

National Athletic Trainers' Association Position Statement: Fluid Replacement for the Physically Active

Brendon P. McDermott, PhD, ATC, FACSM*; Scott A. Anderson, ATC†; Lawrence E. Armstrong, PhD, FACSM‡; Douglas J. Casa, PhD, ATC, FNATA, FACSM§; Samuel N. Cheuvront, PhD, RD, FACSM¶; Larry Cooper, MS, ATC¶; W. Larry Kenney, PhD, FACSM#; Francis G. O'Connor, MD, MPH, FACSM||; William O. Roberts, MD, MS, FACSM**

*University of Arkansas, Fayetteville; †University of Oklahoma, Norman; ‡University of Connecticut, Storrs; §US Army Research Institute of Environmental Medicine, Natick, MA; ¶Trafford High School, Harrison City, PA; #Pennsylvania State University, University Park; ||Uniformed Services University of Health Sciences, Bethesda, MD; **University of Minnesota Medical School, Minneapolis

Objective: To present evidence-based recommendations that promote optimized fluid-maintenance practices for physically active individuals.

Background: Both a lack of adequate fluid replacement (hypohydration) and excessive intake (hyperhydration) can compromise athletic performance and increase health risks. Athletes need access to water to prevent hypohydration during physical activity but must be aware of the risks of overdrinking and hyponatremia. Drinking behavior can be modified by education, accessibility, experience, and palatability. This statement updates practical recommendations regarding fluid-replacement strategies for physically active individuals.

Recommendations: Educate physically active people regarding the benefits of fluid replacement to promote performance and safety and the potential risks of both hypohydration and hyperhydration on health and physical performance. Quantify sweat rates for physically active individuals during exercise in various environments. Work with individuals to develop fluid-replacement practices that promote sufficient but not excessive hydration before, during, and after physical activity.

Key Words: athletic performance, dehydration, hydration protocol, hydration status, hyponatremia, oral rehydration solution, rehydration, overhydration, fluid overload

In humans, total body water and overall hydration are normally maintained within a relatively narrow range (1% hyperhydration to 3% hypohydration).^{1,2} The benefits of optimal hydration status include maintaining athletic performance,^{3–6} maximizing the transfer of metabolic heat,^{5,7} maintaining mood,^{8,9} and facilitating recovery from exercise.^{10,11} All may be compromised at modest levels of hypohydration (approximately 2%).^{5,9} However, extreme deviations on either end of the physiological range (hypohydration or hyperhydration) can compromise health and organ function.^{12–14}

A majority (more than 50%) of athletes in professional sports,¹⁵ collegiate athletics,^{16,17} and high school¹⁸ and

youth sports^{19,20} arrive at workouts hypohydrated. When access to fluids based on thirst and voluntary fluid intake is adequate during activity, humans replace roughly two-thirds of sweat losses.^{21–25}

Maintaining hydration status with minimal variation (+1% to –1%) allows the body to optimally thermoregulate^{5,26,27} and maintain cardiovascular function.^{7,28,29} Evaporative heat loss is the most effective mode of heat dissipation in warm or hot conditions. If the eccrine sweating mechanism is compromised due to a lack of available body fluid, core temperature increases above that expected for the activity and environment.^{30,31} Appropriate hydration is similarly important for physical activity at



altitude, for individuals with chronic disease, and for thermoregulation in cold environments.^{32,33}

Conversely, excessive fluid consumption can lead to life-threatening exercise-associated hyponatremia (EAH), in which extracellular body water enters the cells and causes organ and tissue swelling.^{34,35} Although EAH is uncommon in team-sport athletes, it has been identified in 10% to 20% of distance athletes after events.^{35–38} The condition can be fatal when brain cells swell and brain tissue herniates through the foramen magnum or the brain swelling triggers noncardiogenic pulmonary edema that leads to respiratory failure.³⁴ It is imperative that individuals remain within or close to the normal range of plasma volume and serum osmolality to prevent substantially low or high body water volumes before, during, and after physical activity and to maintain performance and health.

This position paper is an update to the previous National Athletic Trainers' Association (NATA) position statement on fluid replacement for athletes (published in 2000). It expands the scope of recommendations and updates the topic of fluid replacement based on recent literature regarding hydration in physically active individuals.

PURPOSES

This position statement is based on an extensive literature review and includes definitions of normal and abnormal hydration and fluid-balance recommendations to help athletic trainers (ATs) and other health care providers

1. Understand that fluid losses and needs are variable and that fluid-balance needs must be individualized for best results.
2. Educate physically active individuals on how to maintain their hydration status in order to avoid moderate to severe hypohydration and EAH and promote safety and performance.
3. Know the importance of approximating or maintaining euhydration before, during, and after exercise in physically active individuals.
4. Develop hydration strategies to follow before, during, and after physical activity.
5. Recognize the signs and symptoms of hypohydration and EAH to enable differentiation of hydration concerns from exertional heat illness and also understand diagnostic procedures and point-of-care blood analysis.
6. Acknowledge when on-site treatment is appropriate for hypohydrated or hyponatremic patients and when to transfer for evaluation and management at an advanced medical facility.
7. Identify unique personal characteristics (eg, age, disease states) and environmental variances (eg, altitude, cold) that may alter the regulation of fluid balance during exercise.

DEFINITIONS

Euhydration

Euhydration is the state of optimal total body water content as regulated by the brain. Intracellular and extracellular fluid volumes are maintained with minimal physiological adjustment. The body's systems function most efficiently in this state.

Hyperhydration

Hyperhydration is the state of excessive total body water content with expanded intracellular and extracellular fluid volumes. The body normally excretes the excess fluids.

Exercise-Associated Hyponatremia

A potentially fatal condition, *EAH* is defined as a serum sodium concentration of less than 135 mmol·L⁻¹ during or within 24 hours of physical activity.^{13,34–36} Exercise-associated hyponatremia is a potential medical emergency that is typically symptomatic at levels below 130 mmol·L⁻¹.

Dehydration

The process of losing body water is known as *dehydration*. During exercise, body water is most often lost through sweating. Water loss through urine (eg, diuretic use), respiration, feces (especially with diarrhea), or vomiting can also dehydrate the body.

Hypohydration

Hypohydration is a deficit of body water that is caused by acute or chronic dehydration. Hypohydration represents a continuum from both a clinical perspective (mild = 1% to 5%, moderate = 5% to 10%, and severe = >10% body mass deficit) and an athletic perspective (mild to moderate = 2% to 5% and severe = >5% body mass deficit) where mass = volume. In athletes, a deficit greater than 5% is consistently associated with impaired performance, extreme thirst, headache, and other symptoms; such a fluid deficit is difficult to replace, even with extended recovery time.

Drinking ad libitum

Derived from the Latin, *drinking ad libitum* (*ad lib*) means “drinking at one's pleasure.” This consists of consuming fluids when desired and of the selected or preferred concentration, flavor, consistency, temperature, etc. However, this strategy does not necessarily include the ongoing assessment of thirst.²¹

Drinking to Thirst

Consuming fluids as thirst dictates is called *drinking to thirst*. Thirst is the psychological sensation of and motivation for seeking fluids to consume. This strategy involves consuming fluids when thirsty and drinking enough to limit the sensation of thirst before and throughout activity.

EVIDENCE CLASSIFICATION

Strength of Recommendation Taxonomy

The recommendations in this statement are supported using the Strength of Recommendation Taxonomy (SORT) system.³⁷ The letter indicates the consistency and evidence-based strength of the recommendation (*A* reflects the strongest evidence base). For the practicing clinician, any recommendation with an *A* grade warrants attention and should be inherent to clinical practice. Less research supports recommendations with grades *B* and *C*; these should be discussed by the sports medicine staff. Grade *B*

Table 1. Signs and Symptoms of Hypohydration and Hyponatremia

Hypohydration (Decreased Total Body Water)	Hyponatremia (Low Blood Sodium Concentration)
Thirst	Altered mental status
Flushed skin	Muscular twitching or weakness
Apathy ^a	Apathy ^a
Dizziness or lightheadedness ^a	Dizziness or lightheadedness ^a
Nausea, diarrhea, or vomiting ^a	Nausea or vomiting ^a
Heat sensations or chills	Acting “out of sorts”
Headache ^a	Headache (progressive and severe) ^a
Dyspnea (only in severe cases) ^a	Dyspnea ^a
Gastrointestinal cramping	Swelling of hands, feet, or both
General discomfort	Mood changes
Acute body weight loss	Disorientation or confusion
	Grand mal seizure or coma
	Acute weight gain

^a Signs or symptoms that are common in both conditions, necessitating blood-sodium assessment for differentiation before treatment. Note: A patient can be hypohydrated and hyponatremic at the same time.^{35,36,38,50}

recommendations are based on inconsistent or limited controlled research outcomes. Grade C recommendations should be considered as expert guidance despite limited research support.³⁷

RECOMMENDATIONS

Importance of Maintaining Fluid Balance and Regulation

1. Among individuals in free-living conditions, habitual fluid intake and urine production are highly variable.^{1,20,39–41} Furthermore, sweat rate,^{18,42–44} thirst,^{21,45–49} and fluid intake^{19,20,24,43,50–55} during exercise vary greatly. Therefore, individualized fluid-maintenance recommendations need to be considered for physically active people. *Strength of Recommendation (SOR): A*

Importance of Maintaining Euhydration

2. Both severe clinical hypohydration and hyperhydration can degrade athletic performance and are potentially fatal.^{34–36,38,50,56–58} Early signs and symptoms of these conditions may overlap, including
 - a. Thirst
 - b. General malaise
 - c. Fatigue
 - d. Headache
 - e. Vomiting

Later signs and symptoms of hypohydration (eg, thirst, gastrointestinal cramping, heat sensations or chills) and hyperhydration (eg, extremity swelling, altered mentation, mood changes, seizure) begin to distinguish the 2 conditions, but prompt blood analysis (via point-of-care devices if available) and measurement of body weight can expedite accurate diagnosis (Table 1).^{35,36,38,50,58,59} *SOR: B*

3. Hypohydration leads to increased cardiovascular stress during exercise.^{7,28,60} Health care professionals should understand this fact, educate physically active individuals

appropriately, and apply strategies to prevent moderate to severe hypohydration. *SOR: A*

4. Thermoregulation is compromised by hypohydration greater than 1%,⁴ and the risk of exertional heat illness increases at moderate to severe levels (greater than 3%).^{5,27,29,61–64} This is 1 of myriad factors known to contribute to heat illness.⁶⁵ Optimal hydration is a modifiable factor that should be attempted to help prevent the onset of heat illness. *SOR: B*
5. Exercise-associated hyponatremia is caused by excessive consumption of hypotonic fluids (including sports drinks), often combined with reduced renal water clearance, resulting in maintained or increased body weight during exercise lasting 1 hour or more. Physically active individuals should not consume fluid that exceeds their exercise-related body mass losses and should monitor their weight before and after exercise to confirm adherence.^{13,34,36,66} *SOR: A*
6. Individuals should not gain body mass (or body weight) during exercise (from pre-exercise to postexercise) unless they begin activity with an unavoidable fluid deficit.^{13,34–36,58,67,68} Hyperhydration confers no physiological or performance advantages and is not recommended, except in specific situations with medical oversight and when factors necessitating hyperhydration before activity (eg, lack of fluid availability during the event, known excessive sweat losses) are present. Furthermore, if hyperhydration reduces blood sodium concentrations, it can lead to EAH. *SOR: A*
7. Euhydration (+1 to –1% compared with baseline values) aids thermoregulatory control^{5,7,27,28,30,60–63,69–71} and helps prevent symptoms of heat illness.^{63,72} Athletic trainers should promote euhydration in this range before exercise and a body mass loss of less than 2% at the end of exercise. *SOR: A*
8. Physically active individuals should maintain euhydration (+1% to –1%) for optimal exercise performance.^{3–6,62,64,73–77} *SOR: B*

Fluid Replacement

9. Preseason or pre-event education to optimize fluid balance in athletes should be directed at athletes, administrators, coaches, and event directors and should include the following^{17,35,38,56,78,79}:
 - a. The consequences of dehydration or fluid overload.
 - b. Hydration-monitoring strategies.
 - c. How to use reliable and valid measures of pre-exercise and postexercise body mass measurements to assess fluid status.
 - d. How to schedule activities and modify the rules of play to optimize hydration and improve safety.
 - e. Environmental influences on fluid requirements. *SOR: C*
10. Athletic trainers should educate physically active people, the parents of physically active children, and coaches about sweat rate, sweat-rate calculation, and how to develop an individualized hydration plan.^{19,20,78,79} *SOR: B*
11. Athletic trainers or other health care providers should help establish individualized hydration plans for physically active people (including those involved in team

sports). The plans should include rehydration strategies that consider sweat rate, environment, acclimatization state, body size, exercise duration, exercise intensity, and individual fluid preferences and tolerance.^{19,20,79} *SOR: B*

12. Gastric emptying (ie, how quickly fluids exit the stomach) is independently altered by fluid volume, osmolality, pH, carbohydrate type and concentration (if present in the fluid), exercise intensity, environmental stresses, fluid temperature, and the extent of hypohydration. Each of these variables should be considered when an individual hydration strategy is developed.^{78,80–84} *SOR: B*
13. Heat acclimatization affects the fluid and electrolyte requirements of physically active people. Sweat losses increase and sweat-electrolyte concentrations decrease with heat acclimatization.^{85–89} Electrolyte losses may increase or decrease depending on the relative magnitude of each of these factors. Heat acclimatization should be a factor in developing individualized fluid-replacement plans. *SOR: A*
14. Water or other palatable fluids should be easily accessible before, during, and after activity.^{51,90} Athletes often prefer cool, flavored beverages; these should be available, when possible, to promote rehydration.^{51,91,92} *SOR: B*
15. Physically active individuals should refuel (ie, eat and drink) within 2 hours of physical activity to replace fluid, electrolytes, carbohydrates, and protein.^{11,93–106} *SOR: B*
16. Athletic trainers should develop policies that use environmental-condition guidelines to determine work-rest ratios and provide water breaks. They should communicate with coaches and administrators to implement appropriate policies.^{107–110} *SOR: B*

Beverage Additives

17. The athlete's diet and rehydration beverages should include sufficient sodium (enough to replace losses but not an excessive amount) to prevent or resolve imbalances that may occur as a result of sweat and urine losses.^{10,19,93,111} *SOR: B*
18. Pre-exercise sodium ingestion can expand vascular fluid volumes.^{100,112} Ingesting sodium during activity delays blood sodium decreases in some people^{87,88,113} but has a limited preventive effect in others.^{35,58,114,115} Sodium supplementation before and during exercise should be individualized based on specific losses and needs and should be practiced. *SOR: B*
19. Caffeine may increase short-term urine production at rest but does not induce diuresis during exercise.^{116–118} Athletic trainers should not discourage mild or moderate (approximately 3 mg/kg; more than a cup of coffee for a 70-kg individual) caffeine consumption before and every 30 minutes during exercise on the basis of diuretic effects.^{116–121} *SOR: A*
20. Hyperhydration using glycerol is not recommended for athletes due to potential negative side effects (eg, headache, lightheadedness, nausea) and insufficient evidence of performance benefit.^{122–127} *SOR: B*
21. Beverages with $\leq 4\%$ alcohol content do not dehydrate active people.^{128,129} However, beverages with greater alcohol content facilitate excessive diuresis and should be discouraged for fluid replacement. *SOR: B*

Hydration Assessment

22. Calculating body mass change is a quick and effective way for the AT and other health care providers to track hydration status over the course of 24 hours.^{130,131} This measure is valid only when compared with at least 3 consecutive days of euhydrated baseline average mass.^{132–134} Body mass changes are also useful for assessing hydration status between practices on days with multiple workouts and can help educate athletes regarding individual fluid needs. Body mass should be used as an objective hydration measure by physically active individuals and clinicians to ensure maintenance of hydration status. *SOR: B*
23. Assessment of the first morning urine void increases the validity of hydration-status measurement.^{39,135–140} Health care professionals should test the first morning urine for urine specific gravity (USG), when feasible, to evaluate hydration status. Spot urine samples at other times of the day can be confounded by fluid intake, exercise, and food intake and may not be accurate indicators of hydration status.¹³⁷ *SOR: B*
24. Personal cues are important for individuals to gauge their hydration status. Thirst sensation, void frequency, and urine color are valuable indicators over the course of a day or between days for obtaining a relative hydration assessment.^{45,141} These factors should be addressed in hydration education and regarded as personal reminders for individuals in their daily hydration maintenance. *SOR: C*

Unique Situations

25. At events (eg, road races, tournaments) that carry the potential for athletes to develop hypohydration and EAH during and after competition, appropriate personnel should educate participants and staff in advance regarding fluid balance.^{142–145} *SOR: B*
26. If moderate (2% to 5%) or severe (greater than 5%) hypohydration is identified, oral fluids should be administered. Only if oral fluids are not tolerated or fluid losses are ongoing (from vomiting or diarrhea) should intravenous (IV) fluids be administered by an appropriately trained and licensed medical professional. In the absence of a diagnosis beyond hypohydration, preventive IV fluids are not recommended. Administration of IV fluids for same-day return to play should be supervised by a licensed medical professional on-site who is responsible for patient health and safety.^{2,146,147} *SOR: B*
27. Hypohydration and EAH are risk factors for exertional rhabdomyolysis during physical activity and both can increase its severity.^{67,68,148} Athletic trainers should facilitate appropriate education and fluid availability (eg, adequate but not excessive) to help athletes maintain euhydration during physical activity. *SOR: C*
28. Hypohydration is a known predisposing factor for exertional sickling in those with sickle cell trait or disease.⁵⁹ Targeted education and hydration monitoring are warranted for an athlete known to have sickle cell trait or disease.^{149–151} *SOR: B*
29. When determining an athlete's weight-class eligibility, hydration status should be assessed using a valid measure

of hydration status (eg, first voided urine osmolality or refractometer USG).^{90,152–155} *SOR: B*

30. Whole-body sweat losses in children are less than in adults, and children require different rehydration plans than adults.^{24,55,156–158} Hydration education is important for youth and adolescent athletes.^{19,20,79} Athletic trainers should facilitate proper education based on individual needs. *SOR: B*
31. Beyond age 50 years, a person's thirst sensitivity decreases with hypohydration and urine-concentrating ability decreases.¹⁵⁹ Extra consideration for hydration should be directed toward these populations during physical activity.^{24,159,160} *SOR: A*

LITERATURE REVIEW

Fluid Balance and Regulation

The human body maintains total body water within a narrow range to preserve homeostasis. Individual fluid consumption varies from person to person at rest and before, during, and after exercise.^{1,39,40,161} Athletic trainers should promote fluid-balance habits that contribute to overall health and the reduction of injury and illness.

Water is a major component of the human body, accounting for approximately 73% of lean body mass in young adults.¹⁶² Body water is distributed within cells (*intracellular fluid*), between cells (*interstitial fluid*), and in plasma (*intravascular fluid*). At rest, approximately 40% of the total body mass is intracellular fluid, 15% is interstitial fluid, and 5% is intravascular fluid.¹⁶³ Water movement between compartments is due to hydrostatic, osmotic (sodium and potassium), and oncotic (protein) pressures. Sweat is hypotonic relative to body water, so elevated extracellular tonicity results in water movement from the intracellular to extracellular (interstitial and intravascular) spaces. As a consequence, all water compartments can dehydrate with sweating, contributing to a total body-water deficit and hypohydration.^{164,165} The resulting hypovolemic hyperosmolality is thought to precipitate many of the physiological consequences associated with hypohydration.

Importance of Maintaining Euhydration

Physiological Implications of Hypohydration. All physiological systems in the human body are influenced by hypohydration. The degree of hypohydration dictates the extent of systemic compromise. Isolating the physiological changes that contribute to systemic compromise is difficult, as an alteration in 1 system (eg, cardiovascular) influences the function of other systems (eg, thermoregulatory, muscular). In terms of thermoregulation, the body balances metabolic heat production and exogenous heat accumulation by transporting heat via the vascular system to the body surface and dissipating it via conduction, convection, evaporation, and radiation at the skin. The relative contribution of each heat-transfer mechanism depends on the environmental conditions and exercise intensity.^{166–170} Evaporation is the predominant heat-loss mechanism during exercise in warm conditions.^{167,171} The sweating response is therefore critical to maintaining body temperature during exercise in the heat. If water loss via sweating occurs at a greater rate than fluid consumption,

dehydration ensues, affecting both sweating and heat transport from working muscles.

During exercise, the body preferentially directs intravascular fluids to (1) the brain for nutrition and oxygen delivery, (2) the heart and lungs for blood circulation and gas exchange, (3) the peripheral sweat glands and blood vessels for thermoregulation, and (4) the working muscles for nutrition and oxygen delivery.^{7,30,61,71} More than 2% hypohydration causes a decrease in sweat rate and sweating onset.⁶⁴ Severe hypohydration (greater than 5%) threatens the ability to maintain normal body temperature, exercise intensity, and vital organ function. A potential consequence of hypohydration is a generally linear increase in core temperature during physical activity, with core temperature rising approximately 0.15°C to 0.20°C for every 1% of body weight lost (due to sweating) during activity.^{5,28,64}

When a hypohydrated individual exercises, the added thermal strain is due to both impaired skin blood flow^{64,71,172} and altered sweating responses.^{28,31,61} These thermoregulatory changes may negate the physiological advantages resulting from increased fitness and heat acclimatization, both of which increase plasma volume. When combined with exercise, hypohydration decreases the sweating response, increases body temperature, and raises the overall risk of heat illness.^{63,72}

Thermal strain increases *cardiovascular stress*, which is characterized by decreased stroke volume, increased heart rate, increased systemic vascular resistance, and, as strain progresses, decreased cardiac output.^{7,26,28,61,64} Similar to body temperature changes, the magnitude of cardiovascular alterations is proportional to the degree of hypohydration.⁷ For example, heart rate increases 3 to 5 beats per minute for every 1% decrease in body mass.^{60,69} The stroke-volume reduction seen with hypohydration appears to be due to reduced central venous pressure, resulting from reduced blood volume.^{7,28,30,64,71} Both hypovolemia and hypertonicity have been suggested as mechanisms for the altered thermoregulatory and cardiovascular responses during dehydration.

Additionally, hypohydration reduces heat tolerance and the time to exhaustion during exercise; the latter also occurs at lower core temperatures.²⁹ Furthermore, hypohydration is an etiologic factor in the onset of heat exhaustion and exertional heat stroke due to impairments in thermoregulation and cardiovascular compromise.⁶⁵ Hypohydration contributes to many conditions (eg, heat illness, cardiac dysfunction) that reduce exercise performance and safety; however, euhydration does not confer immunity to these conditions. An in-depth review of heat illness during physical activity is presented in the NATA position statement on exertional heat illnesses.⁶⁵

Exercise-Associated Muscle Cramping. Hypohydration has been hypothesized to contribute to the onset of exercise-associated muscle cramps (EAMCs) via contracted extracellular fluid.⁶⁵ Long considered a hydration-related concern,¹⁷³ EAMCs have now also been linked to other causes.^{174–177} The 2014 death of a football player who drank approximately 4 gallons of water and sports drinks to relieve cramping¹⁷⁸ demonstrates that replacement strategies for athletes should be strictly supervised and limited to replacement of actual losses. Education for athletes and coaches must emphasize the life-threatening risks of EAH. A more in-depth discussion of

EAMCs can be found in the NATA position statement on exertional heat illnesses.⁶⁵

Physiological Implications of Hyperhydration. If not promptly recognized and appropriately treated, EAH is potentially fatal via cerebral or noncardiogenic pulmonary edema. This condition had been thought to be limited to endurance activities, such as marathons and the Ironman triathlon,⁷ but the deaths of 2 high school football players during the 2014 season¹⁷⁸ emphasize the need for a better understanding of this condition beyond the scope of endurance medicine.

Although EAH occurs in 10% to 20% of sampled marathon finishers, clinically significant cases are relatively uncommon.^{38,56,58,145} Significantly low serum sodium levels are identified more often in women than in men and after activity that exceeds 4 hours in duration.^{38,56} When physically active individuals adequately replace sodium losses and do not consume excess fluids, EAH is prevented. Exercise-associated hyponatremia typically results from ingesting water or hypotonic beverages (including sports drinks) beyond sweat losses.^{13,34,35} Often, renal water clearance is inadequate due to inappropriate arginine vasopressin release after exercise.¹⁷⁹ Two common, often additive scenarios are (1) ingesting water or hypotonic beverages (including sports drinks) beyond sweat losses, resulting in weight gain during exercise associated with inadequate renal water clearance,¹⁷⁹ and (2) large sweat sodium and water losses that are not adequately replaced or that are replaced with hypotonic fluids.³⁴ Exercise-associated hyponatremia likely occurs on a continuum between these opposite mechanisms.

Sweat sodium losses are generally low in heat-acclimatized athletes and probably do not play a large role in EAH except in activities lasting a very long duration.³⁶ Ultimately, the extracellular fluid space has a decreased solute concentration compared with the intracellular fluid space, and water flows into the cells to equalize solute concentrations across cell membranes, producing intracellular swelling. This, in turn, leads to physiological dysfunction at the cell, tissue, and organ-system levels, with most clinical signs reflecting intracranial pressure changes and reduced oxygen exchange in the lungs. Death from EAH is usually due to herniation of the brainstem.

Signs and symptoms of EAH normally present at serum sodium levels <130 mmol·L⁻¹ (range = 109–131 mmol·L⁻¹)¹¹⁵ and include milder early indications such as lightheadedness, dizziness, nausea, puffiness of the extremities or face, muscle cramps that do not resolve with the usual care, and body weight gain from baseline. Severe later indications include altered mental status, which may consist of disorientation, confusion, agitation, delirium, or feelings of “impending doom”; obtundation; phantom running; seizures; coma; signs of herniation, such as decorticate posturing and mydriasis; and signs of noncardiogenic pulmonary edema, such as dyspnea and frothy sputum.^{35,38,56,58}

Successful treatment of EAH associated with encephalopathy involves rapid sodium replacement in sufficient amounts via hypertonic (3% or greater) saline IV infusion to increase sodium concentration in the intravascular space, which draws water from the intracellular space. For mild cases of EAH, the patient should either be observed while fluids are withheld until he or she begins to urinate or

should ingest oral hypertonic fluids or salty foods to shift water into the gut. Hypovolemic hyponatremic clinical presentations are rare but have been detected in athletes participating in endurance events.^{36,38} In the absence of encephalopathy, these athletes may be cautiously rehydrated with normal saline, but their serum sodium levels should be checked between liters of fluid. If encephalopathy is present, treatment with IV hypertonic saline should be initiated as described earlier.

Performance Implications of Hydration During Exercise. Scientific debate continues with respect to the apparently discordant outcomes between field-based and laboratory studies of the effects of hypohydration on exercise performance. Many laboratory studies have demonstrated a consistent association between hypohydration and decreased exercise performance.^{180,181} However, when the same variables were monitored in some uncontrolled field studies, the data seemed to conflict.^{182–185} When confounding variables were controlled in field studies, thermoregulation was markedly compromised, cardiovascular strain increased, and exercise performance decreased with increased levels of hypohydration.^{4,5} When physical activity takes place on a field, the concepts that govern human physiological regulation of homeostasis remain valid and cannot be ignored.

Endurance Performance. In studies of prolonged aerobic activity, performance was consistently reduced when hypohydration met or exceeded 2% body mass loss.^{3–5,62,74,98,181,186} Physiologically, a decrease in the available body fluid limits how much vascular volume is available for the delivery of nutrients and oxygen to working muscles and the central nervous and cardiovascular systems.^{26,187} When fluids are limited during physical activity, symptoms of dehydration and decreases in performance become more apparent.

Abundant research^{4,5,19,62,70,74} has documented aerobic performance decrements with hypohydration. Contradictory findings generally involved marginal levels (less than 2%) of hypohydration or a lack of exercise-intensity measures.^{23,75,188} Reductions in total body water decrease stroke volume and peripheral sweat gland perfusion.⁶¹ Therefore, in temperate and hot environments, performance is decreased when hypohydration is greater than 2% body mass.¹⁸¹ It has been demonstrated, however, that in cool environments⁷⁴ or when thirst is mitigated,²³ aerobic performance can be maintained. Yet consuming fluids according to thirst alone does not maximize performance.¹⁸⁹ At rest, increased thirst occurs when body mass losses approach 2%.^{48,50} During exercise, thirst signals at similar water-loss thresholds appear to be absent or ignored; this is referred to as *voluntary dehydration*.⁴⁷ Furthermore, despite decreased performance with hypohydration, hyperhydration provides no performance benefits during endurance activity and increases the risk of EAH.^{64,190–192}

Anaerobic Performance. Strength and power are important in some team and individual sports. The multifactorial nature of these tasks makes it difficult to isolate the effects of hydration on performance. Still, when data are combined, decrements in strength, power, and anaerobic endurance are consistently apparent in athletes who are more than 2% hypohydrated.^{76,193} Most studies^{193,194} that have addressed the influence of hypohydration on muscle

Table 2. Sweat-Rate Equation^a

Sweat loss (L) = Body mass before exercise (kg) – Body mass after exercise (kg) + (Volume of fluid consumed during exercise [L]) – (Urine volume, if any [L])

Sweat rate (L/h) = Sweat loss (L) / Exercise duration (h)

^a If body mass is assessed in kilograms and fluid consumed in liters, the sweat rate = L/h.

function showed that a fluid deficit of 3% to 4% elicited a performance decrement. Anaerobic performance research related to hydration status is highly varied (eg, dehydrating protocol, performance outcome, recovery timing),⁷⁶ which makes it challenging to decipher the true mechanisms or specific levels of hypohydration that cause decrements. However, the data consistently support the likelihood that euhydration improves anaerobic performance.

Cognitive Performance. Specific and rapid information processing is necessary for quick and accurate decisions and is fundamental to many sport and military activities. Several investigations^{8,9,195–198} demonstrated that a modest level of hypohydration (greater than 1%) compromised cognitive function, including task performance, reaction time, short-term memory, and mood state. Yet most impairments seem clinically negligible, and others contended that the effect of hypohydration on cognitive function was limited.^{181,195,199,200} At similar hypohydration levels, women seemed to demonstrate fewer consistent cognitive impairments but more mood-state decrements than men.^{8,9,139} Furthermore, heat exposure may induce a more profound negative effect of hypohydration on mood state in both men and women.^{195,198,199}

Fluid Replacement

Hydration safety for physically active individuals can be influenced by body fluid status, but significant variability exists in factors such as habitual daily water intake,^{1,40} sweat rate,^{32,53,201} and gastrointestinal tolerance of consuming a large fluid volume during exercise,²⁰² which makes universal recommendations impossible. Ideally, individual sweat-rate assessments should be performed several times under realistic environmental conditions and at varying exercise intensities while wearing standard clothing and equipment specific to the sport (Table 2). Calculating an athlete's sweat rate facilitates individual education and an understanding of hydration status and fluid loss during activity that can be easily translated into an individualized fluid-replacement plan.^{19,20}

With high-performance athletes, restricting dehydration to no more than 2% body mass loss helps to maintain the physiological, perceptual, and safety aspects of their exercise while aiding in exercise recovery and subsequent training sessions. Rehydration plans often need to be altered during activity, and this is an important educational component of hydration. Ideally, exercise-related body fluid losses should be replaced within a short time frame, and dietary intake should replace body fuels used during exercise. Postexercise body mass losses generally require replacement with 100% to 150% of calculated fluid losses due to fluid bolus-initiated diuresis, particularly when fluid recovery time is limited (ie, less than 4 hours).²⁰³ When recovery time is extended to more than 12 hours, balance is achieved with ad libitum food and fluid consumption.

Most individuals can avoid fluid-balance problems by drinking when thirsty during and after exercise and eating a healthy diet. In healthy individuals, the thirst mechanism is governed by a combination of serum osmolality and intravascular pressure as the body defends blood pressure and volume. Thirst typically increases at about 2% hypohydration⁵⁰ and markedly decreases when rehydration restores this level. The 2% hypohydration threshold has little effect on overall exercise performance in recreational athletes and reduces the risk of EAH due to the overconsumption of fluids.

One anecdotal strategy used by many distance athletes in an attempt to retain fluid or prevent hyponatremia is sodium tablets.²⁰⁴ Little evidence supports this practice for either hyperhydration before activity²⁰⁵ or fluid retention during activity.²⁰⁴ Furthermore, adverse events associated with this practice during activity are unknown.³⁶

Competitive and recreational athletes who have chronic medical conditions should consult their personal physicians regarding hydration recommendations and strategies to avoid exacerbating their conditions.

Sweat-Rate Variability. Recommendations for people participating in physical activity must be individualized. For example, sweat rate can vary according to body size, environmental conditions, exercise intensity, acclimatization status, and other factors.²⁰⁶ Reliable estimates of sweat losses based on some of these variables exist³²; however, they are not valid for every person and should only be used as an estimate when specific calculations cannot be conducted. Individual recommendations on fluid replacement should be based on individual data and not population estimates. In addition, competition goals and experience must be factored into fluid-intake decision planning. A 50-year-old participating in her first marathon who has a 0.4 L/h sweat rate and a goal of finishing in 6 hours should not receive the same hydration plan as a 28-year-old elite male distance runner with a sweat rate greater than 2 L/h who is attempting a 2.25-hour finish time in the same event.

Robust individual variability exists in exercise-related fluid losses and the effect of hydration status on both performance and well-being. Sweat rates for adults (>18 years old) during exercise can range from 0.5 to 4.0 L/h,^{32,43,53,201,207,208} and measured sodium losses during exercise range between 0.2 and 7.3 g/h.^{34,209–212} Sweat sodium concentrations, for example, range from 10 to 100 mEq/L, and these large variations require individual replacement strategies. For athletes who have had hydration complications (hypohydration or EAH) requiring medical attention, formal assessment of sweat rate and sweat-electrolyte concentrations may be necessary to determine a safe individual replacement strategy.⁷⁸

Fluid Intake Exclusive to Exercise. In terms of fluids, on average, free-living individuals habitually consume just over 2 L/d, with the typical range between 0.5 L/d and 4.0 L/d.^{1,42} Despite large individual variations in fluid intake as well as body water volume and hydration status, biomarkers in the blood remain in a relatively tight range due to the wide normal range of urine-concentrating capacity.^{39,40,213} Exercise combined with individual variability in daily fluid needs makes normal fluid intake ranges difficult to establish in athletes.^{1,40}

Factors Influencing Rehydration. The degree of environmental heat stress is determined by temperature, relative humidity, wind speed, and radiant energy load, which induce physiological changes that affect rehydration recommendations. Voluntary fluid intake increases substantially when ambient temperature rises above 25°C; however, the rehydration stimulus may be partially psychological.⁴⁷⁻⁴⁹ Individual differences in learned behavior also play a role in the rehydration process. An athlete who knows from experience that rehydrating enhances subsequent performance is more apt to consume fluid before significant dehydration occurs, so appropriate education of athletes is essential to success.^{79,214}

The physical characteristics of a rehydration beverage can dramatically influence fluid replacement. Salinity, color, sweetness, temperature, flavor, carbonation, and viscosity all affect how much an individual drinks.^{51,91,140} Individuals exercising in the heat will voluntarily ingest more fluid if it is chilled.^{51,140} Because people ingest most of their daily fluids with meals, access to ample fluids during meals and adequate time to eat and drink will improve rehydration.^{101,215}

Hydration Before Exercise. The goal of an individual hydration strategy is to maximize safety and performance during exercise. It is important to begin an exercise bout euhydrated. To ensure euhydration before activity, an athlete should be mindful of individual cues, such as thirst, body weight, urine color, and voiding frequency. Individual variability exists in each of these cues, but all can provide useful information regarding hydration levels.^{40,41,130,141,210,216} Competitive athletes may benefit from subtle hyperhydration (less than 2%) before exercise to avoid more than a 2% body mass deficit during activity.²⁰⁸ However, this recommendation should be pursued under medical oversight and is advised only for athletes in competitions and endurance events, when access to fluids is restricted due to remote locations, or sports in which fluid is not readily available (eg, soccer, trail races). Recreational athletes should not need to consume extra fluids before activity but should begin exercise euhydrated.

Rehydration During Exercise. During exercise, the goal for the physically active is to maintain hydration and not allow more than a 2% body mass loss.^{4,5,27,217} The suggested ideal strategy for exercise performance advises limiting body mass losses to less than 2% throughout activity but not gaining weight during exercise.^{36,66} To maintain euhydration during activity, an athlete should consume enough fluid to approximate personal sweat volume losses and avoid both excessive body fluid losses and overconsumption of fluids.^{66,79} A sample strategy for calculating sweat loss and fluid replacement is outlined in Table 3.

Thirst may be delayed, so for competitive athletes striving to maximize performance, using a “drink when thirsty” strategy may compromise performance.⁴ Therefore, every individual should know his or her personal sweat rate and develop a hydration strategy based on individual needs.^{19,20,66,78,79} An appropriate strategy promotes effective training and competition while maximizing safety. However, a hydration plan may require short-term revisions during competition based on unanticipated factors (eg,

Table 3. Sample Sweat-Rate Calculations

Modifying Factor	Individual A (Recreational Tennis Player, Female, 85 kg)	Individual B (Recreational Runner, Male, 80 kg)	Individual C (Collegiate Football Player, Male, 120 kg)	Individual D (Collegiate Soccer Player, Female, 60 kg)
Wet-bulb globe temperature, °C (°F)	25 (77)	22 (71.6)	29 (84.2)	28.3 (83)
Acclimatized to heat?	Yes	No	Yes	Yes
Exercise mode	1.5 h	10-km Race (0.75 h)	2.5-h Practice	Soccer game (1.5 h)
Exercise intensity	Mild/moderate (50%)	Maximal	Intermittent maximal	Intermittent maximal
Hydration status before activity	1% Hyperhydrated (85.9 kg)	Euhydrated	Euhydrated	Euhydrated
Available breaks	When feasible	Every mile (1.6 km)	Consistent breaks	Half-time (athletic administrators should consider fluid breaks based on environmental factors)
Postexercise hydration status	-1.5% Body mass (1.3 kg)	-1% Body mass (0.8 kg)	-5% Body mass (6.0 kg)	-2.5% Body mass (1.5 kg)
Fluid consumed	0.8 L	0.4 L during race	2 L during breaks	0.5 L at half-time
Sweat rate	1.3 kg + 0.8 L/1.5 h = 1.4 L/h	0.8 kg + 0.4 L/0.75 h = 1.6 L/h	6.0 kg + 2.0 L/2.5 h = 3.2 L/h	1.5 kg + 0.5 L/1.5 h = 1.3 L/h
Recommendation for similar exercise	Drink when thirsty; may also benefit from paying attention to personal hydration cues before exercise to ensure euhydration rather than overhydration.	Doing a great job. Finished the race at 1% body mass loss.	Body mass loss is likely affecting performance and increasing heat-illness risk during activity. Increase fluid consumption and try to approximate sweat rate to avoid >2% (2.4-kg) body mass loss during activity.	Due to a lack of fluid availability, try to begin exercise 0.5% hyperhydrated and ingest a little more fluid at half-time. This will limit body mass loss and prevent >2% hypo-hydration at game end. Slight hyperhydration for an individual with proper oversight may be beneficial in this case.

gastrointestinal upset, discomfort, fluid availability, environmental conditions, fluid type).

If athletes do not know their individual sweat rates, drinking to thirst during activity most likely represents a safe strategy to prevent overdrinking. Drinking to thirst should also be considered when exercising athletes cannot follow their ideal plan for replacing fluids at a rate similar to their sweat rate.

Rehydration After Exercise. Rapidly replacing fluids after exercise restores euhydration, improves recovery, reduces hypohydration symptoms, and decreases postexercise fatigue.* Up to 150% of the estimated fluid deficit needs to be consumed to effectively replace fluid losses after exercise over a short recovery period (less than 4 hours).^{100,101,203} This additional consumption is necessary to compensate for the postexercise diuresis induced by the large fluid load and restore normal arginine vasopressin hormone levels in blood. The exact amount of fluid needed to restore euhydration depends on solid food composition and the timing of food ingestion after exercise, as the electrolyte and water contents of meals contribute to fluid replacement and can enhance fluid retention.²¹⁵

Beverage Additives

Under normal circumstances, physically active people consuming a well-balanced diet should not need to add specific ingredients to their fluids before, during, or after activity. As a general rule, those participating in physical activity lasting less than 1 hour should require no substances other than water.^{34,220} Athletes participating in exercise sessions lasting longer than 1 hour or including intense intervals may benefit from adding carbohydrates or electrolytes (or both) to rehydration fluids, especially in extreme environments.^{34,80,116,221–224} Endurance athletes may be aided by fluids containing carbohydrates and electrolytes during extended training bouts and competitions.^{82,100,116,221,224–226} Individuals with much greater than average sweat sodium concentrations (greater than 60 mEq/L) and high sweat rates (greater than 2.5 L/h) may benefit from sodium supplementation in the fluids consumed during activity.^{34,51} However, no evidence indicates that athletes are helped by sodium supplementation beyond individual losses. Therefore, we recommend that individual assessment of sweat-electrolyte concentrations should occur before consideration is given to supplementing.

The goal of pre-exercise nutrition and hydration is to begin exercise with adequate carbohydrate availability and body water.²²² Before physical activity, individual preferences determine hydration and diet choices.^{24,52,54,213,227,228} Gastric emptying, intestinal absorption, bowel transit time, and urine frequency vary for each individual.^{80,202,229,230} Competitive athletes can benefit from carbohydrate-electrolyte beverages before activity.^{82,116,222,224} Physically active people eating a balanced diet with adequate calories and fluids need not add ingredients to water to maintain hydration status. Beverages that appeal to individual taste preferences may encourage individuals to drink more fluids.^{54,91,231} Adding carbohydrates or electrolytes (or both, especially sodium) to the rehydration drink can help maintain blood glucose, carbohydrate oxidation, and electrolyte balance.^{220,232,233} In some cases, adding protein

to a sports drink may improve exercise performance.²³⁴ Rates of gastric emptying and intestinal absorption (the primary site of fluid absorption) influence rehydration, especially during exercise.^{80,84,229} Fluid volume, fluid calorie content, fluid osmolality, exercise intensity, environmental stress, and fluid temperature are important factors that determine these rates. The single most important variable may be the volume of fluid in the stomach.^{84,229} Maintaining 400 to 600 mL of fluid in the stomach optimizes gastric emptying.^{221,229} If carbohydrates are included in the fluid, the optimal concentration for fluid absorption is between 3% and 8%,²²¹ but concentrations greater than 5% to 8% may slow the rate.^{221,235} Exercise at greater than 80% of \dot{V}_{O_2} max may decrease the rate of gastric emptying.^{229,236} Ingesting about 200 mL of fluid every 15 to 20 minutes may be ideal, but this timing can be difficult in sports with extended playing time between breaks. Lastly, the rate of gastric emptying is slowed by significant hypohydration (greater than 4%), which complicates rehydration and may increase gastrointestinal symptoms.^{83,202}

To facilitate postexercise recovery, competitive athletes may require more carbohydrates or electrolytes in their diet or fluids to assist in fluid balance. Ingesting carbohydrates and protein after exercise provides substantial benefits by restoring muscle glycogen and facilitating muscle recovery,^{93,96–98,237,238} and simultaneous carbohydrate and protein ingestion is better than fluid alone for muscle and blood glucose recovery.^{94,95,106} However, the optimal amount of either carbohydrate or protein has yet to be determined. The overarching recommendation is to replace all fluids and nutrients that were used or lost during exercise.

Caffeine does not compromise rehydration or increase urine output when consumed in small quantities (up to 3 mg/kg) during or after exercise.^{116,118,119,121} Small amounts of caffeine in a rehydration beverage should not cause harm to the physically active postexercise.

Supplements containing creatine in various forms have been studied extensively due to purported dehydration and muscle-cramping episodes in those who were actively consuming them. At recommended doses, however, creatine does not compromise hydration status.²³⁹ Because researchers have not investigated levels above the recommended dosages, no evidence is available regarding hydration changes due to supplementation with greater amounts of creatine.

The osmolyte glycerol has been used to increase body water and potentially avoid hypohydration during events. In controlled settings, glycerol promoted fluid retention.^{122–127} However, the excess fluid in the body does not confer consistent physiological or performance advantages.¹⁹² Furthermore, the side effects of glycerol (headache, nausea, etc) are quite common and not advantageous to physical activity.^{123,192,240}

Alcohol inhibits arginine vasopressin release, and beverages with an alcohol content above 2% reduce fluid retention during rehydration.¹²⁸ However, in well-hydrated individuals, rehydration with beverages containing up to 4% alcohol did not increase urine output.¹²⁹ Research¹²⁹ also suggests that the influence of hypovolemia on renal fluid retention is more potent than the diuretic effect of alcohol. Drinks with increasing alcohol content (greater

*References 82, 84, 93, 100, 113, 146, 147, 203, 218, 219.

than 4%) facilitate excessive diuresis and should be discouraged for fluid replacement.

Hydration Assessment

Hydration status is important yet often difficult to assess accurately and reliably in athletic settings. Measurement techniques can indicate changes in hydration status²⁴¹ but should not be used to diagnose hypohydration. An individual's hydration state is in constant flux and depends on many factors; multiple indicators are needed for adequate assessment.^{66,78}

Thirst. The perception of thirst at rest is accurately quantified using the subjective thirst-sensation chart (ranging from 1 [*not thirsty at all*] to 9 [*very, very thirsty*]). This chart is widely used by researchers to support thirst-sensation measures but not to quantify hydration status. Normally, thirst increases when 2% hypohydration is approached and decreases when fluid balance is restored to a loss of less than 2%. This level may offer some protection against EAH, although current evidence provides insufficient support. Furthermore, first morning thirst is strongly correlated with hypohydration as measured by an acute change in body mass.⁴⁵

Body Mass. Measuring acute body mass changes using a valid and reliable floor scale is an efficient hydration-assessment technique. Body mass is considered a valid measure of hydration status only when losses are acutely observed (eg, prepractice versus postpractice)¹³¹ or compared with a valid euhydrated baseline.¹⁸¹ A valid baseline generally requires 3 consecutive days of euhydrated weight assessments to establish the normal body mass that may be subject to circadian variation and depends on the individual's diet, digestion, fluid intake, and bowel habits.^{131,133,216,242,243} Body mass assessment for hydration status is best used to show short-term changes between pre-exercise and postexercise or changes in status from baseline or in conjunction with other hydration measurements.

Urine Concentration. The concentration and color of urine vary inversely with its volume. As long as the first morning measurements of urine concentration are used to assess hydration, any one of them serves as an acceptable complement to body mass and thirst observations for assessing hydration.¹³⁷ An important consideration when assessing hydration is that urine volume and concentration are affected not only by fluid loss but also by activity, diet, and especially fluid intake.¹³⁷ The stability of urine concentration as a measure of hydration assessment is compromised by all of these variables. The most stable value, which provides a valid and reliable indication of hydration status, is the first morning assessment. When this is not feasible, ATs should know that urine analysis may confound the clinical decision-making process and that body mass assessment provides more reliable information.¹³⁷

Urine color is a popular assessment technique because it is noninvasive, inexpensive, and reliable. The urine color chart (available at www.hydratecheck.com) demonstrated good sensitivity and specificity compared with USG and osmolality measures.^{41,135,136} Urine color should be assessed after a sample is collected in a clear container and then evaluated in adequate lighting without shadows. Assessing color in the toilet bowl after urination is not

reliable, as the sample is diluted with water and cannot be accurately compared with the color chart. Urine color has also demonstrated effectiveness as an educational tool for athletes to assess their own fluid status.^{19,20,79} Lastly, a urine color of 8 on the chart indicates gross muscle damage and myoglobin present in the urine (rhabdomyolysis or kidney dysfunction); a patient presenting with this color should receive prompt referral and follow-up testing.^{135,138}

Urine specific gravity compares the concentration of a urine sample with that of distilled water and can be measured in several ways. Techniques include floating, handheld, optical, or digital refractometry as well as urine reagent strips. Urine refractometry results are valid compared with more complicated but time-tested measures of urine concentration, such as urine osmolality.²⁴⁴ Refractometry is simple and requires only a small urine sample and a relatively inexpensive (less than \$300) handheld device. Urine reagent strips are unreliable, even when manufactured solely for hydration assessment,²⁴⁵ and are not recommended for this purpose.

Other Techniques. Additional techniques available for estimating hydration status include urine and plasma or serum osmolality assessments. However, these techniques are time sensitive and require expensive equipment not typically available in clinical or field settings.²⁴¹ An osmometer is expensive (more than \$3500) and requires regular calibration and sophisticated maintenance. Although urine osmolality is more valid and reliable than other field-accessible methods,²⁴⁴ its cost typically precludes use by ATs. Furthermore, obtaining a plasma or serum sample requires much more equipment (needles, tubes, centrifuge, etc) and phlebotomy training, again restricting access to these measures by ATs. It is important for the evidence-based practitioner to understand all hydration-assessment techniques and extrapolate results from only those studies that incorporated multiple measures.

For the best estimate of hydration status in an athlete, 3 simultaneous measures are recommended: first morning urine color (or USG), thirst sensation, and body mass.¹³⁷ All can be obtained in an athletic training facility with easily accessed equipment and are reliable indicators of hydration status. Body mass is best measured at the same time each morning for valid comparisons.²¹⁶ When body mass is assessed both preactivity and postactivity, individuals can be educated on specific rehydration recommendations after activity.

Recognition of Hypohydration and Fluid Overload

The early signs and symptoms of exercise-related hypohydration include thirst and general discomfort or complaints (approximately 2% body mass deficit). These are followed by flushed skin, weariness, cramps, and apathy. At greater water deficits (more than 2% body mass loss), dizziness, headache, vomiting, nausea, heat sensations on the head or neck, chills, and dyspnea may be present (Table 1).^{50,57,139} The degree of hypohydration, mental status, and general medical condition of the athlete will dictate the mode, amount, type, and rate of recommended rehydration.

A potential difficulty in recognizing hydration abnormalities is that the signs and symptoms of hypohydration may

overlap those of EAH (Table 1).^{50,57,58,142,144} The early signs of EAH include headache, dizziness, physical exhaustion, muscular twitching, and nausea, all of which are also symptoms of hypohydration. Differential signs and symptoms of EAH due to fluid retention include weight gain, history of overdrinking, extremity swelling, and progressively worsening headache.^{38,142} Signs of encephalopathy generally occur when the sodium concentration is less than 125 mEq·L⁻¹ but have been documented with a sodium concentration of 131 mEq·L⁻¹.¹¹⁵ More severe encephalopathy is accompanied by altered mental status, pulmonary edema, collapse, unconsciousness, seizure, and coma. When these conditions cannot be differentiated based on the history and physical examination, a blood sodium measurement is needed for accurate diagnosis, which is imperative because either hypotonic or isotonic fluid given inappropriately to a patient with EAH can be fatal. If point-of-care blood sodium assessment is not available for a patient with severe encephalopathy, the empiric administration of a hypertonic sodium IV can be life saving and will not harm a dehydrated individual.³⁶

Unique Situations

Event Management. Medical professionals responsible for directing, supervising, and coordinating athletic events should include hydration strategies in the medical and safety plan. This includes estimating the maximum fluid volume needed for each participant in the event to optimize both performance and safety. The event safety plan should include athlete education opportunities for understanding fluid balance and should facilitate easy access to fluids for sweat-loss replacement. The event medical staff should be trained and equipped to assess athletes for dehydration, EAH, and heat illness. Promotional and educational materials provided to participants should include basic definitions of hypohydration and hyperhydration,¹⁴² along with strategies to avoid both EAH (overconsumption) and dehydration during the event. Event managers should consult experts in the planning stages to develop effective strategies that reflect the event participants, environmental conditions, resources, and medical support. Mass events with a high potential for participants to develop EAH or dehydration should have a detailed medical plan to appropriately differentiate EAH, hypohydration, exertional heat stroke, and exercise-associated collapse that includes point-of-care portable blood-electrolyte analysis and rectal temperature measurement before initiating treatment.⁵⁹

Environmental Factors. The diuretic effects of moderate-altitude (greater than 2500 m) and high-altitude (greater than 3600 m) exposure have long been recognized by mountaineers as a successful adaptation to altitude whereby hemoconcentration (reduced plasma volume) improves oxygen delivery to the tissues.²⁴⁶ The loss of water is self-limiting to approximately -2% of body mass and stems primarily from the stimulation of peripheral arterial chemoreceptors; the altitude-induced fluid deficit is not corrected by increased fluid consumption. In water sports (eg, swimming, water polo), diuresis occurs secondary to fluid shifts among compartments in the body induced by heat-conserving vasoconstriction.^{190,246} It is important to note that hydration assessment immediately after exercise

in cool water is inaccurate and must be delayed. When physical activity occurs in cold weather, the drive for thirst is blunted and ad libitum fluid consumption is decreased.^{27,47,247} Furthermore, cold air (and the resulting decreased skin temperature with peripheral vasoconstriction) induces a slight diuretic effect.³³ Medical personnel involved in the care of physically active individuals in these settings should be aware of particular nuances that may affect recommendations to ensure athlete safety and performance reasons.

Intravenous Fluids. Intravenous fluids are used to correct symptomatic hypohydration when oral fluids are not tolerated or continued fluid-electrolyte losses exceed fluid intake. Such IV fluids are rarely necessary in otherwise healthy patients. Outcomes after rapid IV rehydration suggest no lasting benefits exceeding those of oral rehydration,^{218,248} and hormonal and fluid balances are facilitated by the oropharyngeal reflex and swallowing.^{146,147,219,249} Oral fluids are recommended as the first-line rehydration strategy for most patients with exercise-related hypohydration, although some recent evidence^{146,147} suggests that recovery from hypohydration (approximately 4% body mass loss) is most efficient with the concomitant use of IV and oral fluids. When oral fluids are not tolerated (because of vomiting, extreme nausea, or excessive diarrhea), IV fluids can be used as a primary intervention. If EAH is suspected, a serum or blood sodium level should be measured before oral or IV (hypotonic or isotonic) fluid is administered.

Sickle Cell Trait and Exertional Rhabdomyolysis. Hypohydration is a known risk factor for an exertional sickling episode.⁵⁹ Hydration status should be part of the education process and then should be closely monitored in athletes known to have sickle cell disease or the sickle cell trait. To facilitate safe participation, extra care is warranted for these individuals to ensure adequate hydration status before physical activity.⁵⁹ Conversely, exertional rhabdomyolysis seems rather common in patients with EAH.⁶⁶ Although relatively novel in observation, true mechanisms have yet to be identified. Osmotic stress and excessive muscle breakdown may be related.²⁵⁰ Therefore, individual euhydration maintenance should be promoted to prevent exertional sickling as well as EAH and exertional rhabdomyolysis.³⁶

Weight-Certification Recommendations. Many athletes purposely dehydrate to qualify for lower weight classes (eg, wrestling, martial arts) or to meet physical appearance expectations (eg, gymnastics). To discourage this unhealthy practice, many state and national organizations require weight certification before or early in the competitive season. Unfortunately, limited agreement exists among governing bodies regarding a safe method to certify athletes in specific weight classes.^{154,155,251,252} Best practice is for trained medical professionals (eg, ATs, physicians) with established independent authority and freedom from team bias to determine the appropriate weight class based on the athlete's best interest.¹⁵³ Following are recommendations for sport weight certification:

1. All measures should be assessed using the first morning urine for the most validity.¹³⁷ Use of other assessment techniques or spot urine samples may result in misclassification of hydration status.¹³⁷

2. If USG is not <1.025 (first morning void), as quantified by a digital or clinical refractometer, body mass and body fat should not be measured. The next measurement should occur at least 24 hours later.
3. Body mass should be measured with a calibrated scale (± 0.2 lb [0.1 kg]).^{131,216}
4. A trained technician should measure body fat. Because some of the available clinical measures are influenced by hydration status (eg, bioelectrical impedance, skin-folds),^{134,152,154,162,253} it is imperative that USG be assessed in conjunction with body mass and body fat assessment.

Due to the many potential negative consequences of rapid exercise-induced dehydration, the following practices should be strongly discouraged for the purpose of “making weight”: impermeable or insulating clothing, excessive exercise in a hot environment (steam room or sauna), fluid restriction, and purposeful fasting.⁶⁶

Aging and Hydration. Under normal conditions of daily life, fluid intake is governed by multiple factors, including thirst. Most large surveys show that daily fluid consumption is the same in healthy, independently living 65- to 80-year-old adults as in 20- to 35-year-old adults: approximately 2100–2400 mL/d.^{1,40,253} However, the timing of drinking and beverage choices often vary in older adults. Less fluid is consumed in the evening hours, presumably to prevent frequent nighttime urination.²²⁷ Dehydration in the elderly often results from clinical conditions, medication use, or accidental or disease-related fluid deprivation or losses (or a combination of these).

The sensation of thirst is blunted in many but not all older exercisers during and after exercise- or heat-induced dehydration.^{227,228,254} Reduced thirst in the elderly is thought to be due to a diminished ability to sense a volume deficit (from hypotension or low blood volume) at the central level.²⁵⁴ With aging, osmoregulation remains intact but central processing of signals by satiety centers in the brain may change.^{254,255} Although healthy older adults eventually restore all fluid losses, this occurs at a slower rate than in younger adults.²⁵³ This age effect is thought to be progressive, yet the rate of decline appears to be highly variable and no longitudinal data are available.

Hydration is important for master’s athletes (older than 40 years) during the first 5 days of heat acclimatization, when plasma volume expansion occurs. This plasma volume expansion requires increased fluid intake. Two studies^{159,160} examining plasma volume expansion during early heat acclimation showed that many active adults over age 50 may not adequately acclimate to exercise-heat stress due to inadequate postexercise and 24-hour fluid intake.

SUMMARY

This position statement is intended to provide clinical ATs with evidence-based hydration recommendations for physically active people. Individual safety and performance are optimized when body mass losses are limited throughout activity to 2% or less without total body water gains from baseline. Competitive athletes striving for maximal performance may benefit from a strategy based on replacing sweat losses during prolonged activity. To reduce the risk of EAH, athletes and recreational exercisers should only replace fluid lost in sweat during exercise and not gain fluid weight.

Exercise performance during intense or long-duration events may be improved by adding carbohydrates and electrolytes to rehydration beverages. Replacement fluids may be more palatable for athletes when chilled and when small amounts of sodium and flavoring are added. Education strategies for physically active people should address personal sweat rates, hydration cues, and rehydration strategies that avoid both hypohydration and fluid overload. These strategies will help prevent hypohydration and EAH, maximize safety during physical activity, and optimize exercise performance.

ACKNOWLEDGMENTS

Brendon P. McDermott, PhD, ATC, FACSM, serves on the Medical and Science Advisory Board of the Korey Stringer Institute (Storrs, CT) and the Advisory Board for the Kendrick Fincher Hydration for Life foundation (Rogers, AR). Scott A. Anderson, ATC, is a member of the Gatorade Sports Science Institute’s Speaker Bureau (Barrington, IL). Lawrence E. Armstrong, PhD, FACSM, is a consultant to, member of the Scientific Advisory Board of, and has received grant funding from Danone Research (Palaiseau, France); he is also a consultant to the Drinking Water Research Foundation (Alexandria, VA). Douglas J. Casa, PhD, ATC, FNATA, FACSM, is a consultant to Gatorade (Chicago, IL); Clif Bar & Co (Emeryville, CA); Jones & Bartlett (Burlington, MA); UpToDate (Alphen aanden Rijn, The Netherlands); Springer International Publishing AG (Berlin, Germany); Lippincott Williams & Wilkins (Philadelphia, PA); Quest Diagnostics (Madison, NJ); and Sports Innovation Lab (Boston, MA); a member of the Scientific Advisory Board of Clif Bar & Co, the National Football League (New York, NY), CamelBak (Petaluma, CA), Quest Diagnostics, Nix Inc (Boston, MA), and Sports Innovation Lab; and has received grant funding from Gatorade; Kestrel Corporation; the National Football League; HeartSmart.com (New Milford, CT); Mission Product Holdings, Inc (New York, NY); Jones & Bartlett; Quest Diagnostics; General Electric (Boston, MA); Nix Inc; the US Air Force (Washington, DC); the US Army (Washington, DC); Halo Wearables (San Francisco, CA); WHOOP, Inc (Boston, MA); the National Collegiate Athletic Association (Indianapolis, IN); Danone Research; Timex Group USA, Inc (Middlebury, CT); Eagle Pharmaceuticals, Inc (Woodcliff Lake, NJ); the National Athletic Trainers’ Association (Carrollton, TX); the National Center for Catastrophic Sport Injury Research (Chapel Hill, NC); dhama Innovations Pvt Ltd (Hyderabad, India); and Polar Electro Inc (Lake Success, NY). He has also provided expert testimony in approximately 35 lawsuits since 2010. Samuel N. Cheuvront, PhD, RD, FACSM, is a consultant to PepsiCo (Purchase, NY); Nike (Beaverton, OR); Entrinsic Health Solutions, Inc (Norwood, MA); and Bitome, Inc (Boston, MA) and a member of the Scientific Advisory Board of Bitome. Larry Cooper, MS, ATC, is a consultant to Gatorade. W. Larry Kenney, PhD, FACSM, is a member of the Scientific Advisory Board of the American Council on Exercise (San Diego, CA) and has received grant funding from Entrinsic Health Solutions, Inc, and the Dairy Research Institute (St Paul, MN). Francis G. O’Connor, MD, MPH, has no conflicts to declare. William O. Roberts, MD, MS, FACSM, is a member of the Scientific Advisory Board of Race Safe, SportzPeak Inc (San Francisco, CA).

We gratefully acknowledge the efforts of Aaron L. Baggish, MD; Jennifer Doane, MS, RDN, CSSD, ATC; Greg Janik, MS, ATC; Ron Maughan, PhD; Kevin C. Miller, PhD, ATC; and the Pronouncements Committee in the preparation of this document.

DISCLAIMER

The NATA and NATA Research & Education Foundation publish position statements as a service to promote the awareness of certain issues to their members. The information contained in

the position statement is neither exhaustive nor exclusive to all circumstances or individuals. Variables such as institutional human resource guidelines, state or federal statutes, rules, or regulations, as well as regional environmental conditions, may impact the relevance and implementation of those recommendations. The NATA and NATA Foundation advise members and others to carefully and independently consider each of the recommendations (including the applicability of same to any particular circumstance or individual). The position statement should not be relied upon as an independent basis for care but rather as a resource available to NATA members or others. Moreover, no opinion is expressed herein regarding the quality of care that adheres to or differs from the NATA and NATA Foundation position statements. The NATA and NATA Foundation reserve the right to rescind or modify its position statements at any time.

REFERENCES

- Raman A, Schoeller DA, Subar AF, et al. Water turnover in 458 American adults 40-79 yr of age. *Am J Physiol Renal Physiol*. 2004;286(2):F394-F401. (Level of evidence [LOE]: 1)
- Casa DJ, Ganio MS, Lopez RM, McDermott BP, Armstrong LE, Maresh CM. Intravenous versus oral rehydration: physiological, performance, and legal considerations. *Curr Sports Med Rep*. 2008;7(4):S41-S49. (LOE: 3)
- Walsh RM, Noakes TD, Hawley JA, Dennis SC. Impaired high-intensity cycling performance time at low levels of dehydration. *Int J Sports Med*. 1994;15(7):392-398. (LOE: 2)
- Bardis CN, Kavouras SA, Arnaoutis G, Panagiotakos DB, Sidossis LS. Mild dehydration and cycling performance during 5-kilometer hill climbing. *J Athl Train*. 2013;48(6):741-747. (LOE: 2)
- Casa DJ, Stearns RL, Lopez RM, et al. Influence of hydration on physiological function and performance during trail running in the heat. *J Athl Train*. 2010;45(2):147-156. (LOE: 2)
- MacLeod H, Sunderland C. Previous-day hypohydration impairs skill performance in elite female field hockey players. *Scand J Med Sci Sports*. 2012;22(3):430-438. (LOE: 2)
- González-Alonso J, Mora-Rodríguez R, Coyle EF. Stroke volume during exercise: interaction of environment and hydration. *Am J Physiol Heart Circ Physiol*. 2000;278(2):H321-H330. (LOE: 1)
- Ganio MS, Armstrong LE, Casa DJ, et al. Mild dehydration impairs cognitive performance and mood of men. *Br J Nutr*. 2011;106(10):1535-1543. (LOE: 1)
- Armstrong LE, Ganio MS, Casa DJ, et al. Mild dehydration affects mood in healthy young women. *J Nutr*. 2012;142(2):382-388. (LOE: 1)
- Vanderlei FM, Moreno IL, Vanderlei LC, Pastre CM, de Abreu LC, Ferreira C. Comparison of the effects of hydration with water or isotonic solution on the recovery of cardiac autonomic modulation. *Int J Sport Nutr Exerc Metab*. 2015;25(2):145-153. (LOE: 2)
- Bergeron MF, Laird MD, Marinik EL, Brenner JS, Waller JL. Repeated-bout exercise in the heat in young athletes: physiological strain and perceptual responses. *J Appl Physiol (1985)*. 2009;106(2):476-485. (LOE: 2)
- Farquhar WB, Morgan AL, Zambraski EJ, Kenney WL. Effects of acetaminophen and ibuprofen on renal function in the stressed kidney. *J Appl Physiol (1985)*. 1999;86(2):598-604. (LOE: 2)
- Montain SJ, Sawka MN, Wenger CB. Hyponatremia associated with exercise: risk factors and pathogenesis. *Exerc Sport Sci Rev*. 2001;29(3):113-117. (LOE: 3)
- Melin B, Jimenez C, Savourey G, et al. Effects of hydration state on hormonal and renal responses during moderate exercise in the heat. *Eur J Appl Physiol Occup Physiol*. 1997;76(4):320-327. (LOE: 2)
- Osterberg KL, Horswill CA, Baker LB. Pregame urine specific gravity and fluid intake by National Basketball Association players during competition. *J Athl Train*. 2009;44(1):53-57. (LOE: 2)
- Volpe SL, Poule KA, Bland EG. Estimation of prepractice hydration status of National Collegiate Athletic Association Division I athletes. *J Athl Train*. 2009;44(6):624-629. (LOE: 2)
- Yeargin SW, Casa DJ, Armstrong LE, et al. Heat acclimatization and hydration status of American football players during initial summer workouts. *J Strength Cond Res*. 2006;20(3):463-470. (LOE: 3)
- Yeargin SW, Casa DJ, Judelson DA, et al. Thermoregulatory responses and hydration practices in heat-acclimatized adolescents during preseason high school football. *J Athl Train*. 2010;45(2):136-146. (LOE: 3)
- Kavouras SA, Arnaoutis G, Makrillos M, et al. Educational intervention on water intake improves hydration status and enhances exercise performance in athletic youth. *Scand J Med Sci Sports*. 2012;22(5):684-689. (LOE: 2)
- McDermott BP, Casa DJ, Yeargin SW, Ganio MS, Lopez RM, Mooradian EA. Hydration status, sweat rates, and rehydration education of youth football campers. *J Sport Rehabil*. 2009;18(4):535-552. (LOE: 2)
- Armstrong LE, Johnson EC, Kunces LJ, et al. Drinking to thirst versus drinking ad libitum during road cycling. *J Athl Train*. 2014;49(5):624-631. (LOE: 2)
- Armstrong LE, Johnson EC, McKenzie AL, Ellis LA, Williamson KH. Endurance cyclist fluid intake, hydration status, thirst, and thermal sensations: gender differences. *Int J Sport Nutr Exerc Metab*. 2016;26(2):161-167. (LOE: 3)
- Berkulo MA, Bol S, Levels K, Lamberts RP, Daanen HA, Noakes TD. Ad-libitum drinking and performance during a 40-km cycling time trial in the heat. *Eur J Sport Sci*. 2016;16(2):213-220. (LOE: 2)
- Rivera-Brown AM, Ramírez-Marrero FA, Wilk B, Bar-Or O. Voluntary drinking and hydration in trained, heat-acclimatized girls exercising in a hot and humid climate. *Eur J Appl Physiol*. 2008;103(1):109-116. (LOE: 2)
- Yeargin SW, Finn ME, Eberman LE, Gage MJ, McDermott BP, Niemann A. Ad libitum fluid consumption via self- or external administration. *J Athl Train*. 2015;50(1):51-58. (LOE: 2)
- Montain SJ, Sawka MN, Latzka WA, Valeri CR. Thermal and cardiovascular strain from hypohydration: influence of exercise intensity. *Int J Sports Med*. 1998;19(2):87-91. (LOE: 2)
- Kenefick RW, Mahood NV, Hazzard MP, Quinn TJ, Castellani JW. Hypohydration effects on thermoregulation during moderate exercise in the cold. *Eur J Appl Physiol*. 2004;92(4-5):565-570. (LOE: 2)
- González-Alonso J, Mora-Rodríguez R, Below PR, Coyle EF. Dehydration reduces cardiac output and increases systemic and cutaneous vascular resistance during exercise. *J Appl Physiol (1985)*. 1995;79(5):1487-1496. (LOE: 1)
- Sawka MN, Young AJ, Francesconi RP, Muza SR, Pandolf KB. Thermoregulatory and blood responses during exercise at graded hypohydration levels. *J Appl Physiol (1985)*. 1985;59(5):1394-1401. (LOE: 2)
- Montain SJ, Coyle EF. Influence of graded dehydration on hyperthermia and cardiovascular drift during exercise. *J Appl Physiol (1985)*. 1992;73(4):1340-1350. (LOE: 2)
- Montain SJ, Latzka WA, Sawka MN. Control of thermoregulatory sweating is altered by hydration level and exercise intensity. *J Appl Physiol (1985)*. 1995;79(5):1434-1439. (LOE: 2)
- Gonzalez RR, Chevront SN, Ely BR, et al. Sweat rate prediction equations for outdoor exercise with transient solar radiation. *J Appl Physiol (1985)*. 2012;112(8):1300-1310. (LOE: 2)
- O'Brien C, Freund BJ, Sawka MN, McKay J, Hesslink RL, Jones TE. Hydration assessment during cold-weather military field training exercises. *Arctic Med Res*. 1996;55(1):20-26. (LOE: 2)
- Montain SJ, Chevront SN, Sawka MN. Exercise associated hyponatraemia: quantitative analysis to understand the aetiology. *Br J Sports Med*. 2006;40(2):98-105. (LOE: 3)

35. Hew TD, Chorley JN, Cianca JC, Divine JG. The incidence, risk factors, and clinical manifestations of hyponatremia in marathon runners. *Clin J Sport Med.* 2003;13(1):41–47. (LOE: 3)
36. Hew-Butler T, Rosner MH, Fowkes-Godek S, et al. Statement of the 3rd International Exercise-Associated Hyponatremia Consensus Development Conference, Carlsbad, California, 2015. *Br J Sports Med.* 2015;49(22):1432–1446. (LOE: 3)
37. Ebell MH, Siwek J, Weiss BD, Woolf SH, et al. Strength of recommendation taxonomy (SORT): a patient-centered approach to grading evidence in the medical literature. *J Am Board Fam Pract.* 2004;17(1):59–67.
38. Kipps C, Sharma S, Tunstall Pedoe D. The incidence of exercise-associated hyponatraemia in the London marathon. *Br J Sports Med.* 2011;45(1):14–19. (LOE: 3)
39. Perrier E, Demazieres A, Girard N, et al. Circadian variation and responsiveness of hydration biomarkers to changes in daily water intake. *Eur J Appl Physiol.* 2013;113(8):2143–2151. (LOE: 3)
40. Perrier E, Vergne S, Klein A, et al. Hydration biomarkers in free-living adults with different levels of habitual fluid consumption. *Br J Nutr.* 2013;109(9):1678–1687. (LOE: 3)
41. Armstrong LE, Pumerantz AC, Fiala KA, et al. Human hydration indices: acute and longitudinal reference values. *Int J Sport Nutr Exerc Metab.* 2010;20(2):145–153. (LOE: 3)
42. Armstrong LE, Johnson EC, Casa DJ, et al. The American football uniform: uncompensable heat stress and hyperthermic exhaustion. *J Athl Train.* 2010;45(2):117–127. (LOE: 2)
43. Godek SF, Bartolozzi AR, Burkholder R, Sugarman E, Peduzzi C. Sweat rates and fluid turnover in professional football players: a comparison of National Football League linemen and backs. *J Athl Train.* 2008;43(2):184–189. (LOE: 3)
44. Gonzalez RR, Chevront SN, Montain SJ, et al. Expanded prediction equations of human sweat loss and water needs. *J Appl Physiol (1985).* 2009;107(2):379–388. (LOE: 3)
45. Armstrong LE, Ganio MS, Klau JF, Johnson EC, Casa DJ, Maresh CM. Novel hydration assessment techniques employing thirst and a water intake challenge in healthy men. *Appl Physiol Nutr Metab.* 2014;39(2):138–144. (LOE: 2)
46. Engell DB, Maller O, Sawka MN, Francesconi RN, Drolet L, Young AJ. Thirst and fluid intake following graded hypohydration levels in humans. *Physiol Behav.* 1987;40(2):229–236. (LOE: 2)
47. Greenleaf JE. Problem: thirst, drinking behavior, and involuntary dehydration. *Med Sci Sports Exerc.* 1992;24(6):645–656. (LOE: 3)
48. Maresh CM, Gabaree-Boulant CL, Armstrong LE, et al. Effect of hydration status on thirst, drinking, and related hormonal responses during low-intensity exercise in the heat. *J Appl Physiol (1985).* 2004;97(1):39–44. (LOE: 2)
49. Takamata A, Mack GW, Gillen CM, Nadel ER. Sodium appetite, thirst, and body fluid regulation in humans during rehydration without sodium replacement. *Am J Physiol.* 1994;266(5, pt 2):R1493–R1502. (LOE: 2)
50. Shirreffs SM, Merson SJ, Fraser SM, Archer DT. The effects of fluid restriction on hydration status and subjective feelings in man. *Br J Nutr.* 2004;91(6):951–958. (LOE: 2)
51. Burdon CA, Johnson NA, Chapman PG, O'Connor HT. Influence of beverage temperature on palatability and fluid ingestion during endurance exercise: a systematic review. *Int J Sport Nutr Exerc Metab.* 2012;22(3):199–211. (LOE: 2)
52. Erdman KA, Tunnicliffe J, Lun VM, Reimer RA. Eating patterns and composition of meals and snacks in elite Canadian athletes. *Int J Sport Nutr Exerc Metab.* 2013;23(3):210–219. (LOE: 3)
53. Godek SF, Bartolozzi AR, Godek JJ. Sweat rate and fluid turnover in American football players compared with runners in a hot and humid environment. *Br J Sports Med.* 2005;39(4):205–211. (LOE: 3)
54. O'Neal EK, Poulos SP, Bishop PA. Hydration profile and influence of beverage contents on fluid intake by women during outdoor recreational walking. *Eur J Appl Physiol.* 2012;112(12):3971–3982. (LOE: 3)
55. Rivera-Brown AM, Gutiérrez R, Gutiérrez JC, Frontera WR, Bar-Or O. Drink composition, voluntary drinking, and fluid balance in exercising, trained, heat-acclimatized boys. *J Appl Physiol (1985).* 1999;86(1):78–84. (LOE: 2)
56. Almond CS, Shin AY, Fortescue EB, et al. Hyponatremia among runners in the Boston Marathon. *N Engl J Med.* 2005;352(15):1550–1556. (LOE: 3)
57. Patel AV, Mihalik JP, Notebaert AJ, Guskiewicz KM, Prentice WE. Neuropsychological performance, postural stability, and symptoms after dehydration. *J Athl Train.* 2007;42(1):66–75. (LOE: 2)
58. Hoffman MD, Fogard K, Winger J, Hew-Butler T, Stuempfle KJ. Characteristics of 161-km ultramarathon finishers developing exercise-associated hyponatremia. *Res Sports Med.* 2013;21(2):164–175. (LOE: 2)
59. Casa DJ, Guskiewicz KM, Anderson SA, et al. National Athletic Trainers' Association position statement: preventing sudden death in sports. *J Athl Train.* 2012;47(1):96–118. (LOE: 3)
60. Ganio MS, Wingo JE, Carroll CE, Thomas MK, Cureton KJ. Fluid ingestion attenuates the decline in VO₂peak associated with cardiovascular drift. *Med Sci Sports Exerc.* 2006;38(5):901–909. (LOE: 2)
61. Sawka MN, Francesconi RP, Pimental NA, Pandolf KB. Hydration and vascular fluid shifts during exercise in the heat. *J Appl Physiol Respir Environ Exerc Physiol.* 1984;56(1):91–96. (LOE: 2)
62. Ebert TR, Martin DT, Bullock N, et al. Influence of hydration status on thermoregulation and cycling hill climbing. *Med Sci Sports Exerc.* 2007;39(2):323–329. (LOE: 2)
63. Sawka MN, Young AJ, Latzka WA, Neuffer PD, Quigley MD, Pandolf KB. Human tolerance to heat strain during exercise: influence of hydration. *J Appl Physiol (1985).* 1992;73(1):368–375. (LOE: 2)
64. Sawka MN, Montain SJ, Latzka WA. Hydration effects on thermoregulation and performance in the heat. *Comp Biochem Physiol A Mol Integr Physiol.* 2001;128(4):679–690. (LOE: 2)
65. Casa DJ, DeMartini JK, Bergeron MF, et al. National Athletic Trainers' Association position statement: exertional heat illnesses. *J Athl Train.* 2015;50(9):986–1000. (LOE: 3)
66. Sawka MN, Burke LM, Eichner ER, Maughan RJ, Montain SJ, Stachenfeld NS. American College of Sports Medicine position stand. Exercise and fluid replacement. *Med Sci Sports Exerc.* 2007;39(2):377–390. (LOE: 3)
67. Bruso JR, Hoffman MD, Rogers IR, Lee L, Towle G, Hew-Butler T. Rhabdomyolysis and hyponatremia: a cluster of five cases at the 161-km 2009 Western States Endurance Run. *Wilderness Environ Med.* 2010;21(4):303–308. (LOE: 3)
68. Ellis C, Cuthill J, Hew-Butler T, George SM, Rosner MH. Case report: exercise-associated hyponatremia with rhabdomyolysis during endurance exercise. *Phys Sportsmed.* 2009;37(1):126–132. (LOE: 3)
69. Adams WM, Ferraro EM, Huggins RA, Casa DJ. Influence of body mass loss on changes in heart rate during exercise in the heat: a systematic review. *J Strength Cond Res.* 2014;28(8):2380–2389. (LOE: 1)
70. Lopez RM, Casa DJ, Jensen KA, et al. Examining the influence of hydration status on physiological responses and running speed during trail running in the heat with controlled exercise intensity. *J Strength Cond Res.* 2011;25(11):2944–2954. (LOE: 2)
71. Montain SJ, Coyle EF. Fluid ingestion during exercise increases skin blood flow independent of increases in blood volume. *J Appl Physiol (1985).* 1992;73(3):903–910. (LOE: 2)
72. Carter R, Chevront SN, Williams JO, et al. Epidemiology of hospitalizations and deaths from heat illness in soldiers. *Med Sci Sports Exerc.* 2005;37(8):1338–1344. (LOE: 3)
73. Bigard AX, Sanchez H, Claveyrolas G, Martin S, Thimonier B, Arnaud MJ. Effects of dehydration and rehydration on EMG

- changes during fatiguing contractions. *Med Sci Sports Exerc.* 2001;33(10):1694–1700. (LOE: 2)
74. Chevront SN, Carter R, Castellani JW, Sawka MN. Hypohydration impairs endurance exercise performance in temperate but not cold air. *J Appl Physiol (1985).* 2005;99(5):1972–1976. (LOE: 2)
 75. Dugas JP, Oosthuizen U, Tucker R, Noakes TD. Rates of fluid ingestion alter pacing but not thermoregulatory responses during prolonged exercise in hot and humid conditions with appropriate convective cooling. *Eur J Appl Physiol.* 2009;105(1):69–80. (LOE: 2)
 76. Judelson DA, Maresh CM, Anderson JM, et al. Hydration and muscular performance: does fluid balance affect strength, power and high-intensity endurance? *Sports Med.* 2007;37(10):907–921. (LOE: 3)
 77. Schoffstall JE, Branch JD, Leutholtz BC, Swain DE. Effects of dehydration and rehydration on the one-repetition maximum bench press of weight-trained males. *J Strength Cond Res.* 2001;15(1):102–108. (LOE: 2)
 78. Maughan RJ, Shirreffs SM. Development of individual hydration strategies for athletes. *Int J Sport Nutr Exerc Metab.* 2008;18(5):457–472. (LOE: 3)
 79. Cleary MA, Hetzler RK, Wasson D, Wages JJ, Stickley C, Kimura IF. Hydration behaviors before and after an educational and prescribed hydration intervention in adolescent athletes. *J Athl Train.* 2012;47(3):273–281. (LOE: 2)
 80. Jeukendrup AE, Moseley L. Multiple transportable carbohydrates enhance gastric emptying and fluid delivery. *Scand J Med Sci Sports.* 2010;20(1):112–121. (LOE: 2)
 81. Mudambo KS, Leese GP, Rennie MJ. Gastric emptying in soldiers during and after field exercise in the heat measured with the [¹³C]acetate breath test method. *Eur J Appl Physiol Occup Physiol.* 1997;75(2):109–114. (LOE: 2)
 82. Clayton DJ, Evans GH, James LJ. Effect of drink carbohydrate content on postexercise gastric emptying, rehydration, and the calculation of net fluid balance. *Int J Sport Nutr Exerc Metab.* 2014;24(1):79–89. (LOE: 2)
 83. Ryan AJ, Lambert GP, Shi X, Chang RT, Summers RW, Gisolfi CV. Effect of hypohydration on gastric emptying and intestinal absorption during exercise. *J Appl Physiol (1985).* 1998;84(5):1581–1588. (LOE: 2)
 84. Mitchell JB, Grandjean PW, Pizza FX, Starling RD, Holtz RW. The effect of volume ingested on rehydration and gastric emptying following exercise-induced dehydration. *Med Sci Sports Exerc.* 1994;26(9):1135–1143. (LOE: 2)
 85. Taylor NA, Machado-Moreira CA. Regional variations in trans-epidermal water loss, eccrine sweat gland density, sweat secretion rates and electrolyte composition in resting and exercising humans. *Extrem Physiol Med.* 2013;2(1):4. (LOE: 3)
 86. Allan JR, Wilson CG. Influence of acclimatization on sweat sodium concentration. *J Appl Physiol.* 1971;30(5):708–712. (LOE: 2)
 87. Buono MJ, Ball KD, Kolkhorst FW. Sodium ion concentration vs. sweat rate relationship in humans. *J Appl Physiol (1985).* 2007;103(3):990–994. (LOE: 3)
 88. Buono MJ, Claros R, Deboer T, Wong J. Na⁺ secretion rate increases proportionally more than the Na⁺ reabsorption rate with increases in sweat rate. *J Appl Physiol (1985).* 2008;105(4):1044–1048. (LOE: 2)
 89. Lorenzo S, Minson CT. Heat acclimation improves cutaneous vascular function and sweating in trained cyclists. *J Appl Physiol (1985).* 2010;109(6):1736–1743. (LOE: 2)
 90. Arnautis G, Kavouras SA, Angelopoulou A, et al. Fluid balance during training in elite young athletes of different sports. *J Strength Cond Res.* 2015;29(12):3447–3452. (LOE: 3)
 91. Minehan MR, Riley MD, Burke LM. Effect of flavor and awareness of kilojoule content of drinks on preference and fluid balance in team sports. *Int J Sport Nutr Exerc Metab.* 2002;12(1):81–92. (LOE: 2)
 92. Wilmore JH, Morton AR, Gilbey HJ, Wood RJ. Role of taste preference on fluid intake during and after 90 min of running at 60% of VO₂max in the heat. *Med Sci Sports Exerc.* 1998;30(4):587–595. (LOE: 2)
 93. Desbrow B, Jansen S, Barrett A, Leveritt MD, Irwin C. Comparing the rehydration potential of different milk-based drinks to a carbohydrate-electrolyte beverage. *Appl Physiol Nutr Metab.* 2014;39(12):1366–1372. (LOE: 2)
 94. Naclerio F, Larumbe-Zabala E, Cooper R, Jimenez A, Goss-Sampson M. Effect of a carbohydrate-protein multi-ingredient supplement on intermittent sprint performance and muscle damage in recreational athletes. *Appl Physiol Nutr Metab.* 2014;39(10):1151–1158. (LOE: 2)
 95. Reidy PT, Konopka AR, Hinkley JM, Udem MK, Harber MP. The effect of feeding during recovery from aerobic exercise on skeletal muscle intracellular signaling. *Int J Sport Nutr Exerc Metab.* 2014;24(1):70–78. (LOE: 2)
 96. Pritchett K, Bishop P, Pritchett R, Green M, Katica C. Acute effects of chocolate milk and a commercial recovery beverage on postexercise recovery indices and endurance cycling performance. *Appl Physiol Nutr Metab.* 2009;34(6):1017–1022. (LOE: 2)
 97. Gilson SF, Saunders MJ, Moran CW, Moore RW, Womack CJ, Todd MK. Effects of chocolate milk consumption on markers of muscle recovery following soccer training: a randomized cross-over study. *J Int Soc Sports Nutr.* 2010;7:19. (LOE: 2)
 98. Ferguson-Stegall L, McCleave EL, Ding Z, et al. Postexercise carbohydrate-protein supplementation improves subsequent exercise performance and intracellular signaling for protein synthesis. *J Strength Cond Res.* 2011;25(5):1210–1224. (LOE: 2)
 99. Maughan RJ, Shirreffs SM. Recovery from prolonged exercise: restoration of water and electrolyte balance. *J Sports Sci.* 1997;15(3):297–303. (LOE: 3)
 100. Merson SJ, Maughan RJ, Shirreffs SM. Rehydration with drinks differing in sodium concentration and recovery from moderate exercise-induced hypohydration in man. *Eur J Appl Physiol.* 2008;103(5):585–594. (LOE: 2)
 101. Shirreffs SM, Taylor AJ, Leiper JB, Maughan RJ. Post-exercise rehydration in man: effects of volume consumed and drink sodium content. *Med Sci Sports Exerc.* 1996;28(10):1260–1271. (LOE: 2)
 102. Shirreffs SM, Maughan RJ. Volume repletion after exercise-induced volume depletion in humans: replacement of water and sodium losses. *Am J Physiol.* 1998;274(5, pt 2):F868–F875. (LOE: 2)
 103. Shirreffs SM, Maughan RJ. Rehydration and recovery of fluid balance after exercise. *Exerc Sport Sci Rev.* 2000;28(1):27–32. (LOE: 3)
 104. Coyle EF. Timing and method of increased carbohydrate intake to cope with heavy training, competition and recovery. *J Sports Sci.* 1991;9:29–51. (LOE: 2)
 105. Burke LM, Collier GR, Davis PG, Fricker PA, Sanigorski AJ, Hargreaves M. Muscle glycogen storage after prolonged exercise: effect of the frequency of carbohydrate feedings. *Am J Clin Nutr.* 1996;64(1):115–119. (LOE: 2)
 106. Hill KM, Stathis CG, Grinfeld E, Hayes A, McAinch AJ. Co-ingestion of carbohydrate and whey protein isolates enhance PGC-1 α mRNA expression: a randomised, single blind, cross over study. *J Int Soc Sports Nutr.* 2013;10(1):8. (LOE: 2)
 107. Moya NE, Mundel T, Du Bois AM, Ciccone AB, Morton RH, Judelson DA. Increasing humidity affects thermoregulation during low-intensity exercise in women. *Aviat Space Environ Med.* 2014;85(9):905–911. (LOE: 2)
 108. Cooper ER, Ferrara MS, Broglio SP. Exertional heat illness and environmental conditions during a single football season in the southeast. *J Athl Train.* 2006;41(3):332–336. (LOE: 3)
 109. Kulka TJ, Kenney WL. Heat balance limits in football uniforms: how different uniform ensembles alter the equation. *Phys Sportsmed.* 2002;30(7):29–39. (LOE: 2)

110. Hughson RL, Green HJ, Houston ME, Thomson JA, MacLean DR, Sutton JR. Heat injuries in Canadian mass participation runs. *Can Med Assoc J*. 1980;122(10):1141–1144. (LOE: 3)
111. Del Coso J, González-Millán C, Salinero JJ, et al. Effects of oral salt supplementation on physical performance during a half-ironman: a randomized controlled trial. *Scand J Med Sci Sports*. 2016;26(2):156–164. (LOE: 2)
112. Armstrong LE, Costill DL, Fink WJ, et al. Effects of dietary sodium on body and muscle potassium content during heat acclimation. *Eur J Appl Physiol Occup Physiol*. 1985;54(4):391–397. (LOE: 2)
113. Moreno IL, Pastre CM, Ferreira C, de Abreu LC, Valenti VE, Vanderlei LC. Effects of an isotonic beverage on autonomic regulation during and after exercise. *J Int Soc Sports Nutr*. 2013;10(1):2. (LOE: 2)
114. Hoffman MD, Myers TM. Case study: symptomatic exercise-associated hyponatremia in an endurance runner despite sodium supplementation. *Int J Sport Nutr Exerc Metab*. 2015;25(6):603–606. (LOE: 3)
115. Speedy DB, Noakes TD, Rogers IR, et al. A prospective study of exercise-associated hyponatremia in two ultradistance triathletes. *Clin J Sport Med*. 2000;10(2):136–141. (LOE: 3)
116. Ganio MS, Klau JF, Lee EC, et al. Effect of various carbohydrate-electrolyte fluids on cycling performance and maximal voluntary contraction. *Int J Sport Nutr Exerc Metab*. 2010;20(2):104–114. (LOE: 1)
117. Millard-Stafford ML, Cureton KJ, Wingo JE, Trilk J, Warren GL, Buyckx M. Hydration during exercise in warm, humid conditions: effect of a caffeinated sports drink. *Int J Sport Nutr Exerc Metab*. 2007;17(2):163–177. (LOE: 1)
118. Wemple RD, Lamb DR, McKeever KH. Caffeine vs caffeine-free sports drinks: effects on urine production at rest and during prolonged exercise. *Int J Sports Med*. 1997;18(1):40–46. (LOE: 2)
119. Fiala KA, Casa DJ, Roti MW. Rehydration with a caffeinated beverage during the nonexercise periods of 3 consecutive days of 2-a-day practices. *Int J Sport Nutr Exerc Metab*. 2004;14(4):419–429. (LOE: 2)
120. Ganio MS, Johnson EC, Klau JF, et al. Effect of ambient temperature on caffeine ergogenicity during endurance exercise. *Eur J Appl Physiol*. 2011;111(6):1135–1146. (LOE: 2)
121. Silva AM, Júdice PB, Matias CN, et al. Total body water and its compartments are not affected by ingesting a moderate dose of caffeine in healthy young adult males. *Appl Physiol Nutr Metab*. 2013;38(6):626–632. (LOE: 1)
122. Freund BJ, Montain SJ, Young AJ, et al. Glycerol hyperhydration: hormonal, renal, and vascular fluid responses. *J Appl Physiol (1985)*. 1995;79(6):2069–2077. (LOE: 2)
123. Inder WJ, Swanney MP, Donald RA, Prickett TC, Hellemans J. The effect of glycerol and desmopressin on exercise performance and hydration in triathletes. *Med Sci Sports Exerc*. 1998;30(8):1263–1269. (LOE: 2)
124. Lyons TP, Riedesel ML, Meuli LE, Chick TW. Effects of glycerol-induced hyperhydration prior to exercise in the heat on sweating and core temperature. *Med Sci Sports Exerc*. 1990;22(4):477–483. (LOE: 2)
125. Magal M, Webster MJ, Sistrunk LE, Whitehead MT, Evans RK, Boyd JC. Comparison of glycerol and water hydration regimens on tennis-related performance. *Med Sci Sports Exerc*. 2003;35(1):150–156. (LOE: 2)
126. Montner P, Stark DM, Riedesel ML, et al. Pre-exercise glycerol hydration improves cycling endurance time. *Int J Sports Med*. 1996;17(1):27–33. (LOE: 2)
127. O'Brien C, Freund BJ, Young AJ, Sawka MN. Glycerol hyperhydration: physiological responses during cold-air exposure. *J Appl Physiol (1985)*. 2005;99(2):515–521. (LOE: 2)
128. Shirreffs SM, Maughan RJ. Restoration of fluid balance after exercise-induced dehydration: effects of alcohol consumption. *J Appl Physiol (1985)*. 1997;83(4):1152–1158. (LOE: 2)
129. Hobson RM, Maughan RJ. Hydration status and the diuretic action of a small dose of alcohol. *Alcohol Alcohol*. 2010;45(4):366–373. (LOE: 2)
130. Lew CH, Slater G, Nair G, Miller M. Relationship between changes in upon-waking urinary indices of hydration status and body mass in adolescent Singaporean athletes. *Int J Sport Nutr Exerc Metab*. 2010;20(4):330–335. (LOE: 2)
131. Baker LB, Lang JA, Kenney WL. Change in body mass accurately and reliably predicts change in body water after endurance exercise. *Eur J Appl Physiol*. 2009;105(6):959–967. (LOE: 2)
132. Muñoz CX, Johnson EC, Demartini JK, et al. Assessment of hydration biomarkers including salivary osmolality during passive and active dehydration. *Eur J Clin Nutr*. 2013;67(12):1257–1263. (LOE: 2)
133. Chevront SN, Ely BR, Kenefick RW, Sawka MN. Biological variation and diagnostic accuracy of dehydration assessment markers. *Am J Clin Nutr*. 2010;92(3):565–573. (LOE: 2)
134. Widjaja A, Morris RJ, Levy JC, Frayn KN, Manley SE, Turner RC. Within- and between-subject variation in commonly measured anthropometric and biochemical variables. *Clin Chem*. 1999;45(4):561–566. (LOE: 2)
135. Armstrong LE, Maresh CM, Castellani JW, et al. Urinary indices of hydration status. *Int J Sport Nutr*. 1994;4(3):265–279. (LOE: 2)
136. McKenzie AL, Muñoz CX, Armstrong LE. Accuracy of urine color to detect equal to or greater than 2% body mass loss in men. *J Athl Train*. 2015;50(12):1306–1309. (LOE: 2)
137. Chevront SN, Kenefick RW, Zambraski EJ. Spot urine concentrations should not be used for hydration assessment: a methodology review. *Int J Sport Nutr Exerc Metab*. 2015;25(3):293–297. (LOE: 3)
138. Armstrong LE, Soto JA, Hacker FT, Casa DJ, Kavouras SA, Maresh CM. Urinary indices during dehydration, exercise, and rehydration. *Int J Sport Nutr*. 1998;8(4):345–355. (LOE: 2)
139. Pross N, Demazieres A, Girard N, et al. Influence of progressive fluid restriction on mood and physiological markers of dehydration in women. *Br J Nutr*. 2013;109(2):313–321. (LOE: 2)
140. Armstrong LE, Johnson EC, Munoz CX, et al. Hydration biomarkers and dietary fluid consumption of women. *J Acad Nutr Diet*. 2012;112(7):1056–1061. (LOE: 2)
141. Burchfield JM, Ganio MS, Kavouras SA, et al. 24-h void number as an indicator of hydration status. *Eur J Clin Nutr*. 2015;69(5):638–641. (LOE: 2)
142. Verbalis JG, Goldsmith SR, Greenberg A, et al. Diagnosis, evaluation, and treatment of hyponatremia: expert panel recommendations. *Am J Med*. 2013;126(10 suppl 1):S1–S42. (LOE: 3)
143. Williams CA, Blackwell J. Hydration status, fluid intake, and electrolyte losses in youth soccer players. *Int J Sports Physiol Perform*. 2012;7(4):367–374. (LOE: 2)
144. Hsieh M, Roth R, Davis DL, Larrabee H, Callaway CW. Hyponatremia in runners requiring on-site medical treatment at a single marathon. *Med Sci Sports Exerc*. 2002;34(2):185–189. (LOE: 2)
145. Kratz A, Siegel AJ, Verbalis JG, et al. Sodium status of collapsed marathon runners. *Arch Pathol Lab Med*. 2005;129(2):227–230. (LOE: 3)
146. McDermott BP, Casa DJ, Lee EC, et al. The influence of rehydration mode after exercise dehydration on cardiovascular function. *J Strength Cond Res*. 2013;27(8):2086–2095. (LOE: 2)
147. McDermott BP, Casa DJ, Lee E, et al. Thermoregulation and stress hormone recovery after exercise dehydration: comparison of rehydration methods. *J Athl Train*. 2013;48(6):725–733. (LOE: 2)
148. Chlíbková D, Knechtel B, Rosemann T, et al. Rhabdomyolysis and exercise-associated hyponatremia in ultra-bikers and ultra-runners. *J Int Soc Sports Nutr*. 2015;12:29. (LOE: 3)
149. Tripette J, Loko G, Samb A, et al. Effects of hydration and dehydration on blood rheology in sickle cell trait carriers during

- exercise. *Am J Physiol Heart Circ Physiol*. 2010;299(3):H908–H914. (LOE: 2)
150. Connes P, Reid H, Hardy-Dessources MD, Morrison E, Hue O. Physiological responses of sickle cell trait carriers during exercise. *Sports Med*. 2008;38(11):931–946. (LOE: 3)
 151. Oh RC, Arter JL, Tiglaio SM, Larson SL. Exertional rhabdomyolysis: a case series of 30 hospitalized patients. *Mil Med*. 2015;180(2):201–207. (LOE: 3)
 152. Cutrufello PT, Dixon CB. The effect of acute fluid consumption following exercise-induced fluid loss on hydration status, percent body fat, and minimum wrestling weight in wrestlers. *J Strength Cond Res*. 2014;28(7):1928–1936. (LOE: 2)
 153. Lingor RJ, Olson A. Fluid and diet patterns associated with weight cycling and changes in body composition assessed by continuous monitoring throughout a college wrestling season. *J Strength Cond Res*. 2010;24(7):1763–1772. (LOE: 2)
 154. Utter AC, Lambeth PG. Evaluation of multifrequency bioelectrical impedance analysis in assessing body composition of wrestlers. *Med Sci Sports Exerc*. 2010;42(2):361–367. (LOE: 2)
 155. Utter AC, McAnulty SR, Riha BF, Pratt BA, Grose JM. The validity of multifrequency bioelectrical impedance measures to detect changes in the hydration status of wrestlers during acute dehydration and rehydration. *J Strength Cond Res*. 2012;26(1):9–15. (LOE: 2)
 156. Bar-Or O. Effects of age and gender on sweating pattern during exercise. *Int J Sports Med*. 1998;19(suppl 2):S106–S107. (LOE: 2)
 157. Meyer F, Bar-Or O, MacDougall D, Heigenhauser GJ. Sweat electrolyte loss during exercise in the heat: effects of gender and maturation. *Med Sci Sports Exerc*. 1992;24(7):776–781. (LOE: 2)
 158. Wilk B, Pender N, Volterman K, Bar-Or O, Timmons BW. Influence of pubertal stage on local sweating patterns of girls exercising in the heat. *Pediatr Exerc Sci*. 2013;25(2):212–220. (LOE: 2)
 159. Takamata A, Ito T, Yaegashi K, et al. Effect of an exercise-heat acclimation program on body fluid regulatory responses to dehydration in older men. *Am J Physiol*. 1999;277(4, pt 2):R1041–R1050. (LOE: 2)
 160. Zappe DH, Bell GW, Swartzentruber H, Wideman RF, Kenney WL. Age and regulation of fluid and electrolyte balance during repeated exercise sessions. *Am J Physiol*. 1996;270(1, pt 2):R71–R79. (LOE: 2)
 161. Sawka MN, Cheuvront SN, Carter R. Human water needs. *Nutr Rev*. 2005;63(6, pt 2):S30–S39. (LOE: 3)
 162. Wang Z, Deurenberg P, Wang W, Pietrobelli A, Baumgartner RN, Heymsfield SB. Hydration of fat-free body mass: review and critique of a classic body-composition constant. *Am J Clin Nutr*. 1999;69(5):833–841. (LOE: 3)
 163. Edelman IS, Leibman J. Anatomy of body water and electrolytes. *Am J Med*. 1959;27(2):256–277. (LOE: 3)
 164. Costill DL, Coté R, Fink W. Muscle water and electrolytes following varied levels of dehydration in man. *J Appl Physiol*. 1976;40(1):6–11. (LOE: 2)
 165. Nose H, Mack GW, Shi XR, Nadel ER. Role of osmolality and plasma volume during rehydration in humans. *J Appl Physiol (1985)*. 1988;65(1):325–331. (LOE: 2)
 166. Moyon NE, Ellis CL, Ciccone AB, et al. Increasing relative humidity impacts low-intensity exercise in the heat. *Aviat Space Environ Med*. 2014;85(2):112–119. (LOE: 2)
 167. Shapiro Y, Pandolf KB, Avellini BA, Pimental NA, Goldman RF. Heat balance and transfer in men and women exercising in hot–dry and hot–wet conditions. *Ergonomics*. 1981;24(5):375–386. (LOE: 2)
 168. Shapiro Y, Pandolf KB, Avellini BA, Pimental NA, Goldman RF. Physiological responses of men and women to humid and dry heat. *J Appl Physiol Respir Environ Exerc Physiol*. 1980;49(1):1–8. (LOE: 2)
 169. Jay O, Bain AR, Deren TM, Sacheli M, Cramer MN. Large differences in peak oxygen uptake do not independently alter changes in core temperature and sweating during exercise. *Am J Physiol Regul Integr Comp Physiol*. 2011;301(3):R832–R841. (LOE: 2)
 170. Kenny GP, Jay O. Thermometry, calorimetry, and mean body temperature during heat stress. *Compr Physiol*. 2013;3(4):1689–1719. (LOE: 3)
 171. Candas V, Libert JP, Vogt JJ. Human skin wettedness and evaporative efficiency of sweating. *J Appl Physiol Respir Environ Exerc Physiol*. 1979;46(3):522–528. (LOE: 2)
 172. Binder K, Lynn AG, Gagnon D, Kondo N, Kenny GP. Hyperthermia modifies muscle metaboreceptor and baroreceptor modulation of heat loss in humans. *Am J Physiol Regul Integr Comp Physiol*. 2012;302(4):R417–R423. (LOE: 3)
 173. Bergeron MF. Heat cramps during tennis: a case report. *Int J Sport Nutr*. 1996;6(1):62–68. (LOE: 3)
 174. Schweltnus MP, Nicol J, Laubscher R, Noakes TD. Serum electrolyte concentrations and hydration status are not associated with exercise associated muscle cramping (EAMC) in distance runners. *Br J Sports Med*. 2004;38(4):488–492. (LOE: 3)
 175. Schweltnus MP, Drew N, Collins M. Increased running speed and previous cramps rather than dehydration or serum sodium changes predict exercise-associated muscle cramping: a prospective cohort study in 210 Ironman triathletes. *Br J Sports Med*. 2011;45(8):650–656. (LOE: 3)
 176. Maughan RJ. Exercise-induced muscle cramp: a prospective biochemical study in marathon runners. *J Sports Sci*. 1986;4(1):31–34. (LOE: 3)
 177. Parisi L, Pierelli F, Amabile G, et al. Muscular cramps: proposals for a new classification. *Acta Neurol Scand*. 2003;107(3):176–186. (LOE: 3)
 178. Armstrong LE, McDermott BP, Hosakawa Y. Exertional hyponatremia. In: Casa DJ, Stearns RL, eds. *Preventing Sudden Death in Sport and Physical Activity*. 2nd ed. Burlington, MA: Jones and Bartlett Learning; 2017:219–238. (LOE: 3)
 179. Armstrong LE, Curtis WC, Hubbard RW, Francesconi RP, Moore R, Askew EW. Symptomatic hyponatremia during prolonged exercise in heat. *Med Sci Sports Exerc*. 1993;25(5):543–549. (LOE: 3)
 180. Sawka MN, Noakes TD. Does dehydration impair exercise performance? *Med Sci Sports Exerc*. 2007;39(8):1209–1217. (LOE: 3)
 181. Cheuvront SN, Kenefick RW. Dehydration: physiology, assessment, and performance effects. *Compr Physiol*. 2014;4(1):257–285. (LOE: 3)
 182. Goulet ED. Dehydration and endurance performance in competitive athletes. *Nutr Rev*. 2012;70(suppl 2):S132–S136. (LOE: 3)
 183. Laursen PB, Suriano R, Quod MJ, et al. Core temperature and hydration status during an Ironman triathlon. *Br J Sports Med*. 2006;40(4):320–325. (LOE: 2)
 184. Stachenfeld NS. The interrelationship of research in the laboratory and the field to assess hydration status and determine mechanisms involved in water regulation during physical activity. *Sports Med*. 2014;44(suppl 1):S97–S104. (LOE: 3)
 185. Maughan RJ. Investigating the associations between hydration and exercise performance: methodology and limitations. *Nutr Rev*. 2012;70(suppl 2):S128–S131. (LOE: 3)
 186. Cheuvront SN, Carter R, Sawka MN. Fluid balance and endurance exercise performance. *Curr Sports Med Rep*. 2003;2(4):202–208. (LOE: 3)
 187. Cheuvront SN, Kenefick RW, Montain SJ, Sawka MN. Mechanisms of aerobic performance impairment with heat stress and dehydration. *J Appl Physiol (1985)*. 2010;109(6):1989–1995. (LOE: 2)
 188. Carvalho P, Oliveira B, Barros R, Padrão P, Moreira P, Teixeira VH. Impact of fluid restriction and ad libitum water intake on an 8% carbohydrate-electrolyte beverage on skill performance of elite

- adolescent basketball players. *Int J Sport Nutr Exerc Metab.* 2011;21(3):214–221. (LOE: 2)
189. Bardis CN, Kavouras SA, Kosti L, Markousi M, Sidossis LS. Mild hypohydration decreases cycling performance in the heat. *Med Sci Sports Exerc.* 2013;45(9):1782–1789. (LOE: 2)
190. Maresh CM, Bergeron MF, Kenefick RW, Castellani JW, Hoffman JR, Armstrong LE. Effect of overhydration on time-trial swim performance. *J Strength Cond Res.* 2001;15(4):514–518. (LOE: 2)
191. Gigou PY, Dion T, Asselin A, Berrigan F, Goulet ED. Pre-exercise hyperhydration-induced bodyweight gain does not alter prolonged treadmill running time-trial performance in warm ambient conditions. *Nutrients.* 2012;4(8):949–966. (LOE: 2)
192. Goulet ED, Aubertin-Leheudre M, Plante GE, Dionne IJ. A meta-analysis of the effects of glycerol-induced hyperhydration on fluid retention and endurance performance. *Int J Sport Nutr Exerc Metab.* 2007;17(4):391–410. (LOE: 1)
193. Savoie FA, Kenefick RW, Ely BR, Chevront SN, Goulet ED. Effect of hypohydration on muscle endurance, strength, anaerobic power and capacity and vertical jumping ability: a meta-analysis. *Sports Med.* 2015;45(8):1207–1227. (LOE: 3)
194. Judelson DA, Maresh CM, Farrell MJ, et al. Effect of hydration state on strength, power, and resistance exercise performance. *Med Sci Sports Exerc.* 2007;39(10):1817–1824. (LOE: 2)
195. Adam GE, Carter R, Chevront SN, et al. Hydration effects on cognitive performance during military tasks in temperate and cold environments. *Physiol Behav.* 2008;93(4–5):748–756. (LOE: 2)
196. Benefer MD, Corfe BM, Russell JM, Short R, Barker ME. Water intake and post-exercise cognitive performance: an observational study of long-distance walkers and runners. *Eur J Nutr.* 2013;52(2):617–624. (LOE: 3)
197. Grego F, Vallier JM, Collardeau M, Rousseu C, Cremieux J, Brisswalter J. Influence of exercise duration and hydration status on cognitive function during prolonged cycling exercise. *Int J Sports Med.* 2005;26(1):27–33. (LOE: 2)
198. Lieberman HR, Bathalon GP, Falco CM, Kramer FM, Morgan CA, Niro P. Severe decrements in cognition function and mood induced by sleep loss, heat, dehydration, and undernutrition during simulated combat. *Biol Psychiatry.* 2005;57(4):422–429. (LOE: 2)
199. Ely BR, Sollanek KJ, Chevront SN, Lieberman HR, Kenefick RW. Hypohydration and acute thermal stress affect mood state but not cognition or dynamic postural balance. *Eur J Appl Physiol.* 2013;113(4):1027–1034. (LOE: 2)
200. Lieberman HR. Methods for assessing the effects of dehydration on cognitive function. *Nutr Rev.* 2012;70(suppl 2):S143–S146. (LOE: 3)
201. Kenefick RW, Chevront SN, Elliott LD, Ely BR, Sawka MN. Biological and analytical variation of the human sweating response: implications for study design and analysis. *Am J Physiol Regul Integr Comp Physiol.* 2012;302(2):R252–R258. (LOE: 2)
202. van Nieuwenhoven MA, Vriens BE, Brummer RJ, Brouns F. Effect of dehydration on gastrointestinal function at rest and during exercise in humans. *Eur J Appl Physiol.* 2000;83(6):578–584. (LOE: 2)
203. Shirreffs SM, Aragon-Vargas LF, Keil M, Love TD, Phillips S. Rehydration after exercise in the heat: a comparison of 4 commonly used drinks. *Int J Sport Nutr Exerc Metab.* 2007;17(3):244–258. (LOE: 2)
204. Speedy DB, Thompson JM, Rodgers I, Collins M, Sharwood K, Noakes TD. Oral salt supplementation during ultradistance exercise. *Clin J Sport Med.* 2002;12(5):279–284. (LOE: 2)
205. Savoie FA, Asselin A, Goulet ED. Comparison of sodium chloride tablets-induced, sodium chloride solution-induced, and glycerol-induced hyperhydration on fluid balance responses in healthy men. *J Strength Cond Res.* 2016;30(10):2880–2891. (LOE: 2)
206. Havenith G, van Middendorp H. The relative influence of physical fitness, acclimatization state, anthropometric measures and gender on individual reactions to heat stress. *Eur J Appl Physiol Occup Physiol.* 1990;61(5–6):419–427. (LOE: 2)
207. Gagnon D, Jay O, Kenny GP. The evaporative requirement for heat balance determines whole-body sweat rate during exercise under conditions permitting full evaporation. *J Physiol.* 2013;591(11):2925–2935. (LOE: 3)
208. Armstrong LE, Hubbard RW, Jones BH, Daniels JT. Preparing Alberto Salazar for the heat of the 1984 Olympic marathon. *Phys Sportsmed.* 1986;14(3):73–81. (LOE: 3)
209. Baker LB, Ungaro CT, Barnes KA, Nuccio RP, Reimel AJ, Stofan JR. Validity and reliability of a field technique for sweat Na⁺ and K⁺ analysis during exercise in a hot-humid environment. *Physiol Rep.* 2014;2(5):e12007. (LOE: 2)
210. Maughan RJ, Merson SJ, Broad NP, Shirreffs SM. Fluid and electrolyte intake and loss in elite soccer players during training. *Int J Sport Nutr Exerc Metab.* 2004;14(3):333–346. (LOE: 2)
211. Shirreffs SM, Maughan RJ. Whole body sweat collection in humans: an improved method with preliminary data on electrolyte content. *J Appl Physiol (1985).* 1997;82(1):336–341. (LOE: 2)
212. Patterson MJ, Galloway SD, Nimmo MA. Variations in regional sweat composition in normal human males. *Exp Physiol.* 2000;85(6):869–875. (LOE: 2)
213. Perrier E, Rondeau P, Poupin M, et al. Relation between urinary hydration biomarkers and total fluid intake in healthy adults. *Eur J Clin Nutr.* 2013;67(9):939–943. (LOE: 2)
214. Dabinett JA, Reid K, James N. Educational strategies used in increasing fluid intake and enhancing hydration status in field hockey players preparing for competition in a hot and humid environment: a case study. *Int J Sport Nutr Exerc Metab.* 2001;11(3):334–348. (LOE: 2)
215. Maughan RJ, Leiper JB, Shirreffs SM. Restoration of fluid balance after exercise-induced dehydration: effects of food and fluid intake. *Eur J Appl Physiol Occup Physiol.* 1996;73(3–4):317–325. (LOE: 2)
216. Chevront SN, Carter R, Montain SJ, Sawka MN. Daily body mass variability and stability in active men undergoing exercise-heat stress. *Int J Sport Nutr Exerc Metab.* 2004;14(5):532–540. (LOE: 2)
217. Charkoudian N, Halliwill JR, Morgan BJ, Eisenach JH, Joyner MJ. Influences of hydration on post-exercise cardiovascular control in humans. *J Physiol.* 2003;552(pt 2):635–644. (LOE: 2)
218. Casa DJ, Maresh CM, Armstrong LE, et al. Intravenous versus oral rehydration during a brief period: responses to subsequent exercise in the heat. *Med Sci Sports Exerc.* 2000;32(1):124–133. (LOE: 2)
219. Casa DJ, Maresh CM, Armstrong LE, et al. Intravenous versus oral rehydration during a brief period: stress hormone responses to subsequent exhaustive exercise in the heat. *Int J Sport Nutr Exerc Metab.* 2000;10(4):361–374. (LOE: 2)
220. Coyle EF, Montain SJ. Benefits of fluid replacement with carbohydrate during exercise. *Med Sci Sports Exerc.* 1992;24(suppl 9):S324–S330. (LOE: 3)
221. Gisolfi CV, Lambert GP, Summers RW. Intestinal fluid absorption during exercise: role of sport drink osmolality and [Na⁺]. *Med Sci Sports Exerc.* 2001;33(6):907–915. (LOE: 2)
222. Kingsley M, Penas-Ruiz C, Terry C, Russell M. Effects of carbohydrate-hydration strategies on glucose metabolism, sprint performance and hydration during a soccer match simulation in recreational players. *J Sci Med Sport.* 2014;17(2):239–243. (LOE: 2)
223. Lee MJ, Hammond KM, Vasdev A, et al. Self-selecting fluid intake while maintaining high carbohydrate availability does not impair half-marathon performance. *Int J Sports Med.* 2014;35(14):1216–1222. (LOE: 2)
224. Meyer LG, Horrigan DJ, Lotz WG. Effects of three hydration beverages on exercise performance during 60 hours of heat exposure. *Aviat Space Environ Med.* 1995;66(11):1052–1057. (LOE: 2)

225. Hill RJ, Bluck LJ, Davies PS. The hydration ability of three commercially available sports drinks and water. *J Sci Med Sport*. 2008;11(2):116–123. (LOE: 2)
226. Siegler JC, Mermier CM, Amorim FT, Lovell RJ, McNaughton LR, Robergs RA. Hydration, thermoregulation, and performance effects of two sport drinks during soccer training sessions. *J Strength Cond Res*. 2008;22(5):1394–1401. (LOE: 3)
227. Ferry M. Strategies for ensuring good hydration in the elderly. *Nutr Rev*. 2005;63(6, pt 2):S22–S29. (LOE: 3)
228. Schols JM, De Groot CP, van der Cammen TJ, Olde Rikkert MG. Preventing and treating dehydration in the elderly during periods of illness and warm weather. *J Nutr Health Aging*. 2009;13(2):150–157. (LOE: 2)
229. Horner KM, Schubert MM, Desbrow B, Byrne NM, King NA. Acute exercise and gastric emptying: a meta-analysis and implications for appetite control. *Sports Med*. 2015;45(5):659–678. (LOE: 1)
230. Maughan RJ, Leiper JB, Vist GE. Gastric emptying and fluid availability after ingestion of glucose and soy protein hydrolysate solutions in man. *Exp Physiol*. 2004;89(1):101–108. (LOE: 2)
231. Wong SH, Sun FH. Effect of beverage flavor on body hydration in Hong Kong Chinese children exercising in a hot environment. *Pediatr Exerc Sci*. 2014;26(2):177–186. (LOE: 3)
232. Coyle EF, Montain SJ. Carbohydrate and fluid ingestion during exercise: are there trade-offs? *Med Sci Sports Exerc*. 1992;24(6):671–678. (LOE: 3)
233. Coyle EF. Carbohydrate feeding during exercise. *Int J Sports Med*. 1992;13(suppl 1):S126–S128. (LOE: 3)
234. Rustad PI, Sailer M, Cumming KT, et al. Intake of protein plus carbohydrate during the first two hours after exhaustive cycling improves performance the following day. *PLoS One*. 2016;11(4):e0153229. (LOE: 3)
235. Vist GE, Maughan RJ. Gastric emptying of ingested solutions in man: effect of beverage glucose concentration. *Med Sci Sports Exerc*. 1994;26(10):1269–1273. (LOE: 2)
236. Leiper JB, Nicholas CW, Ali A, Williams C, Maughan RJ. The effect of intermittent high-intensity running on gastric emptying of fluids in man. *Med Sci Sports Exerc*. 2005;37(2):240–247. (LOE: 2)
237. Breen L, Philp A, Witard OC, et al. The influence of carbohydrate-protein co-ingestion following endurance exercise on myofibrillar and mitochondrial protein synthesis. *J Physiol*. 2011;589(pt 16):4011–4025. (LOE: 2)
238. Thomas DT, Erdman KA, Burke LM. Position of the Academy of Nutrition and Dietetics, Dietitians of Canada, and the American College of Sports Medicine: nutrition and athletic performance. *J Acad Nutr Diet*. 2016;116(3):501–528. (LOE: 3)
239. Lopez RM, Casa DJ, McDermott BP, Ganio MS, Armstrong LE, Maresh CM. Does creatine supplementation hinder exercise heat tolerance or hydration status? A systematic review with meta-analyses. *J Athl Train*. 2009;44(2):215–223. (LOE: 2)
240. Ross ML, Jeacocke NA, Laursen PB, Martin DT, Abbiss CR, Burke LM. Effects of lowering body temperature via hyperhydration, with and without glycerol ingestion and practical precooling on cycling time trial performance in hot and humid conditions. *J Int Soc Sports Nutr*. 2012;9(1):55. (LOE: 2)
241. Armstrong LE. Hydration assessment techniques. *Nutr Rev*. 2005;63(6, pt 2):S40–S54. (LOE: 3)
242. Maughan RJ, Shirreffs SM, Leiper JB. Errors in the estimation of hydration status from changes in body mass. *J Sports Sci*. 2007;25(7):797–804. (LOE: 2)
243. Fortes MB, Owen JA, Raymond-Barker P, et al. Is this elderly patient dehydrated? Diagnostic accuracy of hydration assessment using physical signs, urine, and saliva markers. *J Am Med Dir Assoc*. 2015;16(3):221–228. (LOE: 2)
244. Chadha V, Garg U, Alon US. Measurement of urinary concentration: a critical appraisal of methodologies. *Pediatr Nephrol*. 2001;16(4):374–382. (LOE: 3)
245. Abbey BM, Heelan KA, Brown GA, Bartee RT. Validity of HydraTrend reagent strips for the assessment of hydration status. *J Strength Cond Res*. 2014;28(9):2634–2639. (LOE: 2)
246. Sawka M, Wenger C, Pandolf K. Thermoregulatory responses to acute exercise-heat stress and heat acclimation. In: Fregly M, Blatteis C, eds. *Handbook of Physiology*. New York, NY: Oxford Press; 1996:157–185. (LOE: 3)
247. Dann EJ, Gillis S, Burstein R. Effect of fluid intake on renal function during exercise in the cold. *Eur J Appl Physiol Occup Physiol*. 1990;61(1–2):133–137. (LOE: 2)
248. Givan GV, Diehl JJ. Intravenous fluid use in athletes. *Sports Health*. 2012;4(4):333–339. (LOE: 3)
249. Castellani JW, Maresh CM, Armstrong LE, et al. Endocrine responses during exercise-heat stress: effects of prior isotonic and hypotonic intravenous rehydration. *Eur J Appl Physiol Occup Physiol*. 1998;77(3):242–248. (LOE: 2)
250. Cairns RS, Hew-Butler T. Proof of concept: hypovolemic hyponatremia may precede and augment creatine kinase elevations during an ultramarathon. *Eur J Appl Physiol*. 2016;116(3):647–655. (LOE: 2)
251. Oopik V, Timpmann S, Burk A, Hannus I. Hydration status of Greco-Roman wrestlers in an authentic precompetition situation. *Appl Physiol Nutr Metab*. 2013;38(6):621–625. (LOE: 3)
252. Pettersson S, Berg CM. Hydration status in elite wrestlers, judokas, boxers, and taekwondo athletes on competition day. *Int J Sport Nutr Exerc Metab*. 2014;24(3):267–275. (LOE: 3)
253. Bossingham MJ, Carnell NS, Campbell WW. Water balance, hydration status, and fat-free mass hydration in younger and older adults. *Am J Clin Nutr*. 2005;81(6):1342–1350. (LOE: 2)
254. Kenney WL, Chiu P. Influence of age on thirst and fluid intake. *Med Sci Sports Exerc*. 2001;33(9):1524–1532. (LOE: 2)
255. Stachenfeld NS, Mack GW, Takamata A, DiPietro L, Nadel ER. Thirst and fluid regulatory responses to hypertonicity in older adults. *Am J Physiol*. 1996;271(3, pt 2):R757–R765. (LOE: 2)

Address correspondence to Brendon P. McDermott, PhD, ATC, FACSM, Athletic Training Program, Exercise Science Research Center, University of Arkansas, 326B HPER Building, Fayetteville, AR 72701. Address e-mail to brendonm@uark.edu.