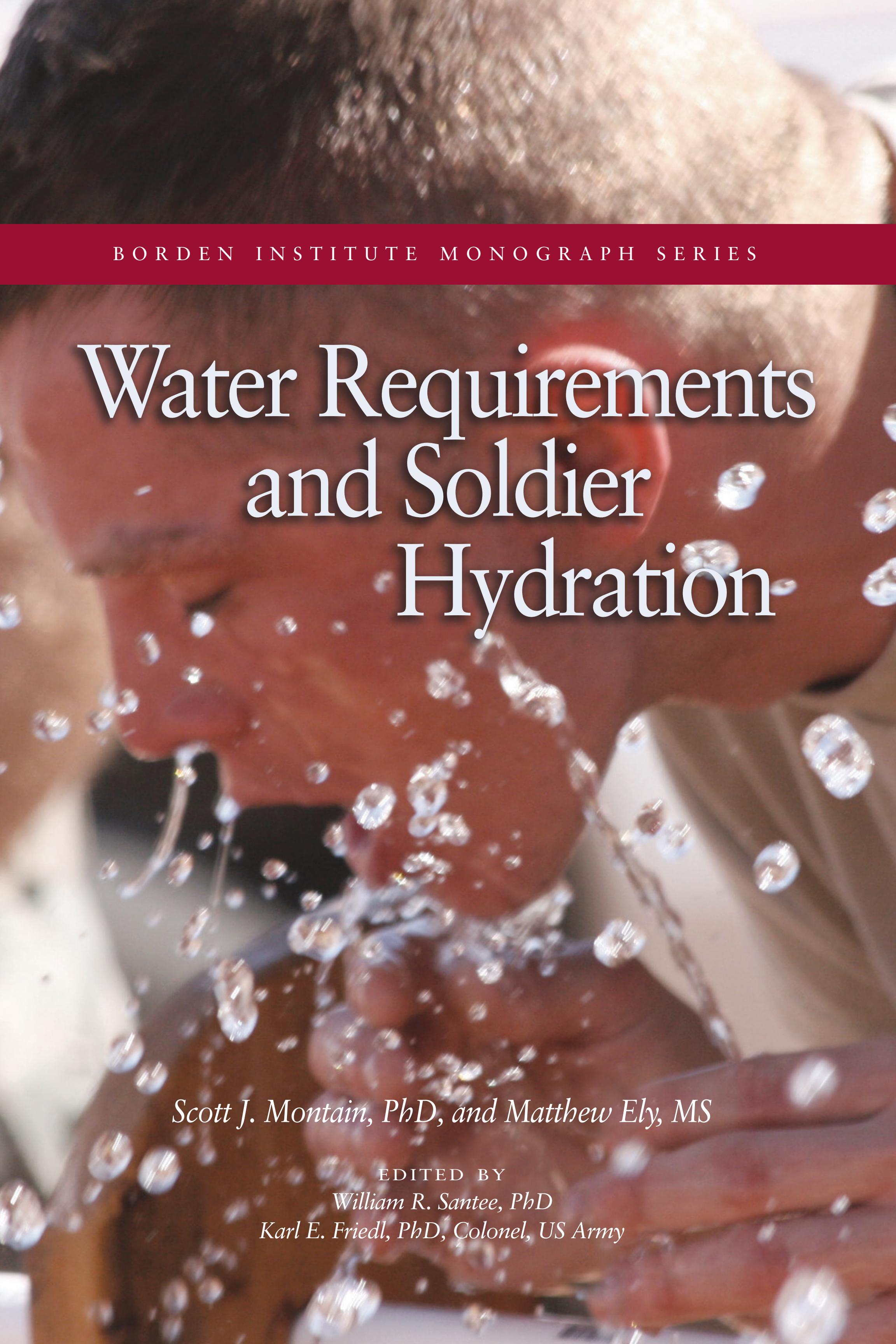

BORDEN INSTITUTE MONOGRAPH SERIES

Water Requirements and Soldier Hydration

Scott J. Montain, PhD, and Matthew Ely, MS

EDITED BY

William R. Santee, PhD

Karl E. Friedl, PhD, Colonel, US Army

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It has long been known that individuals can survive much longer without food than they can without water. Only in recent decades has science been able to quantify the factors that influence the body's ability to maintain optimal water levels and the physiological consequences of water imbalance. This monograph presents information to assist the caregiver—whether physician, medic, unit leader, or fellow soldier—in understanding the influence of environment, physical activity, body size and gender, and load carriage in maintaining water balance.

Borden Institute
Walter Reed Army Medical Center
US Army Medical Department Center & School

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Cover photo: Courtesy of US Army

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Foreword

Water is the largest chemical component of the human body, typically accounting for about 60% of body weight. Animals were able to leave the primordial ocean by developing what Claude Bernard (the grandfather of physiology) called the *milieu intérieur*, an internal saline environment to bathe our cells. This special capability allows us to moderate our internal environment through homeostatic mechanisms and survive in the face of a wide variety of external stressors. Enhancing this capability to endure extreme environments is of particular importance to the Army, wherein any advantage to better exploit hostile conditions may be critical to mission success. Thus, water logistical planning and optimization of soldier osmoregulation are, in essence, tactical weapons. Relatively small derangements in hydration status can significantly impair mission performance. More severe dehydration can produce heat injury casualties. Therefore, it should not be surprising that the Army has been the leader in physiology research regarding water balance. Given the importance of ensuring adequate hydration during military operations, it is actually astounding that there remain large gaps in our knowledge of this critical area. This monograph summarizes the state of our knowledge.

Scott Montain and Matthew Ely have focused on the very pragmatic aspects of various standards and predictions that currently drive military planning factors for water, key operational factors that affect these predictions, and approaches to maintaining appropriate levels of water intake. This monograh reduces a great deal of physiological research to practical guidance that is of great importance to the military. However, hidden behind clear, concise guidance is more specific scientific literature that is the basis for a deeper understanding of the mechanisms governing thirst, sweating, and other (nonsweating) water losses through the skin and respiratory tract, renal regulation, and fluid shifts between compartments affected by exercise, nutrition, and other key factors. Some of these topics are covered in other chapters that will be part of the Borden Institute's volume on *Military Quantitative Physiology*. Other aspects of this area may be found in clinical textbooks on water and electrolyte management of patients.

So, what more is there to be learned about this subject? Consider camels and other mammals that have adapted to extreme desert conditions. Although we cannot mimic animals that have adapted to the desert over millennia, we can learn from them. Camels can lose water totaling 30% of their body weight and still maintain plasma volume. They can also completely restore this water deficit in a single bout of drinking. Humans can tolerate less than half of this magnitude of water loss and, more significantly, reflect the deficit disproportionately in plasma volume losses. This compromise is enhanced with dehydration, especially during work in hot environments when peripheral vasodilation is maximally activated for cooling. We do not replace our losses by the amount of the deficit and must rely on meals to encourage additional rehydration (thus, part of the reason for a need to ensure food consumption in the field in addition to water consumption).

The differences in tolerance to dehydration between humans and camels are remarkable, and there is still much to be learned from other desert adaptations, as well as from the behavioral adaptations of human desert dwellers that might allow elite forces to enhance operations in dry environments. T. E. Lawrence (also known as "Lawrence of Arabia") thought that he and his Bedouin fighters could superhydrate in advance of a challenging event in the desert by forcibly overconsuming water; more recent experiments tried to do this with glycerol-enhanced water loading, and neither of these methods was effective.

US Army doctrine earlier in the past century held that soldiers could adapt to dehydration by training with restricted water consumption. A study with Austrian Special Forces tested this premise and determined that soldiers were seriously and consistently incapacitated with 5 days of restricted water consumption of 1 liter per day during commando training exercises, thus reinforcing earlier research findings.

It may be significant that water doctrine was heavily enforced during the first Gulf War and that there were relatively few heat casualties, or maybe we were simply lucky. However, we did everything that we knew to do to sustain hydration, even to the point of public discussion about the quality of bottled water being provided to troops in the field. In fact, the US Army was so effective in delivering this message of hydration to prevent heat injury that a series of cases of hyponatremia occurred in training units, and new upper limits to the hydration guidance had to be developed. Despite the great efforts by the US Army to reduce environmental injuries, heatstroke cases have not been eliminated from military training and seem to fluctuate with cycles of training cadre and heightened awareness caused by new tragedies.

Technologies exist today to create a minimally invasive hydration monitor that queries the interstitial environment and provides a real-time assessment of hydration status and could alert soldiers, medics, or commanders to a timely intervention. The technologies also exist to create a "Dune suit" (from the Frank Herbert science fiction series) that would collect, purify, and recycle all water leaving the body via cutaneous, respiratory, and urinary routes. Neither of these materiel solutions has been produced. With other modern methods (and a commitment of resources to this effort), many yet unanswered questions about fluid distribution between body compartments, especially in the environments and conditions to which soldiers may be exposed, and the relationship to physical and mental performance, could be addressed. Many other questions, such as apparent sex differences in water turnover rates, need to be further elucidated. Strategies to produce the "human camel" have yet to be proposed, but should not be far behind with the current advances in genomics, proteomics, and genetic engineering.

It is generally understood that there are enduring military needs for research and development in certain fundamental lanes wherein new military options should be continuously evolving with new emerging technologies and understanding. Osmoregulation and water balance are enduring requirements. Much of today's knowledge is founded on the extensive and practical research studies of physiologists mobilized from the Harvard Fatigue Laboratory in World War II, conducted at the Fort Knox Armored Medical Research Laboratory and other Army facilities, by E. F. Adolf and D. B. Dill in their famous desert studies, and by others who followed them, as described in this monograph. Today, the research capability in hydration research resides almost exclusively at the US Army Research Institute of Environmental Medicine (USARIEM) with Dr. Montain and his colleagues. The computational models of water requirements produced in the 1970s and 1980s by USARIEM are cited as national standards by many other federal agencies and standards-creating bodies. The work is essential to the US Army, but the research also benefits workers in industry, athletes, emergency responders, government agencies (eg, NASA [National Aeronautics and Space Administration], OSHA [Occupational Safety and Health Administration], USDA [US Department of Agriculture]), and many others. The National Institutes of Health relies on the US Army for medical research on performance optimization in healthy men and women.

Water and hydration standards are just as relevant today as they were in World War II. We still have deaths in training from inadequate fluid consumption, and, in rare cases, even from excessive hydration and hyponatremia. Today, military operations and humanitarian aid missions frequently take place where the local water resources are lacking. Water is a major logistical burden in Iraq and Afghanistan, putting soldier lives at risk in every water supply convoy and calling for the greatest possible precision in water planning tables. The soldier load on patrol in remote regions is also critical; and water is a significant portion of this load. The availability of potable water throughout the world is becoming an increasing problem that may even drive some future international conflicts. Understanding the impact of water turnover rates and the effects of dehydration will become even more important. Dr. Montain's monograph is a must read for every preventive medicine officer and military medical consultants, advisors, and surgeons assigned to operational units.

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Introduction

The provision of sufficient potable water to sustain soldier hydration is a prerequisite for successful deployment. Adolph et al[1] and Eichna et al[2] documented that dehydration can degrade soldier morale, as well as the desire to work (Figure 1). Body water deficits as little as 2% body weight can impair physical performance.[3] Water deficits of 5% to 7% of initial body weight are associated with dyspnea, headache, dizziness, and apathy.[1] An extreme example of the threat dehydration poses to troops is shown by the deaths of many Egyptian soldiers who were cut off from needed supplies and who suffered water deficits and heat illness during the 1967 Six-Day War.

During military operations, an individual soldier's daily water requirements to sustain hydration can range from 2 L/d to an excess of 12 L/d, depending on weather conditions, workload, and physical size. Although 2 L/d is relatively easily achieved both in garrison and during deployment, 12 L/d will require concerted effort and coordination by military logistic support personnel and field commanders to ensure that adequate fluid is available (Figure 2). It is the responsibility of medical personnel to educate unit leaders about the importance of hydration and the necessary measures to optimize fluid intake and retention. This monograph discusses the effect of harsh environments on fluid requirements and presents methods to sustain water balance during deployment to environmental extremes.

Figure 1. *E. F. Adolph stands alongside a military jeep in the desert in 1943. Adolph and colleagues were in California conducting experiments for the military on the adaptability of man to a desert environment.*
Photograph: Courtesy of the University of Rochester archives.

FIGURE 2. *World War II soldier using steel helmet to hold water and to bathe. Earlier beliefs that water restriction would improve human tolerance to dehydration were not borne out by the careful studies of Adolph and others in the 1940s.*
Photograph: Courtesy of the National Archives, photo no. 208-AA-4NN-24.

Water-Electrolyte Balance

The human body is composed mainly of water. It accounts for 50% to 70% of body weight for an adult man and 40% to 60% of body weight for an adult woman.[4] Water is primarily distributed in nonfat tissue and accounts for 72% to 73% of lean body mass. The large, between-individual variation in total body water relative to body weight is primarily a function of body fat (ie, adipose tissue is a major contributor to an increase in body weight without a corresponding increase in body water). The typical male soldier has 47 L of body water, whereas the typical female soldier has 33 L of body water.

On a daily basis, body water is relatively stable, provided adequate fluid is available to offset water lost by sweating, respiration, and urination. Water balance is regulated daily to within ~0.66% of body weight in healthy, active populations.[5] This tight balance is achieved through fluid ingestion associated with eating and drinking, coupled with metabolic water production and physiological systems that regulate fluid loss (eg, renal, cardiovascular, and hormonal systems). Table 1 illustrates the sources of water losses and production,[3] as well as the lower estimates of the turnover from these sources. It should be recognized, however, that the values presented can vary markedly. Respiratory water losses, for example, can range from 0.2 L/d in humid air to more than 1.5 L/d during exercise at extremely high altitudes. Cutaneous sweating can increase from 0.5 L/d to more than 10 L/d with prolonged exercise in hot environments. Similarly, diarrhea can greatly increase fecal water losses.

Table 1. *Estimates of Minimal Daily Water Losses and Production**

Source	Loss (mL/d)	Production (mL/d)
Respiratory loss	–250 to –350	
Urinary loss	–500 to –1,000	
Fecal loss	–100 to –200	
Insensible loss	–450 to –1,900	
Metabolic production	—	+250 to +350
Total	–1,300 to –3,450	+250 to +350
Net loss	–1,050 to –3,100	

*Assuming conditions in which there is minimal water loss from sweating.
Adapted from: Food and Nutrition Board, Institute of Medicine. ***Dietary Reference Intakes for Water, Potassium, Sodium, Chloride, and Sulfate***. Washington, DC: National Academy Press; 2005.

For more information, the Institute of Medicine has published dietary reference intakes for water (Table 2) and electrolytes.[3]

Body water levels can vary markedly throughout a day. It is not uncommon for athletes or soldiers to lose 2% to 5% of body weight during physical activity,[6–9] and make up the short-term water deficit by drinking during rest periods and at meals.[1,10,11] This pattern of voluntary dehydration during physical activity—followed by drinking the majority of daily water intake at mealtime—results in marked fluctuations that are not apparent during day-to-day examinations of total body water measurements.

Body water is distributed in three principal fluid compartments: (1) intracellular, (2) interstitial, and (3) intravascular. Movement within the intracellular and extracellular compartments is determined largely by osmotic forces;[12] therefore, maintenance of total body water is dependent on total solute and distribution of that solute. Dehydration mediated by sweating influences each fluid space as a consequence of free fluid exchange. Nose and colleagues[13] determined the distribution of body water loss among the fluid spaces, as well as among different body organs in rats when they were dehydrated by 10% initial body weight with exercise-heat stress. The water deficit was apportioned between the intracellular (41%) and extracellular (59%) spaces, and also among the organs as follows:

- 40% from muscle,
- 30% from skin,
- 14% from viscera, and
- 14% from bone.

TABLE 2. *Criteria and Dietary Reference Intake Values* for Total Water†*

		Adequate Intake‡ (L/d)					
		Male			Female		
Life-Stage Group	Criterion	From Foods	From Beverages	*Total* Water	From Foods	From Beverages	*Total* Water
0–6 mos	Average consumption of water from human milk	0.0	0.7	**0.7**	0.0	0.7	**0.7**
7–12 mos	Average consumption of water from human milk and complementary foods	0.2	0.6	**0.8**	0.2	0.6	**0.8**
1 yr	Median total water intake from NHANES III	0.4	0.9	**1.3**	0.4	0.9	**1.3**
4–8 yrs	Median total water intake from NHANES III	0.5	1.2	**1.7**	0.5	1.2	**1.7**
9–13 yrs	Median total water intake from NHANES III	0.6	1.8	**2.4**	0.5	1.6	**2.1**
14–18 yrs	Median total water intake from NHANES III	0.7	2.6	**3.3**	0.5	1.8	**2.3**
>19 yrs	Median total water intake from NHANES III	0.7	3.0	**3.7**	0.5	2.2	**2.7**
Pregnancy 14–50 yrs	Same as median intake for nonpregnant women from NHANES III				0.7	2.3	**3.0**
Lactation 14–50 yrs	Same as median intake for nonlactating women from NHANES III				0.7	3.1	**3.8**

NHANES III: Third National Health and Nutrition Examination Survey (1988–1994)

*No Tolerable Upper Intake Level is established; however, maximal capacity to excrete excess water in individuals with normal kidney function is 0.7 L/h.

†*Total* water represents drinking water, water in other beverages, and water (moisture) from food. (See Table S-1 in *Dietary Reference Intakes for Water, Potassium, Sodium, Chloride, and Sulfate* for the median percentage if *total* water intake from beverages [including drinking water] and from foods reported in the NHANES III.)

‡The observed average or experimentally determined intake by a defined population or subgroup that appears to sustain a defined nutritional status, such as growth rate, normal circulating nutrient values, or other functional indicators of health. Adequate intake is used if sufficient scientific evidence is not available to derive an Estimated Average Requirement.

Bold numbers = adequate intake is not equivalent to a Recommended Dietary Allowance. (Adequate intake is provided where no Recommended Dietary Allowance has been established.)

Adapted from: Food and Nutrition Board, Institute of Medicine. *Dietary Reference Intakes for Water, Potassium, Sodium, Chloride, and Sulfate*. Washington, DC: The National Academies Press; 2005.

Neither the brain nor liver lost significant water content. Thus, dehydration results in water redistribution largely between the intracellular and extracellular spaces of muscle and skin.

Sweat-induced dehydration decreases plasma volume and increases plasma osmotic pressure in proportion to the level of fluid loss. Plasma volume decreases because it provides the precursor fluid for sweat. Osmolality increases because sweat is ordinarily hypotonic relative to plasma.[14,15] Sodium and chloride are primarily responsible for elevated plasma osmolality.[15] It is the plasma hyperosmolality that mobilizes fluid from the intracellular space to the extracellular space and enables plasma volume defense when a person is dehydrated.

Thirst and Satiation

Several factors stimulate thirst and play a role in satiation. The most studied mechanism is in osmoreceptor cells, which are activated by intracellular dehydration. These cells—located in the preoptic/hypothalamic region of the brain—are sensitive to cell volume reductions induced by either extracellular hypertonicity or isoosmotic water loss (eg, hemorrhage, diuretic administration). Activation of these cells stimulates both thirst and arginine vasopressin (AVP) secretion. Stimulation of AVP secretion increases the desire to drink and facilitates water retention by increasing renal water reabsorption.

Changes in extracellular fluid volume also contribute to thirst and water balance. Evidence indicating that water volume is independent of osmotic stimuli comes from experiments that have manipulated blood volume or cardiac filling or both. Increased blood volume or central venous pressure (eg, head-out immersion) leads to diuresis, reduced thirst, and voluntary water intake.[16–18] In contrast, central venous pressure reductions from hemorrhage, diuretics, or lower body negative pressure decrease urine output and increase thirst and drinking.[16] Sensitivity of the response is much lower, however, than the osmotic thirst mechanism and seems to be more effective with intact kidneys,[19] thus suggesting that the renin-angiotensin system contributes to thirst response.

Animal experiments have demonstrated that angiotensin II can be a potent dipsogen.[20] Receptors for angiotensin II exist in the preoptic/hypothalamic regions of the brain. Intraventricular infusion of small quantities of angiotensin II stimulate thirst.[20] Pharmacological blockade of angiotensin I-type receptors and angiotensin II receptors reduces the thirst response accompanying food intake, hemorrhage, and water deficit.[21–23] Whether systemic angiotensin II plays a direct role in stimulating thirst in humans remains unclear. Current evidence suggests that blood-borne angiotensin II binds to receptors within the preoptic/hypothalamic regions, and the transduced signal is integrated with other inputs from systemic arterial blood pressure and volume receptors.[24]

Unpleasant oral sensations also play a role in stimulating voluntary fluid intake. Several studies have demonstrated that 24 hours of fluid abstinence produces a marked increase in the subjective ratings of thirst, mouth dryness, and unpleasant taste.[25] The reversal of these oral sensations is significantly correlated with subsequent water intake. Similarly, induction of graded levels of dehydration by food restriction, fluid restriction, and exercise-heat stress are accompanied by graded increases in the number and magnitude of unpleasant oral sensations.[26] Sensations showing a linear trend with dehydration level include the following:

- dry and irritated throat;
- chapped lips;
- feelings of weariness, dizziness, and appetite loss; and
- thinking of drinking.

To examine if these oral sensations contributed to drinking behavior, Phillips and colleagues[10] obtained blood samples and visual analog scale thirst measurements at hourly intervals and when volunteers drank water during a normal working day. They found that sensations of thirst, mouth dryness, unpleasant mouth taste, and the pleasure of drinking water increased before ad libitum intake, with no concomitant changes in blood tonicity or volume. These results provide evidence that, during free access to water, humans become thirsty and drink before body water deficits accrue, perhaps in response to subtle oropharyngeal cues.[10]

Physiological Consequences of Body Water Imbalance

Dehydration

Body water deficits can occur in all environments, either from inadequate water availability, insufficient voluntary intake to offset water losses in sweat and respiration, or excessive water loss from diuresis or diarrhea. Regardless of the specific process, water deficit or dehydration can reduce the ability of soldiers to perform mission-essential tasks in a timely and effective manner, thus increasing their likelihood of becoming medical casualties.

Symptoms

One of the earliest qualitative signs of dehydration is the development of thirst.[1] With approximately 2% body weight loss, vague discomfort develops, and the number of complaints increase. With additional water loss, soldiers can develop:

- flushed skin,
- heat oppression,
- weariness,
- sleepiness,
- impatience, and
- anorexia.

At 4% loss of body weight, soldiers display signs of apathy, and might complain of muscle fatigue and nausea. At water deficits of 6% body weight and greater, soldiers will likely display

- dizziness,
- headache,
- dyspnea,
- tingling in limbs, and
- very dry mouth.

They might present with indistinct speech and the inability to walk.

Thermoregulatory and Cardiovascular Effects

Body water deficits increase the thermal strain of exercise in temperate and hot environments. Individuals performing the same physical task when dehydrated have higher core temperatures than they would if they were normally hydrated, and the magnitude of the core temperature increase is proportional to the body water deficit. Studies examining the core temperature response to graded water deficits report that core temperature increases 0.15°C to 0.20°C for every 1% body weight lost.[1,27–29] This relationship is maintained independent of exercise intensity[30] and is not affected by changing the pattern of drinking.[1,31] The magnitude of core temperature increase is, however, less in temperate versus warmer environments. In cold environments, dehydration does not seem to increase the risk of hypothermia; limited data available suggest that body temperature falls similarly during whole-body cooling, depending on if an individual is normally hydrated or dehydrated.[32] Whether dehydrated persons are at increased risk of peripheral cold injury is controversial.[33–35]

Dehydration exerts its effects on thermoregulation by altering the ability to dissipate heat to the environment. Both skin blood flow and sweating responses are affected. Fortney and colleagues[36] reported that thermally induced dehydration increased the esophageal temperature threshold for cutaneous vasodilatation and attenuated the increase in cutaneous blood flow per unit increase in body temperature. Dehydration also reduces peak cutaneous vasodilatation in both humans[36] and nonhuman primates.[37,38] Montain and colleagues[39] found that thermally induced dehydration increased the esophageal temperature threshold for sweating and attenuated the increase in sweating per unit increase in body temperature. In addition, the magnitude of the sweating gain and sensitivity alterations increased as a function of body water loss, which is in agreement with the observation that temperature increases in proportion to the water deficit.

Singular and combined effects of hypertonicity and hypovolemia contribute to modulating thermoregulation when an individual is hypohydrated. Hypertonicity, per se, will increase the esophageal temperature threshold for sweating[36] and increase core temperature during exercise-heat stress.[36,40,41] Similarly, the production of an isotonic hypovolemia with diuretic administration adversely affects cutaneous vasodilatation[42] and sweating,[43] and increases core temperature during exercise-heat stress.

Afferent signals responsible for the thermoregulatory effects of dehydration come from several anatomical areas. Osmoreceptor cells located in the preoptic/hypothalamic area are activated when intracellular volume declines. These cells affect the firing of thermosensitive neurons in the thermoregulatory control center.[44,45] Cardiac mechanoreceptors or pulmonary baroreceptors, or both, also modulate the thermoregulatory response to exercise and heat stress because application of lower body negative pressure during heat stress augments heat storage independent of changes in blood volume or tonicity.[46,47] These observations are consistent with the neurophysiological findings that osmotic and blood pressure stimuli modulate the firing of thermosensitive neurons in the preoptic and anterior hypothalamus.[44]

The consequences of dehydration on the cardiovascular response to exercise have also been characterized. During submaximal exercise with little thermal strain, dehydration elicits an increase in heart rate and a reduction in stroke volume with little or no change in cardiac output relative to euhydrated levels.[48] During more vigorous exercise, the increase in heart rate does not fully compensate for reductions in stroke volume, and cardiac output is reduced.[49] In warm environments, the detrimental effects of dehydration are exacerbated. Experiments examining the effect of graded levels of water loss on the cardiovascular response to exercise report graded increases in heart rate[1,27,28,30] and stroke volume reductions,[28,30,48] with increasing water deficit. Cardiac output falls in a graded manner with water deficit[28,30] because the increase in heart rate is not sufficient to offset stroke volume reductions.

Effects on Physical Performance

Dehydration in excess of 2% normal body mass has negative effects on morale and willingness to work. Comments from investigators working with soldiers during World War II illustrate how devastating dehydration can be (Figure 3). Adolph et al[1] reported that, in dehydrated soldiers, "walking was mechanical, and a matter of will power" and that soldiers "threatened to quit unless given water." Eichna and colleagues[2] found that tasks became much more difficult, and "acclimatized subjects who had performed a given task easily, energetically, and cheerfully" were "reduced to apathetic, listless, plodding men straining to finish the same task." More recently, Strydom et al[50,51] reported that dehydrated men became lethargic and morose, and were aggressive and disobedient toward their superiors.

Dehydration in excess of 2% body mass compromises physical performance. Exercise endurance time is shorter during both submaximal and maximal exercise, and less work is accomplished per unit of time when dehydrated beyond 2% body mass (~1.5 L for a 70-kg soldier) in temperate and warmer environments. Detrimental effects of dehydration afflict large[52–56] and small muscle mass activities.[52,53,55,57–59] In contrast, dehydration has little effect on muscle strength, at least up to 5% loss of body weight.[6] Evidence also indicates that somewhat greater dehydration is necessary before endurance performance is affected in cool/cold climates.[60]

Dehydration also reduces heat tolerance. In a 1992 study,[61] scientists had subjects walk to voluntary exhaustion when either euhydrated or dehydrated (8% of total body water). The experiments were designed so that the combined environment (T_a = 49°C, relative humidity = 20%) and exercise intensity (47% maximal oxygen) would not allow thermal equilibrium; thus, heat exhaustion eventually occurred. Dehydration reduced tolerance time from 121 minutes to 55 minutes; but, more importantly, core temperatures at exhaustion were approximately 0.4°C lower when subjects were dehydrated. These findings suggest that dehydration not only impairs exercise performance, but also reduces tolerance to heat strain.

Hyperhydration

Because moderate levels of dehydration can be detrimental to soldier performance, it is important to consider whether overdrinking or taking substances to achieve hyperhydration or greater-than-normal body water would be beneficial for temperature regulation and exercise performance. Studies that directly expanded blood volume have usually reported decreased cardiovascular strain[62–64] during exercise, but disparate results on heat dissipation[63–65] and exercise-heat performance.[64–66] Other studies

Figure 3. (*Top*) *Man falls out of formation as other troops keep marching. He has been overcome by heat exhaustion and collapses.* (*Bottom*) *Two first-aid men helping the GI who has been overcome by heat exhaustion. They have loosened his clothes and are giving him a drink of water.* [*Original caption*]
Photographs: Courtesy of the National Archives, photo nos. SC-391634 (top) and SC-391635 (bottom).

examining the effect of overdrinking to produce a transient hyperhydration have found generally reduced heart rates during submaximal exercise, but disparate results regarding core temperature (reviewed in Sawka et al[6]). Studies observing lower core temperatures were often confounded by lower core temperatures before exercise. When this effect was controlled,[67] hyperhydration had no appreciable effect on thermoregulation during exercise.

Although many studies have attempted to induce hyperhydration by overdrinking water or water-electrolyte solutions, these approaches have produced only a transient expansion of body water. Greater fluid retention can be achieved with aqueous solutions containing small quantities of glycerol.[68–71] Although an early report suggested that glycerol hyperhydration enhanced heat dissipation during exercise-heat stress,[70] this finding has not been confirmed by subsequent investigations.[67,72] In addition, this finding has not improved endurance exercise performance[73] or exercise-heat tolerance.[74]

Water Intoxication or Hyponatremia

Drinking too much can make soldiers sick. A relatively rare but clinically important problem for military personnel is the development of hyponatremia consequent to overdrinking water during training. From 1989 to 1998, 10 to 20 US Army soldiers were hospitalized yearly with symptomatic hyponatremia,[75] and hyponatremia was the cause of at least one soldier's death.[76] The majority of cases occurred during warm weather training and afflicted soldiers in a basic training environment.[77] Symptomatic hyponatremia occurs most often in soldiers and athletes who perform prolonged physical activities that produce (or are believed will produce) relatively high sweat rates and are sustained longer than 5 hours.[78,79] The majority of cases have occurred during physical activities lasting longer than 8 hours.

Symptoms and Etiology

Symptoms of hyponatremia generally occur at serum sodium concentrations <125 mEq/L and include the following:

- mental confusion,
- disorientation,
- malaise,
- weakness,

- nausea,
- transient neurological deficits,
- seizures, and
- coma.

The absence of hyperthermia excludes the diagnosis of heatstroke.[80] Symptoms are most severe when sodium is diluted rapidly (ie, over hours rather than days). This condition is a consequence of the combined loss of sodium in sweat and failure to excrete the large amounts of hypotonic fluid that have been ingested. The net result is a dilution of body sodium. Retention of excess water is not from abnormal renal function, but rather extrarenal factors that suppress renal water excretion[81] and/or inappropriate AVP levels.[82] For example, Poortmans[83] demonstrated that physical exercise reduces urine flow rate even in overly hydrated men. In the experiment, overdrinking before performing exhaustive exercise produced urine flow rates of 12 mL/min. Despite continuing to drink 200 mL of water every 20 minutes during vigorous exercise, the urine flow rate fell to 2 to 3 mL/min. This occurred likely because vigorous exercise reduces the glomerular filtration rate.[81] In addition, various factors enhancing tubular sodium reabsorption causes isoosmotic reabsorption of water to increase. As a consequence of decreased glomerular filtration rate and increased water reabsorption, urine volume will decrease.

Prevention

Episodes of hyponatremia have, in most cases, been associated with excessive water intake relative to sweat losses.[78,79] Soldiers—especially noncommissioned officers, training cadre, and junior officers—need to be educated that overdrinking is not beneficial (ie, it does not enhance thermoregulation or exercise capacity). The key to prevention is to ensure that volunteers drink only in amounts less than or equal to their sweating rate. Dehydration less than 2% body mass does not compromise performance; therefore, full fluid replacement is not essential during work. Because sodium is the major constituent of sweat (20–60 mEq/L), prolonged sweating can produce substantial sodium deficits. To prevent sodium depletion, soldiers should have access to regular meals. In work environments that produce prolonged, persistent sweating, salting food to taste is generally sufficient to prevent salt depletion. However, when conditions do not permit eating meals, adding small quantities of salt (~0.05% NaCl solution) to the water supply, including salt-containing beverages (eg, commercial sports drinks), or using commercially available salt tablets are viable options to replace salt losses.

Factors Influencing Daily Water Requirements

Several factors influence a soldier's daily water requirements. This section summarizes the effect of environment, physical activity, body size, gender, and load carriage on daily water loss. However, these factors rarely occur independently, and it is their interaction that determines a soldier's daily water needs.

Environment

The environment dictates the avenues of heat loss available. In cool and temperate environments, a substantial quantity of heat can be dissipated via radiation and convection. During moderate physical activity in temperate environments, approximately 50% of the heat produced can be dissipated via nonsweating means. In cold environments, almost 75% of the heat produced can be dissipated by nonsweating means. In contrast, in air temperatures 35°C and higher, virtually all heat produced must be dissipated by sweat evaporation. The greater demand on sweating in hot environments can substantially increase a soldier's daily fluid requirements.

Physical Activity

A soldier's daily water requirements increase as a function of the total calories expended per day (Figure 4). This occurs because sweat losses are dependent on exercise intensity and duration of effort. For example, in temperate conditions, moderate-intensity military tasks (~425 watts; 6.1 kcal/min) will elicit sweating rates of approximately 0.3 L/h, whereas hard work (~600 watts, 8.6 kcal/min) will elicit sweating rates approximately 0.7 L/h. The duration of physical activity also has a significant effect on water need. Although moderate-intensity work in temperate conditions might not elicit high rates of sweating (~0.3 L/h) when extended over an 8-hour period, a soldier's daily fluid requirements increase an additional 2.4 L/d.

Body Size and Gender

Because men typically are heavier and sweat more profusely than women during physical activity, they will likely have larger daily fluid requirements. This occurs because the caloric cost of ambulatory activity increases as a function of body mass; therefore, larger persons expend more energy walking 1 mile than do smaller persons. Thus, men will expend more energy during marching, and thus produce more heat, than women. In addition, studies show that men have fewer sweat glands per unit area compared with women, but they produce more sweat per gland.[84] As such, men will generally require larger quantities of fluid than women.

For ambulatory activities, rates of sweating are nearly proportional to the two-thirds power of body weight. Therefore, a 91-kg man will sweat approximately 30% more than his 59-kg companion walking at the same speed.[1]

Load Carriage

The energy cost of marching with an All-Purpose Lightweight Individual Carrying Equipment (ALICE) pack and load-bearing equipment (LBE) is much greater than marching without it. Soldiers wearing a 31-kg ALICE pack and LBE expend 29% more energy to march 3.5 mph. Soldiers carrying a 49-kg ALICE pack–LBE ensemble expend 63% more energy to

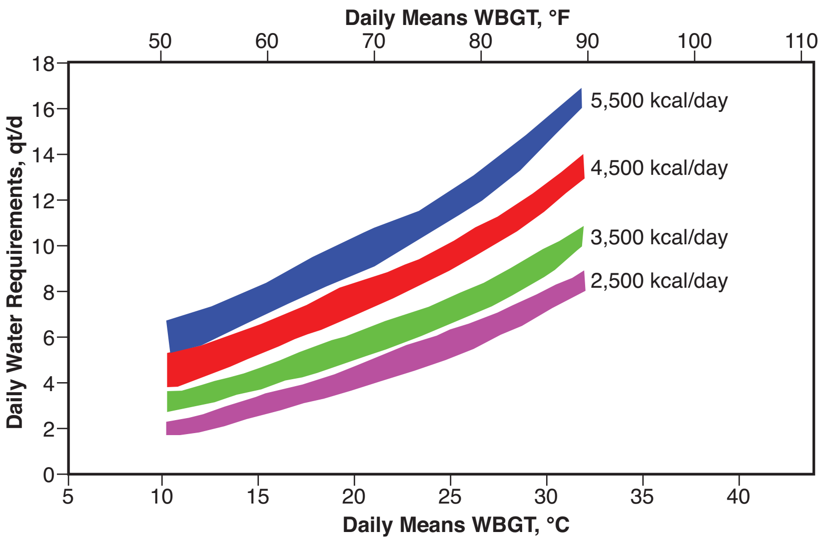

Figure 4. *Estimates of daily water requirements for range of environmental conditions and energy expenditures.*
WBGT: wet-bulb globe temperature
Data source: Sawka MN, Wenger CB, Montain SJ, et al. Heat Stress Control and Heat Casualty Management. *Washington, DC: Headquarters, US Department of the Army and Air Force; 2003: 13. TB MED 507/AFPAM 48-152.*

march at the same speeds without the packs.[85] In temperate environments, the added energy cost of carrying the 31- or 49-kg backpack ensemble would increase the expected sweating rate from approximately 0.3 L/h without the pack to 0.6 and 1.1 L/h for the two packs, respectively. An additional factor affecting sweating requirements is the loss of effective surface area for evaporation of sweat, because the pack blocks sweating evaporation from the back. Most likely, this would further increase sweating beyond the sweating rate calculated from the added energy cost alone. Adolph et al[1] reported that sweating rate increased 7 g/h/kg of backpack weight for packs weighing 10 to 20 kg.

Impact of Hot Environments on Fluid Requirements

In temperate environments, the daily fluid requirements of soldiers typically range from 2 to 5 L/d, depending on the intensity and duration of physical activities. However, as air temperature rises, daily fluid requirements can increase substantially. In extremely hot conditions, water requirements for soldiers performing primarily sedentary activities can increase from approximately 2 to 3 L/d to 5 L/d. Water requirements for soldiers performing heavy work or long hours of moderate work (4,200–5,300 kcal/d) can increase from 4 to 6 L/d in temperate environments and from 8 to 10 L/d in extremely hot environments.

Relative humidity can increase water requirements independent of ambient temperature. Although relative humidity has little impact on sweating and water requirements in temperate environments, high humidity conditions increase water requirements as much as 2-fold in warmer environments.[2] When the humidity is high, the dramatic increase in sweating requirements underscores the tremendous water supply requirements posed when troops are deployed in tropical and desert climates.

Individuals exposed to hot environments generally drink insufficient fluids during physical activity to offset water lost from sweating.[2,86] Heat acclimatization shortens the time delay between when sweating begins and when drinking is initiated.[86] In addition, heat-acclimatized individuals drink more frequently and more closely match fluid intake with sweating rate; this results in less voluntary dehydration.[2,86] During light exercise, heat-acclimatized soldiers can and often will drink sufficient quantities to sustain hydration.[1] However, during moderate-to-heavy intensity exercise, drinking ad libitum generally replaces 50% to 70% of sweat losses,[1,2,87–89] and deficits need to be addressed during rest breaks.

Clothing can have a significant effect on daily water requirements. Typically, clothing adds insulation and hinders vapor permeability, thus increasing the sweating rate (compared with wearing shorts and a T-shirt). The addition of backpacks and body armor increases the energy cost of locomotion and reduces the surface area available for heat transfer, thereby further increasing dependence on sweating. However, there are conditions in which clothing can actually aid in reducing water requirements. For example, in hot, arid environments, fully clothed soldiers wearing light, breathable clothing actually sweat less than minimally clothed men.[1] During desert walks in the full sun, light, breathable fabric that reflects solar radiation can reduce sweating as much as 20%.[1,90]

Effect of Hot Environments on Thirst and Voluntary Dehydration

Thermal stresses associated with hot environments are a positive stimulus for thirst and voluntary intake.[91] It is not uncommon, however, for persons working in the desert to accrue water deficits. As discussed previously, the objective of drinking is to prevent water deficits from exceeding approximately 2% of normal body mass (eg, ~1.5 L for a 70-kg soldier). This level of water deficit is associated with the onset of reduced performance. Any imbalance between sweating rate and voluntary intake will likely be more prevalent and of greater magnitude in persons unacclimatized to working in the heat. Greenleaf et al[92] revealed that volunteers matched water intake to sweating rate during repeated bouts of exercise-heat exposure. They did this by drinking earlier, and the volunteers drank more frequently during the 2-hour exercise-heat exposure period. The average volume consumed per drink did not change.

Effect of Hot Environments on Water Delivery

In tropical regions, water sources are often abundant (eg, rivers, streams, lakes, ponds, wells, and local water systems). However, because of dense vegetation, poor ground transportation (via truck) can impair water distribution and increase reliance on aerial resupply. In desert regions, water sources are limited and widely dispersed. Although water needs are greatest in these hot environments, surface fresh water is almost non-existent, and available subsurface water can vary from region to region. Lack of available water in desert environments increases water storage and distribution requirements.

Hot Weather Water Requirements

In hot, climatic extremes, daily water requirements for soldiers can range from 5 to 12 L/d. The *Water Consumption Planning Factors* study report (also known as the *Potable Water Planning Guide*), published by the US Army Combined Arms Support Command,[93] recommends that each soldier be provided with 11.4 L of water per day (ie, intake for each soldier should *be no more than* 11.4 L of water per day[93a]). Therefore, in an established battlefield situation in which water supply is achieved, sufficient water should be available to sustain the water balance of each individual soldier.

Effect of Cold Weather Operations on Water Requirements

A number of factors can increase fluid requirements during cold weather operations. One factor is the development of cold-induced diuresis. This phenomenon, first described more than 200 years ago,[94] occurs when people become chilled during either cold water or cold air exposure. It is an osmotic diuresis and can increase urine water losses 2-fold above basal conditions.[95,96] Although the precise mechanism is not known, generally it occurs as a consequence of increased central vascular pressure caused by peripheral vasoconstriction. Fortunately, diuresis seems to be self-limiting, because the rate of urine production declines with the development of dehydration.

A second factor is increased respiratory water loss from breathing cold, dry air. The magnitude of water loss is dependent on both the ventilatory volume and water vapor in ambient air.[97,98] Because cold environments increase the water vapor pressure gradient between the lungs and the atmosphere, more water is lost through respiration in cold environments than in warm environments. The effect of cold temperatures on respiratory water loss, however, does not greatly increase daily fluid requirements. Soldiers performing 12 hours of easy-to-moderate exercise, followed by 4 hours of hard exercise in very cold weather, would accrue only a 0.3 L greater daily fluid requirement than if they performed the same activities in a more temperate environment.

A third factor is that wearing bulky, cold weather clothing could contribute to water loss. Military physical training activities can generate substantial metabolic heat that must be dissipated to prevent excessive elevations in body temperature. If clothing insulation is too thick for the activity level, then substantial sweating can occur. For example, during rest and light work, persons wearing protective clothing from the US Army Extended Cold Weather Clothing System are thermally comfortable and are able to dissipate much of their body heat through nonsweating means (Exhibit 1). However, during more vigorous activities, sweating rates can achieve levels in excess of 1 L/h. To minimize these unnecessary sweat losses, soldiers should be trained to use layering and open ventilation options in their clothing level to minimize sweat production during cold weather training.

A fourth factor that can affect water requirements is the added metabolic cost of movement in cold terrain. The addition of bulky clothing reduces mechanical efficiency and can increase the energy cost of a specific activity an additional 10% to 20%.[99,100] The metabolic cost of movement in soft snow can be 2.5 to 4.1 times greater than performing the same activity on a blacktop surface.

Exhibit 1. *Generation III Extended Cold Weather Clothing System*

The Generation III Extended Cold Weather Clothing System consists of protective clothing developed by the US Army Natick Research, Development, and Engineering Center (Natick, Mass) to be functional in cold weather climates. This adjustable, layered insulation system is comprised of the following 12 components:

1. Lightweight undershirt
2. Lightweight underwear
3. Midweight shirt
4. Midweight underwear
5. Fleece cold weather jacket
6. Wind cold weather jacket
7. Soft shell jacket
8. Soft shell trousers
9. Extreme cold/wet weather jacket
10. Extreme cold/wet weather trousers
11. Extreme cold weather parka
12. Extreme cold weather trousers

Effect of Cold Weather on Thirst and Voluntary Dehydration

Investigations studying the effect of air temperatures on thirst and drinking behavior consistently report depressed voluntary drinking during cold weather activities.[96,101,102] Experiments in rats demonstrate that this species will voluntarily dehydrate during cold exposure, but will manifest striking thirst when returned to a warm room.[101] Similar observations have been made in humans.[102] One strategy that has improved voluntary intake is the provision of warm drinks rather than cool drinks during cold exposure.[103]

An additional cold weather problem occurs when individuals purposefully refrain from drinking to avoid having to urinate in the cold. This behavior typically occurs late in the day when soldiers try not to leave a warm tent or sleeping bag to urinate. If the mission scenario requires soldiers to rehydrate late in the day, their behavioral decision to refrain from drinking adequate quantities of fluid can lead to persistent dehydration during the next day's activities. One solution is to ensure that soldiers drink regularly during cold weather activities to avoid development of large water deficits. Snack breaks can also stimulate additional fluid intake. This particular strategy will help soldiers to avoid rehydration with large quantities of water before bedtime and reduce the likelihood of their having to get up and urinate during set sleep periods.

Effect of Cold Weather on Water Delivery

The most important factor regarding fluid intake in the cold is the logistical constraint of potable water delivery. In arctic regions, melting snow and ice will provide only enough water for emergency use by individuals and small units. Because of the extensive fuel requirements to melt snow and ice, this is an impractical water source for larger military units. However, the primary water source is unfrozen water underlying frozen rivers, lakes, and wells constructed by civilians and military personnel. The limited availability of water sources greatly increases distribution requirements, and storage and distribution elements must be augmented with specialized equipment to prevent or retard freezing of packaged water. If small units must rely on melting snow and ice for their water supply, the provision of adequate fuel is essential. In addition, the water must be adequately treated to ensure that it is potable.

Daily Water Requirements

Studies examining the voluntary intake of water by soldiers during field maneuvers report daily fluid intakes ranging from 2 to 4 L/d.[104–106] However, when energy expenditures are high, human water needs can range from 4 to 6 L/d. Accordingly, the *Water Consumption Planning Factors* study report recommends the daily provision of 7.6 L of drinking water per soldier for tactical theater and field training exercises in arctic environments.[93]

Effect of High-Altitude Operations on Water Requirements

Military operations in mountainous areas can affect short- and long-term water balance. For example, acute exposure to moderately high altitudes can often produce a self-limited reduction of body water resulting from reduced fluid intake and increased urine volume. Other factors can also affect voluntary water intake and daily water requirements, including the following: (*a*) symptoms of anorexia and hypodipsia; (*b*) increased respiratory water loss from breathing cold, dry air; and (*c*) cutaneous evaporative losses with physical activity.

Effect of High-Altitude Operations on Water Balance

Unacclimated soldiers exposed to moderate, high-altitude hypoxia (3,500–5,000 m) typically become somewhat dehydrated (losing approximately 1–2 L of water from the body, which equals 3% to 5% of total body water) during the first 1 to 3 days of exposure.[107,108] This water deficit results in decreased extracellular volume, decreased plasma volumes, and some loss of intracellular water. It occurs as a consequence of arterial chemoreceptor activation, which produces a self-limited natriuresis and diuresis, as well as suppressed thirst and reduced voluntary water intake.[107] Attempting to overdrink to prevent the water deficit is not recommended. Diuresis and natriuresis are considered beneficial adaptations because (*a*) increased plasma hemoglobin concentration increases arterial oxygen content and improves tissue oxygen delivery; and (*b*) people who develop natriuretic and diuretic responses have less severe symptoms and less incidence of acute mountain sickness.[107]

The relative dehydrated state produced by moderate-to-high altitude exposure can persist for several weeks. Studies examining water balance in humans exposed to elevations of 3,500 to 5,334 m report persistent reductions in total body water for up to 14 days.[108,109] Over time, however, blood volume increases as the volume of red blood cells increases at altitude, with plasma volume remaining reduced or returning to sea-level values.[107] Observation of increased plasma volume over time suggests some restoration of total body water with chronic hypoxic exposure.

Effect of Hypoxia on Thirst and Voluntary Water Intake

It is not uncommon for voluntary water intake to decrease approximately 1 L/d during the first 1 to 2 days of moderate, high-altitude exposure.[108] Suppressed voluntary water intake does not persist because, generally, daily water intake returns to predeployment levels within the first week of altitude exposure.

Other Factors Associated With High-Altitude Operations That Affect Water Requirements

There is a general belief that increased respiratory evaporative water losses accompanying mountainous operations significantly affect daily water requirements.[110] This may be true at high-altitude extremes; for example, Pugh[111] reported that climbers at 5,500 m had respiratory evaporative water losses of 2.9 g of water per 100 L (body temperature and pressure, saturated with water) of ventilation. However, at more modest elevations, the combined effects of colder air temperatures, lower humidity, and the higher ventilation rates relative to energy expenditure do not add appreciatively to daily water requirements. Over a broad range of energy expenditures (3,500–7,000 kcal/d), the estimated net respiratory water losses at 2,200 to 3,100 m are very similar to the estimated respiratory water losses at sea level.[110] Deployment to 4,300-m altitude will increase daily water requirements approximately 200 to 300 mL/d to compensate for added respiratory water loss.

Cutaneous sweat losses in soldiers working at low, moderate, or high altitudes depend on clothing insulation, ambient weather conditions, and absolute exercise intensity and duration. As in cold weather operations, clothing insulation at high altitudes must be matched to heat production to keep soldiers warm while preventing excessive heat storage and sweat losses. However, vigorous physical activity can produce relatively high rates of sweating and increase daily water requirements.

Effect of High-Altitude Operations on Water Delivery

Water supply in mountainous regions can come from lakes, streams, and local water supplies. Because mountain operations are often associated with cold weather, the same restraints can exist as those described for cold weather operations. An added factor is that high altitude increases the time required to purify water by boiling it. Therefore, if military units rely on melted snow to acquire water, this can have a significant effect on the time required to obtain potable water, as well as on the fuel requirements of small units.

Water Requirements

Military groups operating in high-altitude environments have generally sustained hydration by drinking 4 to 5 L/d less when engaged in heavy work than when performing primarily sedentary activities.[104,112] The *Water Consumption Planning Factors* study report recommends the provision of 5.6 to 7.6 L/d of drinking water per soldier.[93] Therefore, if supply lines are maintained as planned, the water supply should be sufficient to sustain hydration during military maneuvers.

Effect of Water Immersion on Water Requirements

Water immersion increases central venous pressure and produces a transient diuresis and natriuresis. The magnitude is dependent on water depth, temperature of the water, and the initial state of hydration.[113] The quantity of water lost, however, is not sufficient to greatly increase daily water requirements. However, because immersion blunts the thirst response,[16–18] it may also affect voluntary fluid intake and the ability to sustain hydration during prolonged operations in water environments. Whether prolonged partial immersion would sufficiently affect drinking behavior and the ability to sustain hydration have not been studied.

Barriers to Rehydration

Water Availability

Lack of potable water is probably the greatest barrier to sustaining hydration. If water is not available, rehydration cannot take place and soldiers will suffer. Just having potable water, however, is not sufficient. Water must be made available to the troops. Soldiers at work are more likely to refrain from drinking water if they have to travel some distance to obtain it. This is especially true in desert and arctic conditions, because both weather extremes diminish the desire to do additional work.

The collapsible bladder with drink-tube hydration systems provides a practical example of how availability increases voluntary fluid replacement. With these systems, the soldier can drink on the go in a near hands-free manner (Figure 5). When carrying a traditional 0.9-L rigid plastic canteen, the soldier cannot easily access the canteen on the go—particularly when carrying an approach load—and this increases the need to take rest breaks to drink. Although historically the collapsible-bladder hydration systems suffered from poor durability and were difficult to keep clean, advances in the manufacturing process have lessened these deficiencies.

Figure 5. *Hands-free drinking. Competitor Spc. Heyz Seeker gets a drink from a hydration device during the Urban Warfare Orienteering Course event of the Department of the Army Best Warrior competition at Fort Lee, Va.*
Photograph: Courtesy of T. Anthony Bell, Fort Lee Public Affairs Office.

Palatability of Water

If water has an unpleasant taste or odor, voluntary intake will be reduced. Efforts should be made to make water as palatable as possible. Factors that affect palatability include odor, taste, temperature, color, and turbidity of the fluid. The odors and tastes found in water are most commonly caused by algae, decomposed organic matter, and dissolved gases. Chlorination and iodination both add taste to water and can decrease palatability. Water color is derived from colored substances (eg, vegetative matter that is dissolved from roots, leaves, and humus) or from inorganic compounds (eg, iron and manganese salts). Turbidity is caused by suspended clay, silt, organic and inorganic matter, and plankton and other microorganisms. Warm water tastes flat and augments any odors and flavors in it. Water treatment and disinfection remove much of the particulate matter and reduce water color. Cooling water further suppresses odors and tastes, and makes water more palatable.

During the Persian Gulf War (1990–1991), the US military introduced bottled water to combat nonpalatable water. Although bottled water is expensive to buy and deliver to the troops, particularly in warm weather conditions, it avoids the taste issues associated with mass-produced water containing residual chlorine. Flavor additives can mask the unpalatable taste of chlorine, but they should be added to the water just prior to consumption because these additives can completely destroy the effectiveness of the chlorine.

Gastric Emptying

A potential barrier to sustaining hydration is gastric emptying and intestinal absorption. Evidence to date, suggests that, under most conditions faced by the fighting soldier, neither gastric emptying nor intestinal absorption should hinder the ability to sustain hydration during deployment. The stomach and small intestine function extremely well under conditions of exercise and environmental stress.[114] Furthermore, neither gastric emptying nor intestinal absorption are delayed or impaired by exercise intensities ranging up to 70% maximum oxygen uptake, even during prolonged, sustained physical activity.[114,115] It should be recognized, however, that there is a great deal of individual variability in rates of gastric emptying and intestinal absorption. Therefore, some soldiers may be less tolerant of drinking large volumes of fluid, and there are other soldiers who are so tolerant that they can actually drink fast enough to make themselves sick (see section on Water Intoxication or Hyponatremia). Scheduled rest breaks and adequate mealtimes should be included to provide time to rehydrate.

Lost Solutes

Complete restoration of a fluid volume deficit cannot be achieved without electrolyte replacement (primarily sodium) in food or beverages.[89] Electrolytes, primarily sodium chloride and, to a lesser extent, potassium, are lost through sweat during physical activity. The concentration of sodium in sweat averages approximately 30 to 50 mEq/L, but can vary, depending on an individual's state of heat acclimatization, diet, and hydration.[89] Furthermore, the amount and composition can also vary, contingent on exercise intensity and environmental conditions. Potassium concentration in sweat is approximately 4 to 5 mEq/L. In temperate conditions, sodium chloride concentration in sweat can range from 2 to 13 g/d, averaging approximately 6 g/d for the active soldier. Potassium losses will range from 0.1 to 0.9 g/d, averaging approximately 0.5 g/d for the active soldier. In hot environments, sodium chloride and potassium losses can exceed 17 and 1.9 g/d, respectively. Considering that three Meals, Ready-to-Eat contain 12.6 g of sodium chloride and 2.7 g of potassium, and that typically only two Meals, Ready-to-Eat are provided during field operations, there are many situations in which supplemental salt may be required to offset the sodium chloride lost in sweat. Typically, this deficit can be managed by salting food to taste. Figure 6 provides estimates of expected daily sodium losses consequent to working in different environments.

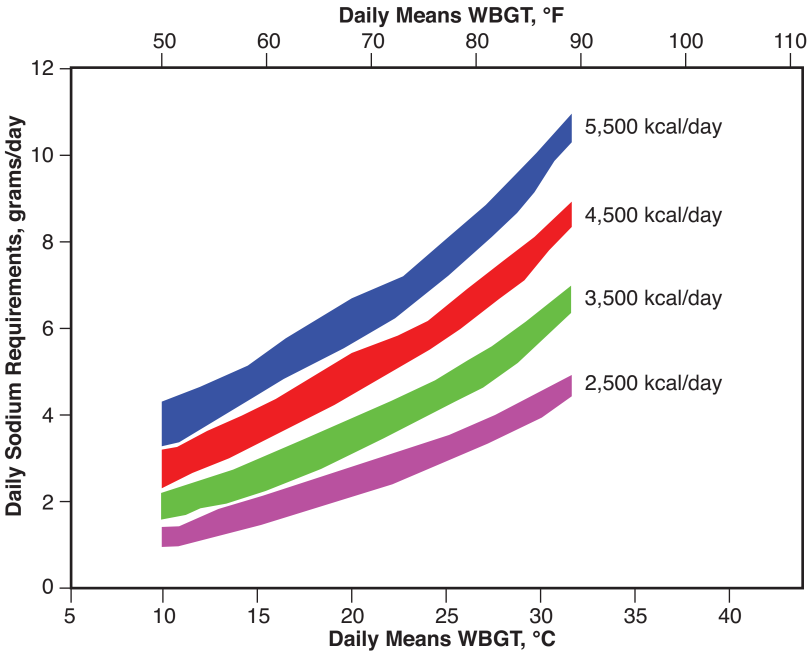

Figure 6. *Estimates of daily sodium requirements for varied weather conditions and energy expenditures.*
WBGT: wet-bulb globe temperature
Data source: Sawka MN, Wenger CB, Montain SJ, et al. Heat Stress Control and Heat Casualty Management. *Washington, DC: Headquarters, US Department of the Army and Air Force; 2003: 13. TB MED 507/AFPAM 48-152.*

Strategies to Sustain Hydration in Harsh Environments

Do Not Skip Meals

Studies on soldiers working in the desert[1] clearly demonstrate that the majority of daily fluid intake occurs at mealtime. As illustrated in Figure 7, soldiers working in the heat voluntarily dehydrated themselves during work periods, but made up the water deficit during mealtime. This same pattern of drinking has since been confirmed by others.[10,11] This observation is important because meals are a valuable time for rehydration and maintenance of fluid balance (Figures 7 and 8). They also provide a source of solutes to offset the electrolytes lost during perspiration. As discussed previously, if missing solutes are not replaced, complete rehydration cannot be achieved.

Make Time to Drink

Soldiers will often underdrink voluntarily relative to the perspiration they produce during work. Rest breaks provide an opportunity for their fluid intake to catch up with their deficit. This is especially relevant when work and weather conditions produce sustained, profuse sweating. To achieve

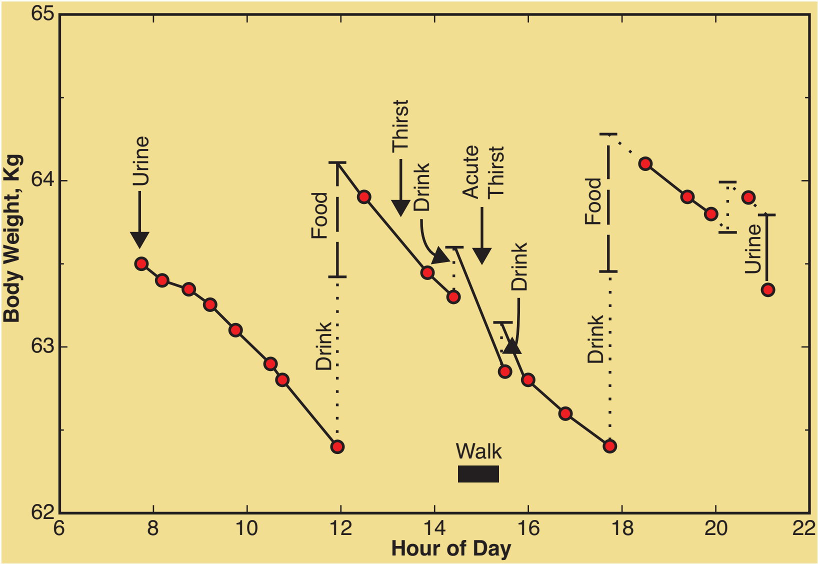

Figure 7. *Changes in body weight of one researcher during a day in the desert. The loss was more rapid in warmer hours and fastest during an afternoon walk, reflecting change in evaporative water loss with conditions of activity and exposure. Most of the fluid was taken with meals.*
Data source: E. F. Adolph and associates. Physiology of Man in the Desert. *New York, NY: Interscience; 1947: 39–40. Chap 3.*

high rates of rehydration, it is advantageous to maintain a high gastric volume, because the speed in which a bolus of fluid leaves the stomach falls exponentially as the stomach volume decreases. A relatively full stomach and high rates of gastric emptying can be achieved by frequently drinking small amounts of fluid during work.[114]

Maximize Palatability

How a drink tastes is a major determinant of the amount of drink consumed. If the provided water tastes disagreeable, soldiers will drink less and will endure greater dehydration.[1] Many factors play a role in palatability, including cultural background, previous experience with the drink, and time of day. Even per individual, palatability is not constant. The decrease in pleasantness can be specific to a particular drink. Therefore,

Figure 8. *US Army Air Force in Tunisia consuming their rations from defensive positions (March 7, 1943). The largest daily fluid intake is generally associated with consumption of meals.*
Photograph: Courtesy of the National Archives, photo no. 208-AA-2U-7.

if the goal is to increase voluntary fluid intake, then switching to a different drink can help to stimulate fluid intake (Figure 9). Rolls and Rolls[116] found that persons offered a choice of three different flavors drank 22% more than when no flavored drinks were provided, and they consumed more of the flavored beverage than the nonflavored beverage.

Adding sweeteners to drinks leads to increased fluid intake.[117] Adding too much sugar can decrease acceptability during physical activity.

Figure 9. *Nutrient on-the-move delivery system attached to standard Army hydration devices. This new system, developed by researchers at the US Army Research Institute of Environmental Medicine (USARIEM), provides the opportunity for soldiers to flavor their water, combined with various drink mixes, and add nutrients (eg, carbohydrate mixes).*
Photograph: Courtesy of the US Patent and Trademark Office (US Patent No. 7,533,786 B2), Alexandria, Va.

Trained endurance athletes reported more symptoms of nausea and fullness when drinks contained 12% glucose compared with drinks containing 6% glucose or water.[118]

Carbonated beverages can be pleasurable with meals or when sedentary, but they make a poor fluid replacement beverage during activity. Sohar and colleagues[119] found that soldiers drank less of the carbonated beverages than either water or flavored beverages. Soldiers who drank the carbonated beverages complained that carbonation made it difficult to drink large quantities of fluid.

Temperature of the preferred drink depends on a number of factors, including culture and learning,[120] climatic conditions, and the physiological state of the individual.[121] In hot and temperate environments, cool drinks increase voluntary intake.[89,122] Drink temperatures of 15°C to 20°C seem optimal when persons need to drink large volumes of fluid.[89] In cold environments, voluntary intake is enhanced when drinks are warmed.[103] In both environmental extremes, the dehydration-induced drive to drink will overcome any initial resistance to drink warm or very cold water.[123]

Minimize Body Water Losses

There are several behavioral actions that soldiers can take to reduce sweat losses and maximize fluid retention. For example, in hot, arid environments, sweating rates can be reduced by working at night. During daylight hours, sweating rates can be reduced by covering the skin with light, vapor-permeable clothing. In cold environments, matching clothing insulation and/or clothing ventilation to the rate of heat production reduces the need for sweating to dissipate heat. Drinking small quantities of fluid frequently results in less urine production than drinking large quantities of fluid less frequently. Similarly, adding small quantities of salt to fluid-replacement beverages improves fluid retention compared with drinking water only, particularly when many hours of labor separate meals. There is no evidence that heat acclimation promotes water conservation; in fact, acclimation leads to earlier onset and more profuse sweating. As such, behavioral strategies are the best solution for minimizing water turnover.

Provide Education

Troop education on the importance of hydration is essential to deployed soldiers. Military planners and logistics personnel must ensure that adequate quantities of potable water are available. Small unit leaders should maximize delivery and availability of potable water to the soldiers. Therefore, these soldiers must understand the importance of drinking, making time to drink, and drinking the right amount.

As previously discussed, dehydration in excess of 2% body weight can have detrimental effects on troop performance. Thus, it is important that soldiers make time to drink during physical activity and drink sufficient quantities to minimize the likelihood of dehydration. It is not essential

Table 3. *Fluid Replacement and Work/Rest Guidelines for Warm Weather Training Conditions*[*]

		Easy Work		Moderate Work		Hard Work	
Heat Category	WBGT[†,‡] Index (°F)	Work/Rest[§,¥] (min)	Water[¶,**] Intake (qt/h)	Work/Rest (min)	Water Intake (qt/h)	Work/Rest (min)	Water Intake (qt/h)
1	78–81.9	NL[††]	½	NL	¾	40/20	¾
2 (green)	82–84.9	NL	½	50/10	¾	30/30	1
3 (yellow)	85–87.9	NL	¾	40/20	¾	30/30	1
4 (red)	88–89.9	NL	¾	30/30	¾	20/40	1
5 (black)	>90	50/20	1	20/40	1	10/50	1

Easy Work	Moderate Work	Hard Work
• Weapon maintenance • Walking on hard surface at 2.5 mph, <30-lb load • Manual of arms • Marksmanship training • Drill and ceremony	• Walking in loose sand at 2.5 mph, no load • Walking on hard surface at 3.5 mph, <40-lb load • Calisthenics • Patrolling • Individual movement techniques (ie, low crawl, high crawl) • Defensive position construction	• Walking on hard surface at 3.5 mph, ≥40-lb load • Walking in loose sand at with load • Field assaults

NL: no limit; MOPP-4: mission-oriented protective posture 4; WBGT: wet-bulb globe temperature
[*]Applies to average size and heat-acclimated soldier wearing battle dress uniform in hot weather.
[†]If wearing body armor, add 5°F to WBGT index in humid environments.
[‡]If wearing nuclear, biological, and chemical clothing (MOPP 4), add 10°F to WBGT index.
[§]Work/rest times and fluid replacement volumes will sustain performance and hydration for at least 4 hours of work in the specified heat category. Fluid needs can vary based on individual differences (±¼ qt/h) and exposure to full sun or full shade (±¼ qt/h).
[¥]Rest means minimal physical activity (sitting or standing), accomplished in shade, if possible.
[¶]CAUTION: Hourly fluid intake should not exceed 1½ quarts.
[**]Daily fluid intake should not exceed 12 quarts.
[††]No limit equals no limit to work time per hour (up to four continuous hours).
Adapted from: Sawka MN, Wenger CB, Montain SJ, et al. ***Heat Stress Control and Heat Casualty Management***. Washington, DC: Headquarters, US Department of the Army and Air Force; 2003: 13. TB MED 507/AFPAM 48-152.

that soldiers fully offset sweat losses during physical activity. They can make up for any water deficit during rest breaks and at mealtime. The best method to prevent excessive dehydration during physical activity is to begin drinking early and continue drinking small amounts of water every 15 to 20 minutes of exercise.

Table 3 provides current Army hot weather guidance for fluid replacement in troops in training environments where work:rest ratios are practical for preventing heat injury.[124] The amounts in each cell reflect the expected hourly fluid intake to fully replace all sweat lost during activity. As such, the numbers in each cell are the average predicted sweating rates for each activity level and environmental condition. Because there is considerable variability between individuals, the numbers in each cell must be considered as approximates. As noted in Table 3 footnotes, actual sweating rates (and 100% fluid replacement) may vary between individuals by ±¼ quart per hour. Similarly, the work:rest ratios are a guide to approximately how much time should be dedicated each hour to work versus rest (assuming work will be sustained for several hours) to prevent body core temperatures from reaching levels associated with premature fatigue and heat exhaustion. Table 3 also specifies an upper limit for hourly (1.5 quarts) and daily (12 quarts) water intake to provide a safeguard against overdrinking and developing water intoxication (hyponatremia) during training.

Summary

It has long been known that individuals can survive much longer without food than they can without water. Only in recent decades has science been able to quantify the factors that influence the body's ability to maintain optimal water levels and the physiological consequences of water imbalance. This chapter has presented information to assist the caregiver—whether physician, medic, unit leader, or fellow soldier—in understanding the influence of environment, physical activity, body size and gender, and load carriage in maintaining water balance. In the not-so-distant past, a lack of understanding of these complex systems led to the deaths of thousands of military personnel in various campaigns. Until science (through the development of biometrics) can accurately and instantly evaluate the water balance of every soldier, it remains the responsibility of each individual—as well as support personnel—to be vigilant in recognizing the potential for and the development of water imbalance situations and to effectively institute rehabilitative measures.

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