superior to water when sodium is included in the beverage.

The advancement of our understanding of fluid hydration procedures has come from research in exercise physiology. Research has clearly demonstrated that body water deficits affect human performance through the increase in core temperature, heart rate, and reduced sweat rates. Carbohydrate-electrolyte solutions have been found to assist in the prevention of body fluid loss and in the rehydration of lost body fluids. The use of carbohydrate-electrolyte solutions by military personnel would be advantageous in the prevention of heat illnesses generally caused by excessive body fluid loss.



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INTRODUCTION

Rapid deployment to and sustained military operations (SUSOPS) in the Persian Gulf theater during Operation Desert Storm caused many logistical concerns for military commanders. When in the desert environments of the Middle East, one potential hazard to military personnel is prolonged exposure to warm/hot temperatures. If SUSOPS continue into the warm/hot months of the spring and summer, the threat of heat stress on military personnel imposes concerns for ways to minimize heat illness and degradation in human performance. A principle concern of operational commanders should be to lessen the impact of heat stress on the effectiveness of military personnel during SUSOPS. This can be achieved by ensuring that personnel: (1) are heat acclimatized to warm/hot environments; (2) maintain strict fluid and food intake schedules; and (3) alter work/rest schedules to changes in air temperature and the intensity of work-load. Since the key factor for survival in hot temperatures is to maintain body fluid balance, the emphasis of the following discussion will be placed on the factors associated with body water homeostasis and how it relates to the effects of dehydration on human performance.

BACKGROUND

It is generally accepted that water composes 60% to 66% of human body weight, or approximately 72% of lean body weight. For a 70 to 80 kilogram (kg) man, there are 42 to 53 liters of water in the body. Body water storage can be perceived as two independent but interconnected compartments separated by water-permeable cell membranes. The intracellular compartment contains 24.5 to 33 liters of water, and the extracellular compartment contains 17.5 to 20 liters of water. The latter compartment consists of plasma volume (3.2 to 4 liters) and interstitial fluid (14.3 to 16 liters).

Water balance between these two compartments is tightly regulated and is maintained by hydrostatic and electrochemical gradients. The principal constituents in body water that create the proper electrochemical gradient inside and outside of the cell are sodium (Na), potassium (K), and their anion chloride. Extracellularly, Na [142 milliequivalents per liter (meq/l)] is the major cation and chloride (103 meq/l) is the major anion, with K (5 meq/l) in a very small concentration outside of the cell. Intracellularly, the major cation is K (145 meq/l), with the anion chloride (2 meq/l) in a small concentration. The concentration of Na inside the cell is approximately 10 meq/l. The total intracellular and extracellular osmolality is the same in these two compartments, allowing the total osmotic concentration [285 to 290 milliosmols per kilogram of water (mOsm/kg H₂O)] to be the same in spite of different concentrations and compositions of cations and anions. It is therefore understood that Na, the

vasopressin affects the permeability of the collecting tubule of the kidney, causing an increase in urinary water excreted from the kidney. The increased water loss, in turn, causes an increase of extracellular osmolality within the normal range.

An important aspect of understanding the principles of fluid hydration and the potential benefits of fluid hyperhydration is the maintenance or increase of extracellular fluid volume. The volume of the fluid compartment is primarily determined by the Na concentration. When the Na content is increased by consuming, for example, foods containing salt, the result is an increase of extracellular osmolality and a decrease in urinary water loss. This causes a return of extracellular osmolality to the previous level; however, this is at the cost of increasing extracellular fluid volume (Vokes, 1987). This is a benefit when high sweat rates are expected in hot environments. This principle is one reason why electrolytes are added to fluid beverages in an effort to maintain or restore fluid balance resulting from whole body dehydration. This concept will also be the basis for recommending military personnel to hyperhydrate with electrolyte beverages prior to SUSOPS in heat. The intent is to increase the extracellular Na and fluid volume content without changing the extracellular and intracellular osmolality. Consequently, by inducing a greater extracellular fluid volume prior to prolonged exposure in heat (hyperhydration), it would be predicted that the rate of dehydration could be prolonged prior to reaching a critical body water deficit that could result in less effective human performance.

Body Water Shifts During Work and Exercise

When work or exercise (SUSOPS) are conducted in warm/hot temperatures, the rise in body temperature is considered to be proportional to the metabolic rate or a function of workload. This has been shown to be independent of the ambient temperature as long as body temperature can equilibrate with the outside environment (Buskirk, 1977). If the metabolic heat gain is large and the body heat storage is greater than the heat dissipation, body temperature increases. During work or exercise, the range of body temperature equilibrium varies considerably, dependent on body size, body composition, gender, aerobic fitness, acclimation state, and hydration status of the body (Buskirk, 1977; Cadarette et al., 1984; Nadel et al., 1974; Pandolf, 1979; Strydom and Holdsworth, 1968). If individuals are fully hydrated, possess high aerobic fitness, and are heat acclimated, they will have lower body heat storage and greater physical performance during heat exposure. Consequently, there is less disruption to physiological homeostasis when compared to individuals who do not possess these characteristics. Paramount to achieving high aerobic fitness, the hydration status of an individual during heat exposure is so fundamental that body fluid

loss with an onset of thirst; however, increasing hypohydration does not increase the intensity of thirst (Adolph, 1947). Significant mental deterioration (mental math, short-term memory, visuomotor tracking) has been documented to occur at this lower hypohydration (2%) state (Gopinathan et al., 1988). Additionally, this marginal level of water deficit does not increase heart rate, core temperature, sweat rate, or skin blood flow (Sawka et al., 1984). When hypohydration reaches 4% to 6%, water deficit symptoms of anorexia, impatience, and headache occur. Additionally, core temperature increases with reductions in sweat rate and skin blood flow. Heart rate has been reported to be increased at 5% hypohydration as a result of reduced plasma volume. This causes a reduction in the end diastolic volume, thereby reducing stroke volume. Heart rate increases to compensate for the decrement in stroke volume, enabling the maintenance of cardiac output. With greater thermal strain and exercise, cardiac output is divided between peripheral blood flow to the skin and central circulation. Consequently, cardiac output cannot be maintained. With a reduced sweat rate and skin blood flow, core temperature rises because less heat is dissipated through skin sweat evaporation and convection. At 6% to 10% water deficit, symptoms of vertigo, cyanosis, and spasticity are evident. An individual with a 12% water deficit is unable to swallow, and a 15% to 25% water deficit is considered lethal (Adolph, 1947). When hypohydration (6% to 7%) occurs in thermoneutral temperatures, maximal exercise capacity is minimally affected (Buskirk et al., 1958). However, during heat exposure of the same water deficit, maximal aerobic power and physical work capacity are both reduced (Craig and Cummings, 1966). A reduction in cardiac output due to reduced plasma volume is the mechanism for the reduction in aerobic power.

Effect of Various Fluid Beverages on Body Water Homeostasis

Hyperhydration Prior to Work or Exercise: Many different strategies have been employed to minimize the rate of dehydration during rest and exercise in heat. The concept of overhydration or hyperhydration has been utilized in research with varying benefits on the cardiovascular and thermoregulatory mechanisms. Nielsen and associates (1971) administered a liter of water to volunteers before one hour of heavy exercise, resulting in a decrease of esophageal temperature by 0.5°C when compared to a nonfluid treatment. Consuming one liter of a 2% sodium chloride (NaCl) solution caused an elevation of core temperature when compared to a nonfluid condition. Nielsen and associates (1974) also reported beneficial effects by consuming one liter of a 2% calcium (Ca) solution several hours before 60 minutes of stationary cycling. Compared to intake of a 2% NaCl solution, an earlier onset of sweating, greater sweat rate, and a lower rise of core temperature resulted. Greenleaf and Brock (1980), however, found no benefits by consuming one liter of a 1.5% Ca gluconate solution 30 to 90 minutes before cycling 60 minutes when compared to intake of normal

Hydration During Work or Exercise: The efficacy of ingesting water or saline solutions during physical activity has been demonstrated for many decades. Early work by Pitts and associates (1944) demonstrated that when men were marching in the desert, lower heart rates, lower core temperatures, and greater sweat rates were recorded in those who consumed water, a 0.2% saline solution, or a 3.5% carbohydrate solution when compared to a nonfluid treatment. Furthermore, Francis (1979) examined three different fluid conditions while men cycled ($50\% \text{VO}_{2\text{max}}$) eight 15-minute bouts separated by 5-minute rest periods in a 32°C environment. In the nonfluid condition, plasma volume loss was 17.7%, whereas no loss of plasma volume occurred with the other two fluid beverages. There were lower heart rates [15 to 20 beats per minute (bpm)] and core temperatures (1°C) with the glucose and saline solution when compared to the nonfluid treatment.

Costill and associates (1970) reported lower core temperatures in four marathon runners who ran on a treadmill at $70\% \text{VO}_{2\text{max}}$ for two hours when consuming fluids relative to a nonfluid treatment. The subjects consumed either 100 ml of water every 5 minutes during the first 100 minutes or 100 ml of a 4.4% glucose-electrolyte solution every 5 minutes. Other research (Candas et al., 1986) has also demonstrated that relative to nonfluid treatments, consuming either hypotonic, isotonic, or hypertonic solutions during four hours of intermittent cycling in a hot environment (34°C) decreased core temperature, heart rate, and plasma osmolality and minimized plasma volume loss. However, the hypertonic solution was less effective on these variables, while the isotonic solution demonstrated a plasma volume expansion.

There is some merit to the addition of electrolytes in fluid beverages. Substantial quantities of NaCl and K can be secreted in sweat, particularly in heat. Concern should be directed at nonacclimated individuals to heat since they lose a greater amount of electrolytes relative to a heat-acclimated person. Electrolytes are added in fluid replenishment drinks to replace electrolytes lost in sweat. In general, a diet will replace any lost electrolytes in sweat, but this may become a potential problem in individuals during prolonged work/exercise who chronically sweat day after day, who may skip meals, or who are on low salt diets. An electrolyte imbalance has been reported in endurance and ultra-endurance athletes. A low Na concentration (hyponatremia) can occur when these athletes lose excessive Na in sweat. This is further complicated in people who consume only water throughout the endurance event, causing a dilution of plasma Na concentration (Noakes, 1990; O'Toole, 1988). This electrolyte imbalance is infrequent, but this complication is known to cause cerebral edema and seizures (personal communication, R.H. Lind, M.D., Medical Director, Western States

five days is primarily cardiovascular. The need for supplemental salt intake will preserve plasma volume and extracellular fluid volume.

In response to the hydration needs of the Marine Corps and Navy personnel in Operation Desert Storm, Bennett and associates (unpublished data, 1991) have conducted two studies on the influence of forced hydration and hyperhydration with different fluids solutions on thermoregulation and fluid balance during four hours of an intermittent work/rest protocol in a hot, dry (115°F dry bulb, 78°F wet bulb) environment. In the hydration study, the results indicate that an optimal concentration of electrolytes is necessary in the carbohydrate-electrolyte (sport drinks) solutions to minimize the loss of plasma volume and body water loss. Furthermore, there was no superior advantage by consuming a carbohydrate-electrolyte and glycerol solution when compared to the most effective carbohydrate-electrolyte solution. In the hyperhydration study, these results indicate that hyperhydrating two liters before heat exposure and ingesting up to two liters of water during four hours of heat exposure do not appear to be more effective for maintaining plasma volume than solely ad libitum water consumption in heat. Furthermore, at the end of heat exposure, there was no advantage in body fluid retention or in thermoregulation by consuming either glycerol and water, carbohydrate-electrolyte and glycerol, or a carbohydrate-electrolyte solution.

SUMMARY

Adequate hydration during SUSOPS and rehydration after field missions depends on retaining the osmotic drive for drinking. The loss of body fluids as sweat during rest and physical activity in heat will influence the ability to effectively dissipate the metabolic heat load. Sweat flow is an effective means of cooling the body through evaporation, but at the cost of losing Na and body water. Consequently, plasma volume is reduced, which decreases the amount of blood ejected from the heart per minute. Physical performance in endurance activities will degrade and incidence of heat illness will occur as dehydration increases. The inability of the human body to consume and retain fluids at the same rate is a great limitation, particularly during prolonged heat exposure. This can be explained by the fact that water consumption causes a dilution of the blood. This, in turn, removes the salt-dependent portion of the thirst drive, and urinary water is produced. When consuming carbohydrate-electrolyte beverages containing Na, the salt-dependent thirst drive will be prolonged for a greater period of time. Urinary water production will be minimal, allowing for a greater hydration and body water storage. The rate of decline and replenishment of plasma volume during and after SUSOPS is superior to water when Na is included in the beverage.

specific circumstances in which the solution is used. The ideal solution would be one that could be diluted in different ways to meet the relative specific needs of the personnel.

The goal of such a solution should be to maximize fluid intake, to replace electrolyte losses, and to provide a carbohydrate source for energy and rapid replenishment of muscle and liver glycogen stores during and following physical activity. The use of electrolyte-carbohydrate-containing beverages may be applicable to a number of circumstances in the military, such as:

1. Maintaining adequate fluid intake prior to military operations during which voluntary dehydration is probable.
2. Providing fluid, electrolyte, and carbohydrate replacement during physical work in a variety of environmental conditions, including high temperatures, humidity, or wearing of chemical protective clothing. In such situations, sweat rates are high and account for a large fluid and electrolyte loss.
3. Providing rapid rehydration following heavy and prolonged physical work, thereby facilitating recovery from heat injury.
4. Providing carbohydrates during and following physical activity to maintain plasma glucose concentrations, furnishing carbohydrates for energy, and enhancing replenishment of glycogen stores during postoperational recovery.
5. Replacing gastrointestinal losses due to vomiting or diarrheal diseases.

Below are the Committee's recommendations developed following this workshop (Nesheim, 1990):

1. The solution should provide approximately 20 to 30 meq/l of Na, 2 to 5 meq/l K, and chloride as the only anion.
2. The carbohydrate content should be provided as glucose, sucrose, malto-dextrin, or other complex carbohydrate in a concentration of 5% to 10%.

3. Two to three hours per day of physical activity in heat will increase the rate of heat acclimation.
4. New arrivals to hot environments have a greater need for salt in their diet until they are heat acclimated.
5. New arrivals to a hot environment are at greater risk for heat illness.
6. Heat acclimation does not reduce daily body water requirements.
7. Fluid hydration and food consumption schedules should be rigidly enforced.
8. Meals and fluid consumption should not be repeatedly delayed or missed.
9. The consumption of three MREs provides the necessary caloric balance and electrolytes (e.g., NaCl and K) while in hot environments.
10. Water supply is as critical to survival as any other resource in the field.
11. The intensity of physical activity, sweat volume, and environmental temperatures will dictate fluid consumption requirements.
12. Wearing a chemical defense suit increases body temperature and sweat rates. Fluid hydration requirements will be increased with prolonged suit usage.
13. Daily body weight loss is a sign of low fluid consumption.
14. For every pound of weight loss, it is recommended that two cups (16 ounces) of water be consumed, or preferably a carbohydrate-electrolyte solution.
15. Do not delay fluid consumption in the field.
16. Thirst is not a good indicator of body water requirements. When thirst appears, a loss of 2% body weight (4 pounds loss for a 200-pound male) has occurred.

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