# REPORT DOCUMENTATION PAGE

*Form Approved*
*OMB No. 0704-0188*

| | | |
|---|---|---|
| **1. REPORT DATE** *(DD-MM-YYYY)*<br>2012 | **2. REPORT TYPE**<br>Book Chapter-Wilderness Medicine Textbook | **3. DATES COVERED** *(From - To)* |

| | |
|---|---|
| **4. TITLE AND SUBTITLE**<br>Dehydration and Rehydration | **5a. CONTRACT NUMBER** |
| | **5b. GRANT NUMBER** |
| | **5c. PROGRAM ELEMENT NUMBER** |
| **6. AUTHOR(S)**<br>R.W. Kenefick, S.N. Cheuvront, L.R. Leon, K.K. O'Brien | **5d. PROJECT NUMBER** |
| | **5e. TASK NUMBER** |
| | **5f. WORK UNIT NUMBER** |
| **7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)**<br>Thermal and Mountain Medicine Division<br>U.S. Army Research Institute of Environmental Medicine<br>Natick, MA 01760-5007 | **8. PERFORMING ORGANIZATION REPORT NUMBER**<br>MISC 10-37 |
| **9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)**<br>Same as #7 above. | **10. SPONSOR/MONITOR'S ACRONYM(S)** |
| | **11. SPONSOR/MONITOR'S REPORT NUMBER(S)** |

**12. DISTRIBUTION/AVAILABILITY STATEMENT**

Approved for public release; distribution unlimited.

**13. SUPPLEMENTARY NOTES**

**14. ABSTRACT**

Body fluid balance is controlled by both physiological and behavioral actions.44,84 However, when there is lack of fluid availability, exposure to extreme environments, or illness, inability to maintain fluid balance can seriously jeopardize health and the ability to perform.84 This chapter presents an overview of topics surrounding hydration, dehydration, and rehydration. The terms euhydration, hypohydration, and hyperhydration will be used. Euhydration defines a “normal,” narrow fluctuation in body water content, whereas the terms hypohydration and hyperhydration define, respectively, a general deficit (hypohydration) and surfeit (hyperhydration) in body water content beyond normal. The term dehydration specifically defines the condition of hypertonic hypovolemia brought about by the net loss of hypotonic body fluids. Isotonic or hypotonic hypovolemia, manifest by large losses of solute and water, is defined simply as hypovolemia.75,109 Table 70-1 lists the two principal forms of body water deficit and the physiology and particular circumstances associated with each form of deficit.

**15. SUBJECT TERMS**

rehydration, euhydration, hypohydration, hyperhydration

| **16. SECURITY CLASSIFICATION OF:** | | | **17. LIMITATION OF ABSTRACT** | **18. NUMBER OF PAGES** | **19a. NAME OF RESPONSIBLE PERSON** |
|---|---|---|---|---|---|
| **a. REPORT** | **b. ABSTRACT** | **c. THIS PAGE** | | | R.W. Kenefick |
| Unclassified | Unclassified | Unclassified | Unclassified | 16 | **19b. TELEPHONE NUMBER** *(Include area code)*<br>508-233-6344 |

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**Standard Form 298** (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

# CHAPTER 70

# Dehydration and Rehydration*

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## Introduction and Definition of Terms

Body fluid balance is controlled by both physiological and behavioral actions.[44,84] However, when there is lack of fluid availability, exposure to extreme environments, or illness, inability to maintain fluid balance can seriously jeopardize health and the ability to perform.[84] This chapter presents an overview of topics surrounding hydration, dehydration, and rehydration. The terms *euhydration*, *hypohydration*, and *hyperhydration* will be used. *Euhydration* defines a "normal," narrow fluctuation in body water content, whereas the terms *hypohydration* and *hyperhydration* define, respectively, a general deficit (hypohydration) and surfeit (hyperhydration) in body water content beyond normal. The term *dehydration* specifically defines the condition of hypertonic hypovolemia brought about by the net loss of hypotonic body fluids. Isotonic or hypotonic hypovolemia, manifest by large losses of solute and water, is defined simply as hypovolemia.[75,109] Table 70-1 lists the two principal forms of body water deficit and the physiology and particular circumstances associated with each form of deficit.

## Body Water, Fluid Turnover, and Fluid Requirements

Total body water (TBW) is the principal chemical component of the human body and represents 50% to 70% of body mass[7] for the average young adult male. It is regulated within ±0.2 to 0.5% of daily body mass.[2,35] Body water is required to sustain the cardiovascular and thermoregulatory systems and to support cellular homeostasis. While "normal" hydration is achieved with a wide range of water intakes by sedentary and active people across the life span, homeostasis of body water can be difficult to maintain when challenged by strenuous physical work, heat stress, or illness. Despite population variability in age, body composition, and physical fitness, it is important to note that variability in TBW is accounted for almost entirely by body composition, since lean body mass contains ~73% water and fat body mass consists of ~10% water.[196] Trained athletes have relatively high TBW values by virtue of having a high muscle mass and low body fat. In contrast, obese individuals with the same body mass as their lean counterparts will have markedly smaller TBW volumes. Any absolute fluid deficit will have more severe consequences for individuals with a smaller TBW.

Daily water balance depends on the net difference between water gain and water loss.[84] Approximately 5% to 10% of TBW is turned over daily[152] via obligatory (nonexercise) fluid loss avenues. Water gain occurs from consumption (liquids and food) and production (metabolic water), while water losses occur from respiratory, gastrointestinal, renal, and sweat losses. Water loss in respiration is influenced by the inspired air and pulmonary ventilation. Of important note, the volume of metabolic water produced during cellular metabolism (~0.13 g/kcal) is approximately equal to respiratory water losses (~0.12 g/kcal),[45,122] which results in water turnover with no net change in TBW. Gastrointestinal tract losses tend to be negligible (~100-200 mL/day); however, certain illnesses, such as diarrhea, can lead to loss of large amounts of fluid and electrolytes. The ability to vary urine output represents the primary means to regulate net body water balance across a broad range of fluid intake volumes and losses from other avenues. Water losses in urine approximate 1 to 2 L/day. However, urine output volumes may be larger or smaller depending on daily fluid consumption and activity.[84] Minimum outputs of ~20 mL/hr and maximal volumes of ~1000 mL/hr are possible.

Net body water balance (loss = gain) is regulated remarkably well day-to-day as a result of thirst and hunger, coupled with ad libitum access to food and beverages, which offset water losses.[84] Although acute mismatches between fluid gain and loss may occur due to illness, environmental exposure, exercise, or physical work, it is a reproducible phenomenon that intakes are generally adequate to offset net loss from day to day.[47] It is recognized, however, that after significant body water deficits like those associated with physical work or heat stress, many hours of rehydration and electrolyte consumption may be needed to reestablish body water balance.[183] For example, if hypohydrated by more than about 4% of total body mass, it may take >24 hours to fully rehydrate via water and electrolyte replacement.[4,129,138] While daily strenuous activity in a hot environment can result in mild water balance deficits even with unlimited access to food and fluids,[9,183] adherence to recognized water intake guidance[9,30,165] minimizes water deficits, as determined by daily body mass stability.[35]

An adequate intake (AI) for daily total water is 3.7 L and 2.7 L for adult males and females, respectively.[84] Of these prescribed volumes, 20% of the AI for water is found in food eaten during meals and snacks and the remaining 80% (~3 L for males and 2.2 L for females) can come from beverages of all types. Daily

**TABLE 70-1** Two Principal Forms of Body Water Deficit

| Form | Physiology | Circumstances |
|---|---|---|
| Hypertonic hypovolemia | • Body water loss > solute loss<br>• Movement of water from ICF to ECF space<br>• Partial restoration of ECF space | • Sweat loss (exercise, environmental heat stress, or fever)<br>• Inadequate fluid intake<br>• Osmotic diuresis due to glucosuria |
| Isotonic hypovolemia | • Isotonic loss of body water and solute<br>• No net movement of water among body fluid compartments<br>• Larger contraction of ECF space than equivalent hypertonic body water deficit | • Cold or high-altitude exposure<br>• Gastrointestinal losses (diarrhea, vomiting)<br>• Diuretic therapy |

ICF = intracellular fluid; ECF = extracellular fluid.

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*The views, opinions, and/or findings in this report are those of the authors and should not be construed as official Department of the Army position, policy, or decision unless so designated by other official designation.

**TABLE 70-2** Hydration Assessment Techniques Summary[41]

| Technique | Advantages | Disadvantages |
|---|---|---|
| **Complex Markers** | | |
| Total body water (dilution) | Accurate, reliable (gold standard) | Analytically complex, expensive, requires baseline |
| Plasma osmolality | Accurate, reliable (gold standard) | Analytically complex, expensive, invasive |
| **Simple Markers** | | |
| Urine concentration | Easy, rapid, screening tool | Easily confounded, timing critical, frequency and color subjective |
| Body mass | Easy, rapid, screening tool | Confounded by changes in body composition |
| **Other Markers** | | |
| *Blood:* | | |
| Plasma volume | No advantages over osmolality (except hyponatremia detection for plasma sodium) | Analytically complex, expensive, invasive, multiple confounders |
| Plasma sodium | | |
| Fluid balance hormones | | |
| Bioimpedance | Easy, rapid | Requires baseline, multiple confounders |
| Saliva | Easy, rapid | Highly variable, immature marker, multiple confounders |
| Physical signs | Easy, rapid | Too generalized, subjective |
| Tilt test (orthostatic challenge) | Rapid | Highly variable, insensitive, requires tilt table or ability to stand |
| Thirst | Positive symptomology | Develops too late and is quenched too soon |

water intake, however, varies greatly for individuals and between groups. For example, the daily water needs of sedentary men are ~1.2 L or ~2.5 L[1,137] and increase to ~3.2 L if performing modest physical activity.[76,79] Compared with sedentary adults, active adults who live in a warm environment are reported to have daily water needs of ~6 L,[201] and highly active populations have been reported to have markedly higher values.[162] Data are limited regarding fluid needs for women, but typically they exhibit lower daily water turnover rates than do their male counterparts. In general, fluid requirements vary based on an individual's body size, activity level, and the environment in which they work, live, or perform activity.

## HYDRATION ASSESSMENT

Human hydration assessment is a key component for prevention and proper treatment of fluid and electrolyte imbalances.[41,109,146] When fluids are limited, illness strikes, or there is exposure to extreme environments, cumulative fluid deficits can threaten homeostasis, health, and performance.[109,165] Health is also threatened by fluid deficits, which can increase the risk of serious heat illness, and by fluid surfeits, which increase the risk of hyponatremia.[28,123] In many clinical and most sports and wilderness medicine situations, hypertonic-hypovolemia occurs when there is net loss of hypotonic body fluids.[41,109,165] However, substantial solute (electrolyte) can also be lost in situations where there is heavy work and heat stress induces profuse sweating, during cold or high-altitude exposure, and in numerous illnesses and disorders (e.g., gastroenteritis, hyperemesis, diuretic treatment, dialysis) producing an isotonic or hypotonic-hypovolemia.[41,109,165] An appreciation for the different types of body fluid losses that occur in response to illness, fluid restriction, or exposure to extreme environments is fundamental to proper hydration assessment[41,109] (Table 70-1).

Most circumstances involving strenuous work in austere environments require formation and vaporization of sweat as a principal means of heat removal. Thus, when sweat losses result in a body water deficit, there is a predictable rise in extracellular tonicity, which modulates renal function and urine composition in accordance with the body water deficit.[156] The basic principles of body fluid regulation thus provide the framework for using blood (osmolality, sodium, fluid regulatory hormones) and urine (osmolality, specific gravity, color) as principal body fluid hydration assessment measures. Similarly, because humans maintain a relatively stable total body water pool despite diverse factors that affect water requirements (e.g., climate, activity, dietary solute load),[84] acute changes in body mass may be used to accurately measure dehydration across medical disciplines.[14,35,195] Physical signs and symptoms (dizziness, headache, tachycardia, capillary refill time, sunken eyes, skin turgor) only manifest when fluid losses are severe and become debilitating.[64,191] These findings are too generalized to be useful in athletic settings[116] since they share symptoms indicative of other ailments (e.g., acute mountain sickness) and their use in assessment could lead to an incorrect diagnosis.

All hydration assessment methods vary greatly in applicability because of limitations such as the necessary circumstances for reliable measurement, principles of operation, cost and complexity.[84,146] Table 70-2 provides the advantages and disadvantages of numerous approaches and should be consulted when deciding on the choice of hydration marker. Definitive hydration assessment requires monitoring of changes in hydration state.[38,117] Although change can provide good diagnostic accuracy, it requires a valid baseline, control over confounding variables, and serial measures.[38,117] Large population heterogeneity explains, in part, why there are presently few hydration status markers that display potential for high nosological sensitivity from a more practical, single measure.[38,103] Although Table 70-3 provides euhydration thresholds for the most useful of hydration assessment measures, they too require considerable methodological control, expense, and analytical expertise to be of practical use for day-to-day hydration monitoring of athletic sojourners.

There is presently no scientific consensus for how to best assess hydration status in a field setting. However, in most field settings, the additive use of first morning body mass measurements in combination with some measure of first morning urine concentration and gross thirst perception provides a simple and inexpensive way to dichotomize euhydration from gross dehydration resulting from sweat loss and poor fluid intakes. This

**TABLE 70-3** Biomarkers of Hydration Status[41]

| Measure | Practicality | Validity (Acute vs. Chronic Changes) | Euhydration Cut-Off |
|---|---|---|---|
| TBW | Low | Acute and chronic | <2% |
| Plasma osmolality | Medium | Acute and chronic | <290 mOsmol |
| Urine specific gravity | High | Chronic | <1.020 g/mL |
| Urine osmolality | High | Chronic | <700 mOsmol |
| Urine color | High | Acute and chronic | <4 |
| *Body weight | High | Acute and chronic | <1% change |

*Potentially confounded by changes in body composition during very prolonged assessment periods. Fluid balance should be considered adequate when the combination of any two assessment outcomes is consistent with euhydration.

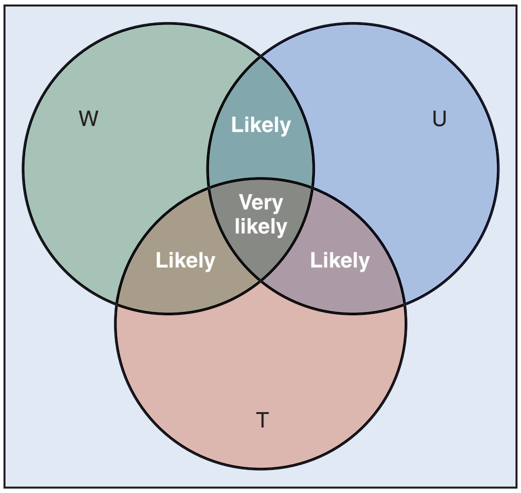

FIGURE 70-1 **W** stands for "weight." **U** stands for "urine." **T** stands for "thirst." When two or more simple markers of dehydration are present, it is likely that you are dehydrated. If all three markers are present, dehydration is very likely.[41]

approach is represented using a Venn Diagram decision tool (Figure 70-1).[41] It combines three of the simplest markers of hydration, including body mass (weight), urine, and thirst (WUT). No marker by itself provides enough evidence of dehydration, but the combination of any two simple self-assessment markers means dehydration is likely. The presence of all three makes dehydration very likely. The balance between science and simplicity in the choice of these measures for field hydration assessment is outlined below.

**Urine Concentration.** Urinalysis is a frequently used clinical measure to distinguish between normal and pathologic conditions. Urinary markers for dehydration include urine volume, urine specific gravity (USG), urine osmolality ($U_{Osm}$) and urine color ($U_{Col}$). Urine is a solution of water and various other substances. Thus, its concentration varies inversely with volume, which is reduced with dehydration. Urine output generally approximates 1 to 2 L/day but can be increased by an order of magnitude when consuming large volumes of fluid.[84] This large capacity to vary urine output represents the primary avenue to regulate net body water balance across a broad range of fluid intake volumes and losses from other avenues. Whereas the quantification of urine volume is impractical on a daily basis, the quantitative (USG, $U_{Osm}$) or qualitative ($U_{Col}$) assessment of its concentration is far simpler. As a screening tool to dichotomize euhydration from dehydration, urine concentration (USG, $U_{Osm}$, $U_{Col}$) is a reliable assessment technique[9,17,182] with reasonably definable thresholds.

In contrast, urine measures often correlate poorly with "gold standards" like plasma osmolality and fail to reliably track documented changes in body mass corresponding to acute dehydration and rehydration.[97,151] It appears that changes in plasma osmolality that stimulate endocrine regulation of renal water and electrolyte reabsorption are delayed at the kidney when there occur acute fluxes in body water.[151] It is also likely that drink composition influences this response. Shirreffs and Maughan[186] demonstrated that drinking large volumes of hypotonic fluids results in copious urine production long before euhydration is achieved. Urine concentration measurements can also be confounded by diet, which may explain large cross-cultural differences in urine osmolality.[110] However, use of the first morning void following an overnight fast minimizes confounding influences and maximizes measurement reliability.[9,182] Urinalysis of specific gravity, osmolality, and color can therefore be used to assess and distinguish euhydration from dehydration so long as the first morning void is used.

Inexpensive and easy-to-use commercial instruments are available for assessing USG and conductivity (osmolality equivalent)[17,182]; a urine color chart is also available.[9] The simplest of these, color, is included in the Venn diagram. Under ideal circumstances, the urine (first morning) should be in a clean, clear vial or cup and the color assessed against a white background. Urine color can be compared against a urine color chart[9] or assessed relative to the degree of darkness. Paler color urine (similar to lemonade) indicates adequate hydration and the darker yellow/brown the urine color (similar to apple juice), the greater degree of dehydration. Assessing urine that has been diluted in toilet water or while in mid-flow may alter the urine color. When in less than ideal conditions, urine in a urinal is less dilute and in the field, snow can provide a suitable background. Example photos of urine color with corresponding numerical color,[9] USG, and urine osmolality values are presented in Figure 70-2.

**Body Mass.** Body mass is an often used measurement for rapid assessment of athlete hydration changes in both laboratory and field environments. Changes in acute hydration are calculated as the difference between pre- and postexercise body mass. The level of dehydration is best expressed as a percentage of starting body mass rather than as a percentage of TBW, since the latter ranges widely.[84] Use of this technique implies that 1 g of lost mass is equivalent to 1 mL of lost water. So long as total body water loss is of interest, failure to account for carbon exchange represents the only small error (~10%) in this assumption.[39] Indeed, acute body mass changes (water) are frequently the standard against which the resolution of other hydration assessment parameters are compared in the laboratory. In fact, if proper controls are made, body mass changes can provide a more sensitive estimate of acute total body water changes than can repeat measurements by dilution methods.[78]

There is also evidence that body mass is a sufficiently stable physiological parameter for potential daily fluid balance monitoring, even over longer periods (1-2 weeks) that include hard exercise and acute fluid flux.[35,102] Young, healthy men undergoing daily exercise-heat stress maintain a stable first morning body mass so long as they make a conscious effort to replace exercise sweat losses.[35] Similarly, ad libitum intakes of food and fluid will balance sweat losses incurred with regular exercise, resulting in a stable daily body mass.[102] Over longer time frames, changes in body composition (fat and lean mass) that occur with chronic energy imbalance are also reflected grossly as changes in body mass, thus limiting this technique. Clearly, if first morning body mass stability is used to monitor changes in hydration, it should be used in combination with another hydration assessment technique (urine concentration) to dissociate gross tissue losses from water losses if long-term hydration status is of interest.

**Thirst.** Although genuine thirst develops only after dehydration is present and is alleviated before euhydration is achieved,[75,84] thirst is one of the only reliable subjective feelings reported by a person in response to fluid restriction.[184] Plasma osmolality near 295 mmol/kg will produce an arginine vasopressin (AVP) level of around 5 pg/mL, which results in a maximal urine concentrating capacity.[156] The average plasma osmolality at which thirst is stimulated above baseline is also approximately 295 mmol/kg.[156] If we assume that a normal resting plasma osmolality of 285 becomes concentrated to 295, the ratio 285/295 multiplied by a normal 42 L total body water gives an estimated 40.5 L or 1.5 L

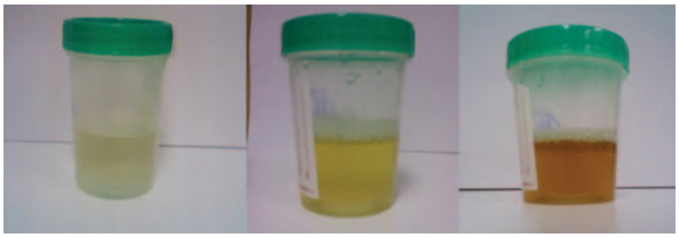

FIGURE 70-2 Samples of first morning urine with urine specific gravity (USG) and associated osmolality (mmol/kg) and color values.

total body water deficit, which is 2.1% dehydration for a 70-kg person. This is consistent with general observations of thirst insensitivity below a "threshold" fluid deficit (notion that thirst develops late). However, it is important to recognize that there is substantial individual variability in the plasma osmolality "set point" and the osmotic thresholds for AVP release and thirst perception.[157] For example, Robertson reports as much as a 10-fold difference between individuals in the slope of the line relating AVP to plasma osmolality.[157] Clearly, thirst is a qualitative tool for hydration assessment, but positive thirst symptoms coupled with at least one additional Venn Diagram marker suggests an increasing likelihood of dehydration.

Although plasma osmolality and total body water measurements are the hydration assessment measures for large-scale fluid needs,[84] there is presently no consensus for using any one approach over another in a field or athletic setting. In most circumstances, the use of first morning body mass combined with some measure of first morning urine concentration (USG, urine osmolality, and/or color) offers simple assessment and allows ample sensitivity (low false negative) for detecting meaningful deviations in fluid balance (>2% body mass). This approach is represented using a Venn Diagram decision tool (Figure 70-2).[41] It combines three of the simplest markers of hydration, including weight, urine, and thirst (WUT). No marker by itself provides enough evidence of dehydration, but the combination of any two simple self-assessment markers means dehydration is likely, and the presence of all three makes dehydration very likely. In a field setting, where a scale may not be available for body weight measures, the combination of first morning urine color and thirst may provide a reasonable indication of the presence of dehydration.

## Sweat and Sweat Prediction

Muscular contractions involved with activity/exercise produce metabolic heat that is transferred from the active muscles to blood and then the body core. Subsequent body temperature elevations elicit heat loss responses of increased skin blood flow and increased sweat secretion so that heat can be dissipated to the environment.[173,175] Heat exchange between the skin and environment is governed by biophysical properties dictated by surrounding temperature, humidity and air motion, sky and ground radiation, and clothing.[67] When ambient temperature is greater than or equal to skin temperature, evaporative heat loss accounts for all body cooling. Eccrine sweat glands secrete fluid onto the skin surface, permitting evaporative cooling when liquid is converted to water vapor. Sweat glands respond to thermal stress primarily through sympathetic cholinergic stimulation, with catecholamines having a smaller role in the sweat response.[175] The rate of sweat evaporation depends on air movement and the water vapor pressure gradient between the skin and environment, so in still or moist air, sweat does not evaporate readily and collects on the skin. Sweat that drips from the body or clothing provides no cooling benefit. If secreted sweat drips from the body and is not evaporated, higher sweating will be needed to achieve the evaporative cooling requirements.[36,173] Conversely, increased air motion (wind, movement velocity) will facilitate evaporation and minimize wasted (dripping) sweat.[36] Sweat losses can vary widely and depend on the amount and intensity of physical activity and environmental conditions.[71,180] In addition, a number of factors can alter sweat rates and ultimately fluid needs. Heat acclimatization results in higher and more sustained sweating rates.[173,175] Similarly, aerobic exercise training has a modest effect on enhancing sweating rate responses.[173,175] Wearing heavy or impermeable clothing or protective equipment can increase heat stress[115] and sweat rate, but can limit evaporation of sweat and ultimately heat loss. Likewise, wearing heavy or impermeable clothing while exercising in cold weather can elicit unexpectedly high sweat rates,[63] which can increase fluid needs. Conversely, factors such as wet skin (e.g., from high humidity) and dehydration can act to suppress the sweating rate response.[173]

Sweat is hypotonic relative to plasma and is typically half of plasma osmolality (~145 mmol/kg vs. ~290 mmol/kg, respectively).[46] Losses of electrolytes in sweat depend on total sweat losses (over a given period of time) and sweat electrolyte concentrations. Typical sweat sodium concentration averages ~35 mEq/L (range 10-70 mEq/L) and varies depending on genetic predisposition, diet, sweating rate, and heat acclimatization state.* Sweat concentration of potassium averages 5 mEq/L (range 3-15 mEq/L), calcium averages 1 mEq/L (range 0.3-2 mEq/L), magnesium averages 0.8 mEq/L (range 0.2-1.5 mEq/L), and chloride averages 30 mEq/L (range 5-60 mEq/L).[22] Sex, maturation, or aging do not appear to have discernible effects on sweat electrolyte concentrations,[120,130] although dehydration can increase the sweat concentrations of sodium and chloride.[128] Sweat glands reabsorb sodium and chloride by active transport, but the ability to reabsorb these electrolytes does not increase proportionally with the sweating rate. As a result, the sodium and chloride concentrations of sweat increase as a function of sweating rate.[5,47] Heat acclimatization improves the ability to reabsorb sodium and chloride; thus, heat-acclimatized individuals usually have lower sweat sodium concentrations (e.g., >50% reduction) for any given sweating rate.[5]

The ability to predict sweat losses is critical for calculating water needs, particularly for individuals who are exposed to heat stress. For large cohorts such as the U.S. military, fluid requirements in the field are based on water tables generated from existing sweat prediction equations. Sweat rates differ between various work activities and between individuals.[173] Specifics on determining individual sweat rate and fluid requirements are covered later in the chapter in the fluid replacement recommendations section. Figure 70-3[84] depicts generalized modeling approximations for daily sweating rates as a function of daily metabolic rate (activity level) and air temperature. Metabolic rate and air temperature both have marked effects on water needs. In addition to air temperature, environmental factors such as relative humidity, air motion, solar load, and protective clothing influence heat strain and water needs.

Although Figure 70-3 shows approximations of water needs, mathematical models exist that more specifically predict fluid needs. The Shapiro equation[180] has been used extensively to estimate sweating rates and calculate daily water needs. This model calculates sweat rate ($M_{sw}$; expressed as g m$^{-2}$ h$^{-1}$) and thus fluid needs as the following:

$$M_{sw} = 27.9 \times E_{req} \times (E_{max})^{-0.455},$$

where $E_{req}$ is the required evaporative cooling (in W/m$^2$) and $E_{max}$ is the maximal evaporative cooling capacity. $E_{req}$ is calculated from metabolic heat production, clothing heat transfer characteristics, and the environment. $E_{max}$ is derived from the vapor transfer

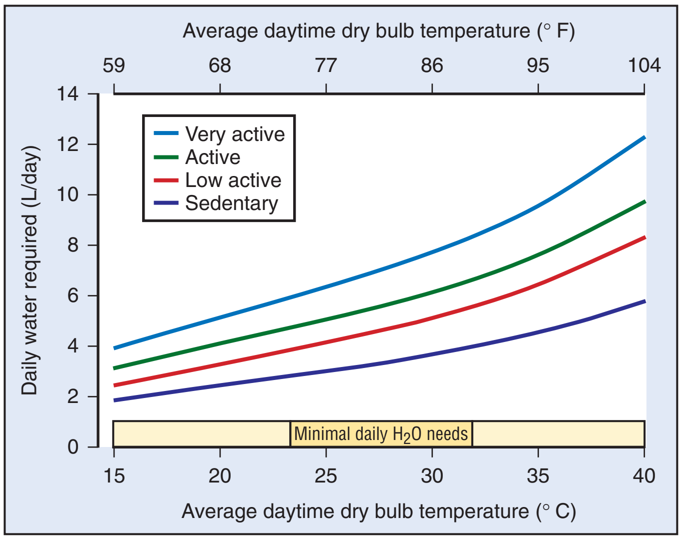

**FIGURE 70-3** Generalized modeling approximations for daily sweating rates as a function of daily metabolic rate (activity level) and air temperature.[84]

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*References 5, 22, 47, 65, 185, and 197.

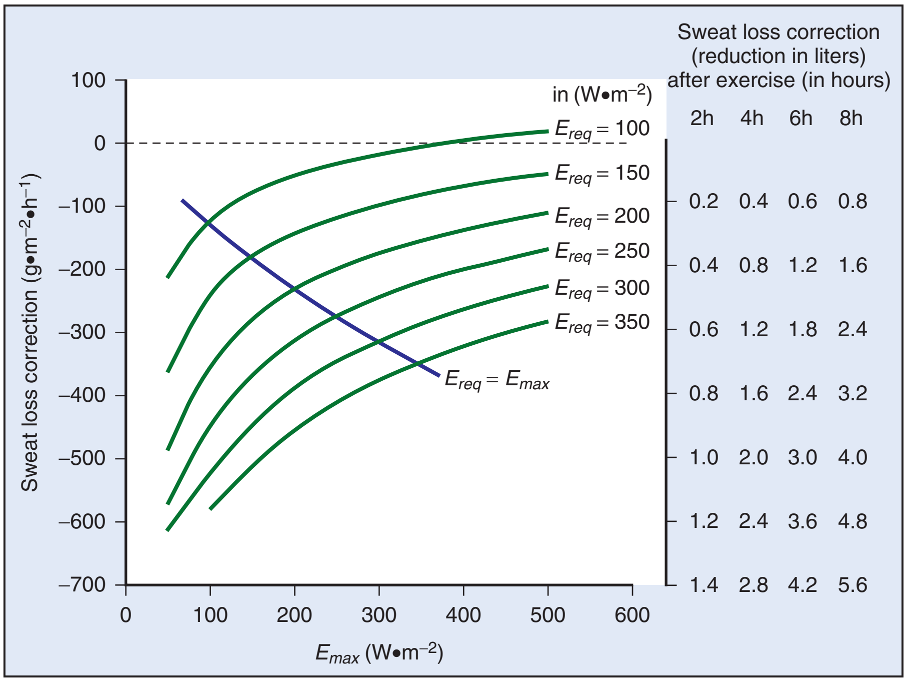

**FIGURE 70-4** Where $E_{req}$ is the amont of evaporation required to achieve heat balance; $E_{max}$ is the maximum rate of evaporation possible. The range of validity: $E_{req}$ >50 W/m2 and <360 W/m2; $E_{max}$ >20 W/m2 and <525 W/m2. Calculations for reference male with body surface area of 1.8 m2.[86]

properties of the clothing worn and the environment. However, this equation has been shown to have limitations,[40] in that it often overpredicts fluids needs when exercise is greater than 2 hours, when improved uniforms and body armor are worn, and when activity takes place in lower air temperatures and the activity is of high intensity. In response to these limitations, Gonzalez et al.[71] developed a correction for the Shapiro equation in addition to a new prediction equation using independent data across a wide range of environmental conditions, metabolic rates, and environmental conditions. Figure 70-4, taken from Jay et al.,[86] depicts the adjustment to the sweat loss values yielded by the corrected Shapiro equation derived by Gonzalez et al.[71] Future work in this area may be required to further increase the applicability of sweat rate prediction equations, in particular under conditions with variable solar loads, in lower air temperatures (~15° C [59° F]), with clothing having low water vapor permeability or with specialized equipment (e.g., American football), and with individuals possessing greater body mass and surface areas.[86] At present, use of such equations has been predominantly limited to the military. Future commercial applications of such equations to predict fluid needs by the general population in hiking/trekking/wilderness scenarios may be possible via commonly used devices, such as personal digital assistants (PDAs).

## Physiological Consequences of Dehydration

By virtue of tonicity and volume changes, dehydration has negative consequences on thermoregulation and performance. Dehydration is brought about by voluntary fluid restriction, insufficient rehydration following daily activity, or physical activity/exercise in the form of thermoregulatory sweating. The most common form of dehydration during exercise in the heat is that where water deficit occurs without proportionate sodium chloride loss.[166] Individuals often start an exercise task with normal total body water and dehydrate over an extended duration; however, in some situations, an individual might initiate activity/exercise with a body water deficit because the interval between exercise sessions is inadequate or chronic fluid intake is insufficient to replace losses. During multiple-day treks or expeditions where individuals take part in prolonged daily sessions of activity/exercise, possibly in hot conditions, a fluid deficit may be carried from one activity/exercise session to the next or from one day to the next.[70] In addition, individuals medicated with diuretics may be dehydrated prior to initiating exercise. Use of medications, such as acetazolamide taken prophylactically or while at altitude for acute mountain sickness, can have such an effect (and may increase risk for hyponatremia). This drug causes the kidneys to excrete bicarbonate, which acidifies the blood, increasing ventilation and blood $O_2$ content; however, it also increases fluid and electrolyte losses. If large sodium chloride deficits occur during exercise, then the extracellular fluid volume contracts and causes "salt depletion dehydration."

Dehydration increases physiological strain as measured by core temperature, heart rate, and perceived exertion responses during exercise heat stress.[166] The greater the body water deficit, the greater the increase in physiological strain for a given exercise task.[3,124,125,176] Dehydration can augment core temperature elevations during exercise in temperate[26,136,170] as well as in hot environments.[43,168,178] The typical reported core temperature augmentation with dehydration is an increase of 0.1° to 0.2° C (32.18° to 32.36° F) with each 1% of dehydration.[167] The greater heat storage associated with dehydration is associated with a proportionate decrease in heat loss. Thus, decreased sweating rate (evaporative heat loss) as well as decreased cutaneous blood flow (dry heat loss) are responsible for greater heat storage observed during exercise when hypohydrated.[59,60,134] The degree to which each of these mechanisms dissipates heat from the body depends on environmental conditions. However, both avenues of heat loss are unfavorably altered by dehydration.

When dehydrated, the sweating rate is lower for any given core temperature, and heat loss via evaporation is reduced.[176] In addition, as dehydration increases, there is reduction in total body sweating rate at a given core temperature during exercise heat stress.[176] During submaximal exercise with little or no thermal strain, dehydration results in increased heart rate and decreased stroke volume, and typically no change in cardiac output relative to euhydration levels.[163,188] The addition of heat stress in combination with dehydration during exercise results in decreased blood volume, reducing central venous pressure and cardiac output,[94,129] and creates competition between the central and peripheral circulation for limited blood volume.[133,161] As body temperature increases during exercise, cutaneous vasodilation occurs and superficial veins become more compliant, decreasing venous resistance and pressure.[161] A result of reduced blood volume (due to dehydration) and increased blood displacement to cutaneous vascular beds (due to heat stress) is decreased central venous pressure, venous return and, ultimately, cardiac output below euhydration values.[135,169]

## ENVIRONMENTAL HEAT STRESS, DEHYDRATION, AND PERFORMANCE

Physiological factors that contribute to dehydration-mediated aerobic exercise performance decrements include increased body core temperature, increased cardiovascular strain, increased glycogen utilization, and perhaps altered central nervous system function.[141,166,175] Although each factor is unique, evidence suggests that they interact to contribute in concert, rather than in isolation, to degrade aerobic exercise performance.[35,166,175] The relative contribution of each factor may differ depending on the specific activity, environmental conditions, heat acclimatization status, and athlete prowess, but elevated hyperthermia probably acts to accentuate the performance decrement.

In a field or wilderness setting, individuals may perform activities that require anaerobic power or muscular strength. Dehydration likely does not degrade muscular strength[58,77] or anaerobic performance.[34,85] However a recent critical review of the related literature[89] suggests that hypohydration decreases (1%-3%) strength, power, and high-intensity endurance activities. Dehydration >2% of body mass has been shown to degrade aerobic exercise performance in temperate, warm, and hot environments.[31,37] As the level of dehydration increases, aerobic exercise performance is degraded proportionally.[84] The critical water deficit (>2% body mass for most individuals) and magnitude of performance decrement are likely related to environmental temperature, exercise task, and the individuals' unique biological characteristics (e.g., tolerance to dehydration). Therefore, some individuals are more or less tolerant to dehydration. Adolph[3] was one of the first to document that during long duration exercise in temperate or slightly warm environments, thermoregulatory sweating would lead to progressive dehydration and result in lower exercise output (Figure 70-5). Adolph derived this figure from limited exercise capability data and heart rate responses from a variety of exercise, heat stress, and dehydration conditions.

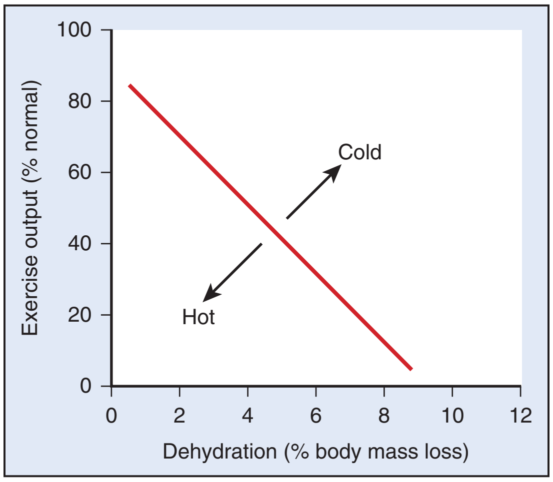

**FIGURE 70-5** Percentage decrement in exercise performance relative to percent dehydration (body mass loss). (*Redrawn from Adolph EF:* Physiology of Man in the Desert. *NewYork, 1947, Interscience.*)

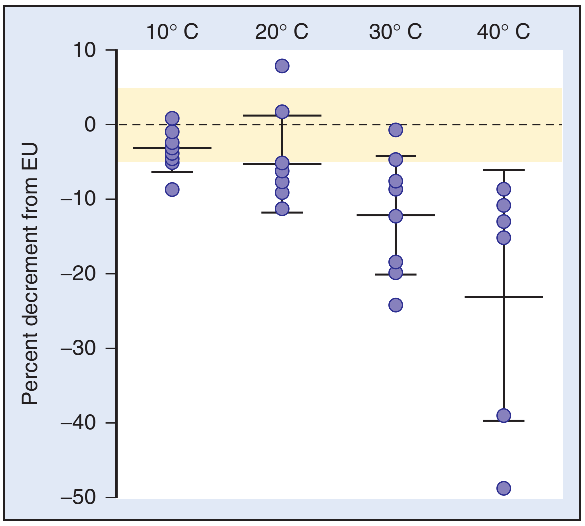

**FIGURE 70-6** Percent decrement in total work performance relative to euhydration (EU) trial for all subjects (*n* = 32) in 10°, 20°, 30°, and 40° C (50°, 68°, 86°, and 104° F) environments. Data are means; bars are 95% CI. Shaded area represents CV (±5%) based on performance variability measured during 2-week familiarization sessions.

Exercise tasks that primarily require aerobic metabolism and that are prolonged will be more adversely influenced by dehydration than are exercise tasks that require anaerobic metabolism or muscular strength and power.[171] As demonstrated by Gonzalez-Alonso et al.,[72] the greater the level of dehydration, the greater the magnitude of cardiovascular and thermoregulatory strain. It has previously been demonstrated that high levels of aerobic fitness and acclimatization status provide some thermoregulatory advantage. However, dehydration seems to cancel out this protective effect during exercise heat stress.[25,119,172] A comprehensive review[164] of a number of studies that investigated the impact of dehydration on physical exercise capacity and maximal aerobic power found that in the majority of studies, exercise capacity decreased with levels of dehydration of as little as 1% to 2% body mass, although maximal aerobic power was not altered. In addition, the reduction in exercise capacity when dehydrated was further accentuated by combination with heat stress.[51,140,150] In temperate environments, body water deficits of <2% body mass did not have a significant impact on maximal aerobic power. In a hot environment, however, a small to moderate water deficit (≥2%body mass) resulted in a large decline in maximal aerobic power.[51,140] A review of studies[37] that observed the effects of progressive dehydration (>2% body mass) specifically on aerobic exercise performance found that in environments of >30° C (86° F), aerobic exercise performance was decreased by anywhere from 7% to 60%. It also appears that the magnitude of the effect increases as exercise extends beyond 90 minutes. Overall what can be taken from this review is that the impact of dehydration on prolonged work efforts is magnified by hot environments, and probably worsens as the level of dehydration increases.

Few investigations have studied the impact of dehydration on aerobic performance across a range of environmental temperatures. Cheuvront et al.[25] observed 8% reduction in total work during a cycling time trial when dehydrated by ≥2% of body mass in a 20° C (68° F) environment. However, in 2° C (35.6° F), no effect of dehydration was observed. Kenefick et al.[92] reported decrements in aerobic performance (15-minute cycling time trial) of −3%, −5%, −12%, and −23% in 10° C (50° F), 20° C (68° F), 30° C (86° F), and 40° C (104° F) respectively, when volunteers were dehydrated by ≥2% of body mass. Figure 70-6 depicts the change in performance relative to euhydrated trials and relative to the coefficient of variation (test variability; shaded area) of the cycling test itself. Mean values that lie inside of the shaded area are considered to be within the noise of the test and those that lie outside are considered to be meaningful. Based on the findings, it would appear that the temperature cusp where dehydration of 4% of body mass altered aerobic exercise performance occurred at 20° C (68° F). It is important to note that these reported results are the minimal decrement in performance that could be expected. Greater decrements could be expected during more prolonged work or with greater levels of dehydration.

Table 70-4 depicts the decrement in aerobic time trial (<60 minutes) performance across a continuum of environmental temperatures and at an altitude of ~3000 m with and without hypohydration (>2% body mass loss). Without any degree of dehydration, certain environments (warm/hot, high altitude) themselves have a negative impact on aerobic exercise performance. It is important to note that in combination with these environments, dehydration further degrades aerobic exercise performance and that with longer duration exercise (>60 minutes), greater degradations in performance can be expected. However, by maintaining a

**TABLE 70-4** Percentage Decrement in Aerobic Exercise Performance

| Environment | Euhydrated | Dehydrated |
|---|---|---|
| Cold (2-10° C; 36-50° F) | _ | ~3%[33,92] |
| Temperate (~20° C; 68° F) | _ | ~5 to 7%[33,92] |
| Warm (~30° C; 86° F) | ~8%[194] | ~12%[92] |
| Hot (~40° C; 104° F) | ~17%[56] | ~23%[92] |
| Altitude (~3000 m; 9,843 ft) | ~11 to 15%[32,66] | ~33%[32] |

Percent decrement in aerobic exercise performance (compared to temperate) across a continuum of environmental temperatures and at ~3000 m with and without dehydration (≥2% body mass).

well-hydrated state, the contribution of dehydration to the degradation in exercise performance can be alleviated.

One explanation for the impact of dehydration on exercise performance is that during exercise in the heat, sweat output can often exceed water intake and lead to overall loss of body water and reductions in plasma and blood volume. The amount of body fluid lost through thermoregulatory sweating can vary widely, but commonly is in the range of 0.5 to 1.5 L/h. The upper limits for fluid replacement during exercise heat stress are set by the maximal gastric emptying rates, which have been reported to be 1.0 to 1.5 L/hr for the average adult,[121,132] but are reduced by exercise heat stress and dehydration.[33] Although gastric emptying may or may not be sufficient to maintain hydration (depending on sweating rate), people tend to drink only after thirst develops. As presented earlier in the chapter, the sensation of thirst appears at ~295 mmol/kg[156] or ~2% of body mass loss. Thus, a significant amount of fluid loss occurs before the sensation of thirst drives fluid intake. During activity, if fluid intake occurs after being signaled by thirst sensation and is less than fluid loss through thermoregulatory sweating, the outcome is progressive dehydration. As a result of blood pooling in the skin and reduction in plasma volume secondary to sweating, cardiac filling is reduced and larger fractional utilization of oxygen is required at any given workload.[11] Ultimately, these responses have a negative impact on exercise/work performance, especially in warm/hot environments.

The negative impact of dehydration on work performance can increase risk in a field or wilderness setting. Dehydration, in combination with heat stress, reduces maximal oxygen uptake, increases relative effort, and reduces work output. When dehydrated, an individual will either not be able to trek as far or as fast compared to when euhydrated. For example, when on a hike, dehydration can increase the duration of time required to complete the hike beyond what is to be expected for a given distance and terrain, especially when in warm/hot environments. In the scenario of a day hike, or a hike to a destination, this increases the time to complete the hike and could result in a hiker being caught unprepared. If the expected plan for the day's trek is to complete the hike during daylight hours, or to arrive at a destination that has supplies, adequate food and water, proper clothing, maps, then GPS, headlamps or a compass may not be brought. Without the supplies and equipment mentioned, hikers may run the risk of getting lost or injuring themselves in the dark (trip or fall), becoming more dehydrated without sufficient food and water, or becoming hypothermic as temperatures fall.

## DEHYDRATION AND WORK PRODUCTIVITY

As previously discussed, during physical work in the heat, sweat output often exceeds water intake, which leads to body water losses. Bishop et al.[19] observed that in simulated industrial work conditions, encapsulated protective clothing produced sweating rates up to 2.25 L/hr. Likewise, wearing protective equipment such as full- or half-face masks can make fluid consumption more difficult and further contribute to dehydration in the workplace. Firefighters wear heavy protective clothing and are exposed to intense heat. Rossi[160] reported that firefighters wearing protective clothing and equipment while performing simulated work tasks in the heat can have sweat rates up to 2.1 L/hr. It is also the case that workers often not only become dehydrated on the job but also may start the work day with a fluid deficit. Brake et al.[21] observed fluid losses and hydration status of mine workers under thermal stress working extended shifts (12 hours). By measuring USG at the start of a work shift, they observed that 60% of the miners reported to work dehydrated and that their hydration status did not improve during the 10- to 12-hour shift.

While many studies have observed the effect of dehydration on physical work capacity, few studies have observed dehydration's impact on manual labor productivity. Wasterlund and Chaseling[200] studied forest workers in a 15° C (59° F) environment in two scenarios, one where subjects consumed fluid sufficient to maintain a normal hydration state and a second where subjects consumed limited fluid, which resulted in 0.7 kg body mass loss (>1% dehydration). The measure of productivity was the amount of time to stack and debark 2.4 cubic meters of pulpwood. When subjects were dehydrated, productivity of stacking and debarking pulpwood was reduced by 12%.

## DEHYDRATION AND COGNITIVE FUNCTION

Cognitive/mental performance, which is important when concentration, skilled tasks, and tactical issues are involved, is degraded by dehydration and hyperthermia.[80,158] The evidence is stronger for a negative effect of hyperthermia than for mild dehydration on degrading cognitive/mental performance,[42] but the two are closely linked when performing exercise in warm/hot weather. The relative hyperthermia associated with dehydration could diminish psychological drive[24] or perhaps alter central nervous system function independent of temperature. Adolph[4] reported that dehydrated subjects fainted more quickly when faced with a change in body posture (orthostatic challenge test). Likewise, Carter et al.[27] reported that subjects who were dehydrated by >2% of body mass from heat exposure exhibited significant reduction in cerebral blood flow velocity and possibly cerebral oxygen availability, when going from a seated to a standing posture. Intracranial volume is altered in response to dehydration,[54] although the exact functional consequence of this is unknown. Dehydration has been shown to adversely influence decision making and cognitive performance, which may contribute to decline in work capacity and could possibly be associated with increased risk of accidents. Dehydration has been reported to impair visual motor tracking, short-term memory, attention, and arithmetic efficiency[74] and to bring about greater tiredness, reduced alertness, and higher levels of perceived effort and concentration,[192] with as little as 2% dehydration. The negative impact of dehydration on short-term memory and fatigue may persist for up to 2 hours following rehydration.[42]

It is possible that factors associated with dehydration such as greater tiredness, reduced alertness, difficulty in concentrating/decision making, or orthostatic intolerance could contribute to accidents. Although there are no reported links, it is also possible that dehydration-mediated reductions in cognitive function and reaction time may be indirectly connected. In a classic study by Vernon,[198] accident rates were shown to be at their lowest at temperatures of ~20° C (68° F) and increased by 30% in environments of ~24° C (75° F). It is in warm/hot environments that fluid turnover is highest and individuals most likely to become dehydrated.

Changes in reaction time have been reported to accompany dehydration. Figure 70-7 depicts a 23% change in reaction time[74] when subjects were 4% dehydrated, in comparison to a study[131] that related the effects of blood alcohol content to driving skills. A blood alcohol level of 0.08 (legal limit in all states) yielded 17% slowing of drivers' response time.[131] Although these two studies[74,131] are not equivalent, because different tests were used to measure reaction time, a point of comparison can be made. Blood alcohol content at or above the legal limit in all U.S. results in significant impairment in the ability to operate a vehicle; it is possible that the changes in reaction time reported with dehydration may cause similar impairment and increase the potential risk for accidents to occur.

Accidents that occur as a result of delayed reaction time or those that are the result of a trip or fall can occur anywhere. However, when these accidents occur in wilderness situations, medical help may not be readily available and the consequences may be dire. Accidents such as trips or falls (dehydration-related orthostatic intolerance) can result in broken bones, lacerations, or death (fall from a height). In addition, accidents occurring

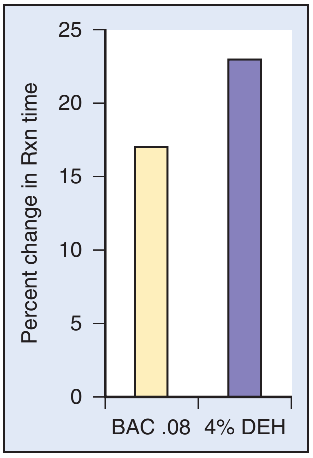

**FIGURE 70-7** Percent change (slowing) in reaction (Rxn) time relative to percentage loss in body mass (74) and blood alcohol content.[131]

during expeditions or when mountaineering can be traced to a poorly made initial decision (dehydration-related mental fatigue, reduced alertness and concentration) that led to subsequent bad decisions, further compounding the severity of the situation.

## DEHYDRATION, REHYDRATION RELATED ILLNESS

Dehydration increases the risk for heat exhaustion[3,118,177] and is a risk factor for heat stroke.[28,57,73,154] Other factors, such as lack of heat acclimatization, certain medications, genetic predisposition, and illness, often play a large role.[28,55] Historically, unexpected cases of heat-related illness were attributed solely to dehydration, as dehydration has been shown to impair thermoregulation and increase cardiovascular strain. However, it is now suspected that previous sickness or injury might increase susceptibility to serious heat illness.[90] Dehydration was present in ~17% of all heat stroke hospitalizations in the U.S. Army over a 22-year period.[28] In a series of 82 cases of heat stroke in Israeli soldiers, dehydration was present in ~16%.[57] Team physicians for American football have observed during summer practice that dehydration, occasionally brought on by emesis, contributes to heat stroke.[55,155] Dehydration has been associated with reduced autonomic cardiac stability,[29] altered intracranial volume,[54] and reduced cerebral blood flow velocity responses to orthostatic challenge.[27]

## HYPONATREMIA

Hyponatremia describes a state of lower than normal blood sodium concentration; typically <135 mEq/L. It is also used to describe a clinical syndrome that can occur when there is rapid lowering of blood sodium, usually to a level below 130 mEq/L and accompanied by altered cognitive status. This is a serious medical condition that can result in death. Exercise-associated hyponatremia occurs as a consequence of prolonged work (typically >5 hours), where sweating is the primary means of heat dissipation. Because sweat contains not only water but small quantities of electrolytes, there is a progressive loss of water, sodium, chloride, and potassium. Hyponatremia most often occurs when individuals consume low-sodium drinks or sodium-free water in excess of sweat losses (typified by body mass gains), either during or shortly after completing exercise. However, drinking sodium-free water at rates near to or slightly less than the sweat rate can theoretically produce biochemical hyponatremia when coupled with progressive loss of electrolytes. Reductions in solute concentration of extracellular fluid promote water movement from the extracellular space into cells. If this fluid shift is of sufficient magnitude and occurs rapidly, it can congest the lungs, result in brain swelling, and alter central nervous system function. Signs and symptoms of hyponatremia often mimic those of heat injury and include confusion, disorientation, loss of faculties, headache, nausea, vomiting, aphasia, loss of coordination, and muscle weakness. In general, hyponatremia can be distinguished from heat injury by the presence of repeated vomiting and abdominal distention and production of copious clear urine. Complications of severe and rapidly evolving hyponatremia include seizures, coma, pulmonary edema, and cardiorespiratory arrest.

Hyponatremia tends to be more common in long-duration activities and is precipitated by consumption of hypotonic fluid (water) alone. The interaction between drinking rate (water only) and plasma sodium concentration is illustrated in Figure 70-8A and B for a 70-kg individual, in 28° C (82° F) hiking at a moderate pace (6 km/hr), drinking at three different rates (200, 400, and 600 mL/hr). Figure 70-8A predicts the percentage change in body mass over time for the three drinking rates, whereas Figure 70-8B predicts the expected plasma sodium concentration. The slowest drinking rate (200 mL/hr) over the duration of the hike (12 hours) predicts an elevated plasma sodium level well above that of asymptomatic hyponatremia (135 mEq/L). However, this drinking rate also results in a >4% level of dehydration, a level of fluid loss that would substantially degrade performance (Figure 70-8A grey zone). Because the drinking rate is well in excess of sweating rate, the fastest drinking rate (600 mL/hr) actually results in a body mass gain and is predicted to result in asymptomatic hyponatremia within 5 to 6 hours of activity and symptomatic hyponatremia (sodium <130 mEq/L; grey zone Figure 70-8B) by 10 hours. It is important to note that predicted changes

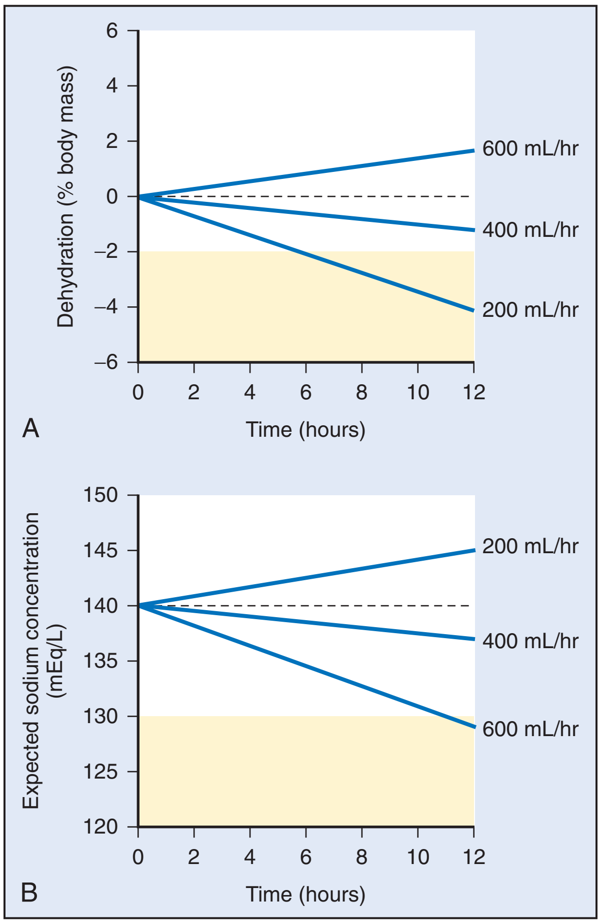

**FIGURE 70-8** Prediction of the percentage change in body mass (**A**) and plasma sodium concentration (**B**) over 12 hours for three drinking rates, 200, 400, and 600 mL/hr for a 70-kg individual, in 28° C (82° F) hiking at 6 km/hr. The grey zone in graph **A** represents the area where a substantial degradation in performance can be expected. The grey zone in figure **B** represents the plasma sodium concentration where symptomatic hyponatremia will occur. (Calculations from *Montain SJ, Cheuvront SN, Sawka MN: Exercise associated hyponatraemia: quantitative analysis to understand the aetiology.* Br J Sports Med *40:98, 2006.*)

in plasma sodium concentrations are different for individuals of greater or lesser body mass, varying sweat rates and sweat sodium concentrations. For example, in the case of individuals who lose large amounts of sodium in their sweat (salty sweaters), it is possible that matching fluid intake to sweat loss can still result in hyponatremia because of the progressive sodium loss over long-duration activity.[123] Overdrinking hypotonic fluid is the mechanism that leads to exercise-associated hyponatremia. In general, consumption of water should never exceed 12 quarts (~11 L). Consumption of an electrolyte-supplemented drink should substantially delay or prevent this outcome. This may be accomplished using prepared beverages or by adding electrolytes (e.g., Elete) to water.

Exercise-associated hyponatremia has been observed during marathon and ultramarathon competition,[52,81,187] military training,[68,145] and recreational activities.[13] In athletic events, the condition is more likely to occur in females and slower competitors, both of whom gain weight (due to drinking) during the event. The severity of the symptoms is related to the magnitude by which serum sodium concentration falls, and the rapidity with which it develops.[95] If hyponatremia develops over many hours, it might cause less brain swelling and less adverse symptoms.[95] Unreplaced sodium losses contribute to the rate and magnitude of sodium dilution and may in certain situations (e.g., salty sweaters) be the primary reason for development of exercise-associated hyponatremia.[123,127] Nausea, which increases AVP (antidiuretic hormone) secretion, and exercise heat stress, which reduces renal blood flow and urine output, can negatively affect the ability of kidneys to rapidly correct the fluid–electrolyte imbalance.[205] The syndrome can be prevented by not drinking in excess of sweat rate, and by consuming salt-containing fluids or foods when participating in exercise events that result in many hours of continuous or near-continuous sweating.

## DEHYDRATION AND LIMITS OF SURVIVAL

Severe elevations in blood osmotic pressures are incompatible with life. Just as hyponatremia (blood hypo-osmolality) can produce fatal brain swelling, severe hypernatremia (hyper-osmolality) can produce fatal brain shrinkage. The physical forces of each can produce tearing of intracerebral veins and cerebral hemorrhage.[8] Although other pathologic outcomes of severe dehydration may also have fatal consequences, the effects of hyper-osmolality on central nervous system function have long been suspected as primary.[20]

Acute elevations in plasma osmolality ($P_{osm}$) >350 mmol/kg produce neurologic symptoms in animals, such as seizures and coma; death in humans has been consistently observed in patients with $P_{osm}$ >370 mmol/kg.[8] Postmortem analysis of human vitreous humor samples in cases of death from dehydration show marked sodium elevations (>170 mmol/L).[108] By using the formula $2.1 \times Na^+$ to estimate osmolality,[82] a value of 357 mmol/kg is obtained. It therefore appears that a plasma osmolality value of 350 mmol/kg can be considered as an approximate limit for human survival.

The level of lethal dehydration ($P_{osm}$ >350 mmol/kg) and the time required to reach it can be estimated. If we assume that a 70-kg person possesses 42 L of body water and has a resting $P_{osm}$ of 285 mmol/kg, then the degree of pure water loss required to concentrate $P_{osm}$ to the lethal limit is $(285/350) \times 42 = 34.2$ L, or 7.8 L water loss. However, since electrolytes are also lost in urine and sweat, a reasonable correction can be applied (7.8/0.94), which gives 8.3 L. This gives a level of dehydration of almost 12% body mass and 20% of total body water. Although higher estimates have been made (~20% body mass), it is cautioned that as much as half of fasting weight losses derive from nonwater sources.[23] Under fasting conditions, Brown et al.[23] estimate that urine losses will stabilize at 0.5 L/day after the first day. The remaining losses from sweat depend on environmental temperature and body heat production.

Under hospitable indoor conditions, obligatory urine[23,84] and insensible sweat losses[84,98] add up to about 1.2 L/day, which makes survival without water possible for almost 7 days. This is longer than the 100-hour rule of thumb (about 4 days),[149] but highly dependent on environmental and behavioral factors. For example, in a worst-case desert scenario where there is 10 hours of daytime temperature exposure (>40° C [104° F]) and 14 hours of nighttime temperature exposure (<20° C [68° F]),[23] approximately 3.0 L/day of sweat loss can be added to the 0.5 L/day losses of urine when at rest.[23] This would limit survival to about 2.5 days. If the lost desert sojourner was to travel by night (14 hours) on foot through sand[69] at 4.8 km/hr (3 mph) and rest unshaded during the day, 8.6 L/day fluid losses[23,71] would limit survival to less than 1 day (23 hours). If traveling by day and night, sweat losses of approximately 0.60 L/hr (day) and 0.40 L/hr (night)[71] would limit survival to about 16 hours. In each case when traveling, the distance covered would be roughly the same (42-48 miles).

## DEHYDRATION AND SUSCEPTIBILITY TO COLD INJURY

A common response to cold exposure is cold-induced diuresis (CID), an increase in urine production associated with shift in fluid centrally induced by vasoconstriction.[174] In addition, when in a cold environment, attention to replacement of fluid losses is often neglected. If skin temperatures fall significantly, thirst is less noticeable in cold compared to hot weather.[93] In addition, individuals may voluntarily not drink fluid in an effort to decrease the need to urinate brought on by CID. Given the fluid loss brought on by CID, attenuation of thirst when exposed to cold, and voluntarily not ingesting fluid, dehydration can result. Dehydration in the cold may be more important during heavy exercise in the cold when core temperature is elevated and blood flow to skin increases to dissipate heat. If individuals in the cold are heavily clothed and/or traversing in snow (resulting in high metabolic rates),[147] they may overheat more readily and increase fluid losses due to thermoregulatory sweating. During cold-weather outdoor activities, individuals can still become dehydrated by 3% to 8% of their body mass 62. For these reasons, maintaining hydration is important when performing work in cold environments.

It appears that the impact of dehydration while in a cold environment does not have the same impact on exercise performance as in temperature or warm/hot environments. Recent data[33] show that if the skin temperatures are low, 4% dehydration has no effect on cycling performance in the cold. However, if cold strain is minimized by clothing, thereby maintaining skin and core temperatures near those observed in temperate or even hot environments, dehydration will likely degrade performance.[62] Dehydration does not alter heat conservation, heat production, or CIVD responses[143,144] and thus does not appear to increase the likelihood of peripheral cold associated injuries. However, lack of significant impact on exercise performance and injury does not negate the importance of maintaining hydration while in a cold environment. Little is known regarding the impact of long term, chronic dehydration similar to that experienced on long duration expeditions/missions in cold environments, where water availability is limited and sense of thirst is diminished. Individuals should drink adequately during endurance activity to replace fluid losses and prevent dehydration, even when in a cold environment. When returning to a warm environment, individuals who have free access to food and fluid will rehydrate on their own. When in the field, ice and snow can be melted. However, the source of ice or snow should be known, because only clean snow or ice should be melted for drinking water. If unsure, water melted from snow or ice should either be filtered, boiled or sanitized by addition of disinfection tablets.

# Fluid Replacement (Before, During, After)

The U.S. Army has developed fluid replacement and work pacing guidelines that incorporate work intensity, environment, work-to-rest cycles, and fluid intake as shown in Table 70-5.[126] These guidelines use wet bulb globe temperature (WBGT) to mark levels of environmental heat stress and emphasize both the need for sufficient fluid replacement during heat stress and concern for the dangers of overhydration. The WBGT takes environmental variables such as solar radiation, humidity, and ambient temperature into account in its calculation; automated systems for WBGT

**TABLE 70-5** Fluid Replacement Guidelines for Warm-Weather Training (Applies to Average Heat Acclimated Soldier Wearing BDU)

| | | Easy Work | | Moderate Work | | Hard Work | |
|---|---|---|---|---|---|---|---|
| Heat Category | WBGT Index, ° F | Work/Rest (min) | Water Intake (qt/hr) | Work/Rest (min) | Water Intake (qt/hr) | Work/Rest (min) | Water Intake (qt/hr) |
| 1 | 78°-81.9° | NL | ½ | NL | ¾ | 40/20 min | ¾ |
| 2 (green) | 82°-84.9° | NL | ½ | 50/10 min | ¾ | 30/30 min | 1 |
| 3 (yellow) | 85°-87.9° | NL | ¾ | 40/20 min | ¾ | 30/30 min | 1 |
| 4 (red) | 88°-89.9° | NL | ¾ | 30/30 min | ¾ | 20/40 min | 1 |
| 5 (black) | >90° | 50/10 min | 1 | 20/40 min | 1 | 10/50 | 1 |

Fluid Intake should not exceed 1.5 quarts (1.42 L) per hour or 12 quarts (11.36 L) per day.
BDU, battle dress uniform; NL, no limit to work time per hour.
The work/rest times and fluid replacement volumes will sustain performance and hydration for at least 4 hours of work in the specified heat category.
Individual water needs will vary ±0.25 quarts (0.24 L) per hour. Rest defined as minimal physical activity (sitting or standing), accomplished in shade if possible.
Wearing body armor: add 5° F to WBGT index.
Wearing mission-oriented protective posture (MOPP, chemical protection) over-garment, add 10° F to WBGT index.
Easy work: Weapon maintenance; walking hard surface at 2.5 mph (4 km/hr), ≤30-lb (13.6-kg) load; manual handling of arms; marksmanship training; drill and ceremony.
Moderate work: Walking loose sand at 2.5 mph (4 km/hr), no load; walking hard surface at 3.5 mph (5.6 km/hr), ≤40-lb (18.14-kg) load; calisthenics; patrolling; individual movement techniques(e.g., low crawl, high crawl); defensive position construction; field assaults.
Hard work: Walking hard surface at 3.5 mph (4 km/hr), ≥40-lb (18.14-kg) load; walking loose sand at 2.5 mph (4 km/hr) with load.

measurement are commercially available. The fluid-replacement guidelines in Table 70-5 were designed to be simple and practical for use with large cohorts in situations where determining individual sweat rates would be impractical. These recommendations specify an upper limit for hourly and daily water intake, which safeguards against overdrinking and water intoxication. However, it is recommended that individuals performing endurance activities validate their sweat rates, because the guidelines do not account for individual variability.

## ACSM FLUID REPLACEMENT RECOMMENDATIONS

The most current knowledge regarding exercise with respect to fluid replacement is presented in the 2007 American College of Sports Medicine Position Statement on Exercise and Fluid Replacement.[165] The position statement summarizes current knowledge regarding exercise with respect to fluid and electrolyte needs and the impact of their imbalances on exercise performance and health. The recent statement stresses the fact that individuals have varying sweat rates and as such, fluid needs for individuals performing similar tasks under identical conditions can be very different. Specifically the ACSM Position Statement provides recommendations in relation to hydration prior to, during, and following exercise/activity.

**Before Exercise.** The objective is to begin the physical activity euhydrated and with normal plasma electrolyte levels. If sufficient beverages are consumed with meals and a protracted recovery period (8-12 hours) has elapsed since the last exercise session, then the person should already be close to being euhydrated.[84] However, if the person has suffered substantial fluid deficits and has not had adequate time or fluids/electrolytes in quantities sufficient to reestablish euhydration, then an aggressive pre-hydration program may be merited. When hydrating prior to exercise the individual should slowly drink beverage (for example, ~5-7 mL/kg body mass, 350-490 mL for a 70-kg individual) at least 4 hours before the exercise task. If the individual does not produce urine, or the urine is dark or highly concentrated, the individual should slowly drink more beverage (e.g., another ~3-5 mL/kg body mass, 210-350 mL for a 70-kg individual) about 2 hours before activity. By hydrating several hours prior to exercise, there is sufficient time for urine output to return toward normal before activity. Consuming beverages with sodium (20-50 mEq/L) and/or small amounts of salted snacks or sodium-containing foods at meals will help to stimulate thirst and retain the consumed fluids.[113,153,183]

Hyper-hydration can be achieved either by overdrinking or ingesting fluids (e.g., water) that expand the extra- and intracellular spaces. Simple overdrinking usually stimulates urine production,[84] and body water rapidly returns to euhydration within several hours.[61,142,183] This means of hyperhydrating greatly increases the risk of having to void during activity/exercise[61,142] and provides no clear physiological or performance advantage over euhydration.[91,99,100] In addition, hyperhydration can substantially dilute and lower plasma sodium[61,142] before starting exercise and therefore increase the risk of dilutional hyponatremia if fluids are aggressively replaced during exercise.[123] Enhancing palatability of ingested fluids is one way to help promote fluid consumption, before, during, or after exercise. Fluid palatability is influenced by several factors, including temperature (preferred between 15° and 20° C [59° and 68° F]), sodium content, and flavoring.

**During Exercise.** The objective is to drink enough fluid to prevent excessive dehydration (>2% body mass loss from water deficit) during exercise by replacing sweat losses to help sustain performance. The amount and rate of fluid replacement depends on the individual sweating rate, exercise duration, and opportunities to drink. Individuals should periodically drink (as opportunities allow) during activity; if it is expected, they will become excessively dehydrated from not drinking. Care should be taken in determining fluid replacement rates, particularly in prolonged exercise lasting greater than 3 hours. The longer the exercise duration, the greater the cumulative effects of slight mismatches between fluid needs and replacement, which can exacerbate dehydration or dilutional hyponatremia.[123] It is recommended that individuals should monitor body mass changes during training/activity to estimate their sweat lost during a particular exercise task with respect to the weather conditions. This allows customized fluid replacement programs to be developed for each person's particular needs; however, this may not always be practical.

The Institute of Medicine also provides general guidance for composition of "sports beverages" for persons performing prolonged physical activity in hot weather.[83] They recommended that fluid replacement beverages should contain ~20 to 30 mEq/L sodium (chloride as the anion), ~2 to 5 mEq/L potassium and ~5% to 10% carbohydrate.[83] The need for these different components (carbohydrate and electrolytes) will depend on the specific exercise task (e.g., intensity and duration) and weather conditions. The sodium and potassium are to help replace sweat electrolyte losses, while sodium also helps to stimulate thirst, and carbohydrate provides energy. These components also can be consumed using non-fluid sources such as gels, energy bars and other foods.

Carbohydrate consumption can be beneficial to sustain exercise intensity during high-intensity exercise events of ~1 hour or longer, as well as less intense exercise/activity sustained for longer periods.[18,49,50,88,202] Carbohydrate-based sports beverages are sometimes used to meet carbohydrate needs, while attempting to replace sweat water and electrolyte losses. Carbohydrate consumption at a rate of 1 g/min has been demonstrated to maintain blood glucose levels and exercise performance.[49,50] Most typical sport beverages contain carbohydrate sufficient to achieve this goal if drinking a liter per hour or less. It should be noted that this rate of carbohydrate consumption was observed in highly fit, elite athletes. Most individuals would not work or perform exercise at a high enough intensity or for long enough duration to utilize 1g/min. The greatest rates of carbohydrate delivery are achieved with a mixture of simple sugars (e.g., glucose, sucrose, fructose, maltodextrin). If fluid replacement and carbohydrate delivery are going to be met with a single beverage, the carbohydrate concentration should not exceed 8%, or even be slightly less, as highly concentrated carbohydrate beverages reduce gastric emptying.[87,199] Finally, caffeine consumption might help to sustain exercise performance[48] and likely will not alter hydration status during exercise.[50,203]

**After Exercise.** If recovery time and opportunities permit, consumption of normal meals and snacks with a sufficient volume of plain water will restore euhydration, provided the food contains sufficient sodium to replace sweat losses.[84] If dehydration is substantial (>2% body mass) with a relatively short recovery period (<12 hours), then an aggressive rehydration program may be merited.[112,113,183]

Failure to sufficiently replace sodium losses prevents return to a euhydrated state and stimulates excessive urine production.[112,139,182] Consuming sodium helps retain ingested fluids and stimulates thirst. Sodium losses are more difficult to assess than are water losses and it is well known that individuals lose sweat electrolytes at vastly different rates. Drinks containing sodium, such as sports beverages, may be helpful, but many foods can supply the needed electrolytes. A little extra salt may be added to meals and recovery fluids when sweat sodium losses are high. Table 70-6 presents the electrolyte content of common sport drinks, tablets, and powdered additives.

Individuals looking to achieve rapid and complete recovery from dehydration should drink ~1.5 L of fluid for each kilogram of body mass lost.[182] The additional volume is needed to compensate for the increased urine production accompanying the rapid consumption of large volumes of fluid.[182] Therefore, to maximize fluid retention, fluids should be consumed over time (and with sufficient electrolytes) rather than being ingested in large boluses.[96,204] The use of intravenous fluid replacement after exercise may be warranted in individuals with severe dehydration, nausea, vomiting, or diarrhea, or who for some reason cannot ingest oral fluids.

**Education.** Alleviating dehydration should involve a combination of strategies that include assessment, education, and inclusion of practices that encourage fluid intake. Education is a vital component to help individuals maintain hydration before, during, and after activity. Informing individuals, especially those who perform work/activity in a hot environment, about hydration assessment, signs and dangers of dehydration, and strategies in maintaining hydration, can help to reduce incidences of dehydration. Brake et al.[21] reported that individuals working in a thermally stressful environment were better able to maintain hydration when they were educated about dehydration, assessed their hydration state, and used a fluid replacement program while performing working.

## MODIFYING FACTORS

**Diet.** One important aspect of an education and hydration program should stress the importance of consuming meals. Meal consumption is critical to ensure full hydration on a day-to-day basis.[2,3,186] Eating food promotes fluid intake and retention[84] and sweat electrolyte (e.g., sodium and potassium) losses can be replaced during meals with most individuals.[106,139,183] De Castro[53] observed food and fluid intake of 36 adults over 7 consecutive days and concluded that the amount of fluid ingested was primarily related to the amount of food ingested and that fluid intake independent of eating was relatively rare. In addition, Maughan et al.,[114] among others, reported that meals play an important role in helping to stimulate the thirst response, causing the intake of additional fluids and restoration of fluid balance. Using established meal breaks may help replenish fluids and can be important in replacing sodium and other electrolytes.

Caffeine is contained in many beverages and foods. Recent evidence suggests that caffeine consumed in relatively small doses (<180 mg/day) will likely not increase daily urine output or cause dehydration.[10] Maughan et al.[111] performed a review of literature concerning the effect of caffeine ingestion on fluid balance. They concluded from their review of the literature that doses of caffeine equivalent to the amount normally found in standard servings of tea, coffee, and carbonated soft drinks appear to have no diuretic action and that their consumption will not result in fluid losses in excess of the volume ingested. Therefore, there would appear to be no clear basis for refraining from caffeine-containing drinks in situations where fluid balance might be compromised. However, because alcohol can act as a diuretic (particularly at high doses) and increase urine output, it should be consumed in moderation, particularly during the postexercise period when rehydration is a goal.[181]

**Clothing.** Anecdotal statements and interviews have revealed that individuals will purposefully not drink fluid (voluntary dehydration) in certain situations, such as when bathroom facilities are not available, or when in cold environments where exposure to the environment may be an issue, or due to clothing systems that are difficult to remove. While logistical factors and conditions in the field may complicate access to facilities, there are a number of alternatives (e.g., toilet tents) that can help to address this issue and reduce the practice of voluntary dehydration.

**TABLE 70-6** Electrolyte Content of Common Sport Drinks, Tablets, and Powdered Additives That Can Be Used to Help Replace Electrolytes Lost During Activity/Exercise

| Product | Serving Size | CHO | $Na^+$ | $K^+$ | $Ca^{2+}$ | $Mg^{2+}$ |
|---|---|---|---|---|---|---|
| CeraSport | fl. oz. | 5 g | 200 mg | 100 mg | 0 mg | 0 mg |
| Ensure | fl. oz. | 42 g | 200 mg | 460 mg | 375 mg | 62.5 mg |
| Elete Electrolyte Add-in | ½ teaspoon | 0 g | 125 mg | 130 mg | 0 mg | 45 mg |
| Elete Tablytes® | 1 tablet | 0 g | 150 mg | 95 mg | 40 mg | 30 mg |
| Gatorade (G2 Series) | 8 fl. oz. | 14 g | 110 mg | 30 mg | 0 mg | 0 mg |
| Gatorade (Pro Series) | 8 fl. oz. | 14 g | 200 mg | 90 mg | 0 mg | 0 mg |
| Lucozade Lite | 8 fl. oz. | 5 g | 0 mg | 0 mg | 92.5 mg | 0 mg |
| Nutrilite | 8 fl. oz. | 14 g | 110 mg | 3 0 mg | 0 mg | 0 mg |
| Pedialyte | 8 fl. oz. | 6 g | 253 mg | 192 mg | 25 mg | 2.5 mg |
| Powerade | 8 fl. oz. | 14 g | 100 mg | 25 mg | 0 mg | 0 mg |
| Powerade Zero | 8 fl. oz. | 0 g | 55 mg | 35 mg | 0 mg | 0 mg |
| Vitaminwater Essential | 8 fl. oz. | 13 g | 0 mg | 70 mg | 50 mg | 0 mg |
| Vitalyte | 8 fl. oz. | 10 g | 68 mg | 92 mg | 2.1 mg | 1.6 mg |

**Sex.** Women typically have lower sweating rates and electrolyte losses than men.[12,172,179] Women appear to be at greater risk than men to develop symptomatic hyponatremia when competing in longer duration events such as marathon or ultra-marathon races.[6,81] This risk can be alleviated by not overdrinking fluid.

**Age.** Older (age >65 years) persons are generally adequately hydrated.[84] However, there is an age-related blunting of thirst response to water deprivation,[101,107,159] making older persons more susceptible to becoming dehydrated.[101] Older adults have age-related increase in resting plasma osmolality and are slower to restore body fluid homeostasis in response to water deprivation[148] and exercise[107] than are younger adults. If given sufficient time and access to water and sodium, older adults adequately restore body fluids.[105,107] Older persons are also slower to excrete water following fluid loads.* This slower water and sodium excretion increases sodium retention, which may lead to increased blood pressure.[105]

While thirst sensitivity to a given extracellular fluid loss is reduced in older adults, osmoreceptor signaling remains intact.[107,189,190] The osmotic and volume stimuli that result from dehydrating impart important drives for thirst and drinking in older adults just as they in younger people.[15] Older adults should be encouraged to rehydrate during or after exercise. Pre-pubescent children have lower sweating rates than adults, with values rarely exceeding 400 mL per hour.[16,120] However, sweat electrolyte content is similar (or slightly lower) in children compared to adults.[16] Lower sweating rates in children are probably the result of smaller body mass and metabolic rate, depending on age and the fact that thermoregulatory sweating is not fully developed until adolescence. While older adults and young children represent the extremes within the population, no matter the age, if attention is paid to the hydration guidelines, overdrinking will not occur and hydration can be maintained.

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*Complete references used in this text are available online at www.expertconsult.com.*

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*References 104, 107, 189, 190, and 193.

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