

Fluids and Hydration in Prolonged Endurance Performance

Serge P. von Duvillard, PhD, FACSM, William A. Braun, PhD, Melissa Markofski, MS, Ralph Beneke, MD, PhD, FACSM, and Renate Leithäuser, MD

From the Human Performance Laboratory, Department of Health, Kinesiology and Sports Studies, Texas A&M University-Commerce, Commerce, Texas, USA; and the Department of Biological Sciences, Centre of Sports and Exercise Science, University of Essex, Essex, UK

Numerous studies have confirmed that performance can be impaired when athletes are dehydrated. Endurance athletes should drink beverages containing carbohydrate and electrolyte during and after training or competition. Carbohydrates (sugars) favor consumption and Na^+ favors retention of water. Drinking during competition is desirable compared with fluid ingestion after or before training or competition only. Athletes seldom replace fluids fully due to sweat loss. Proper hydration during training or competition will enhance performance, avoid ensuing thermal stress, maintain plasma volume, delay fatigue, and prevent injuries associated with dehydration and sweat loss. In contrast, hyperhydration or overdrinking before, during, and after endurance events may cause Na^+ depletion and may lead to hyponatremia. It is imperative that endurance athletes replace sweat loss via fluid intake containing about 4% to 8% of carbohydrate solution and electrolytes during training or competition. It is recommended that athletes drink about 500 mL of fluid solution 1 to 2 h before an event and continue to consume cool or cold drinks in regular intervals to replace fluid loss due to sweat. For intense prolonged exercise lasting longer than 1 h, athletes should consume between 30 and 60 g/h and drink between 600 and 1200 mL/h of a solution containing carbohydrate and Na^+ (0.5 to 0.7 g/L of fluid). Maintaining proper hydration before, during, and after training and competition will help reduce fluid loss, maintain performance, lower submaximal exercise heart rate, maintain plasma volume, and reduce heat stress, heat exhaustion, and possibly heat stroke. *Nutrition* 2004;20:651–656. ©Elsevier Inc. 2004

KEY WORDS: dehydration, electrolytes, endurance exercise

INTRODUCTION

Fluid intake and adequate hydration during exercise are essential and, more importantly, critical during prolonged training sessions and competition events. Fluid intake maintains hydration and helps to maintain body temperature (thermoregulation), avoid dehydration, and maintain adequate plasma volume. For events lasting longer than 1 h, athletes should consume fluids containing carbohydrates (CHOs) and electrolytes rather than water alone. Reduction in body water, availability of CHOs, and an inadequate electrolyte balance during prolonged exercise events will hamper performance and may lead in some cases to serious medical problems (heat exhaustion or heat stroke). A 1% reduction in body weight due to water loss may evoke an undue stress on the cardiovascular system accompanied by increases in heart rate and inadequate heat transfer to the skin and the environment, increase plasma osmolality, decrease plasma volume, and may affect the intracellular and extracellular electrolyte balance.¹

Fluid in the body is contained mainly in two areas (compartments). These are the extracellular (fluid outside the cells) and the intracellular (fluid in the red blood cells) fluids. The extracellular fluid is subdivided into interstitial fluid and blood plasma. In humans, body water constitutes about 60% of an individual's body weight, with a few minor differences depending on sex, age, training status, percentage of body fat, etc. About 40% of body

water is housed in the intracellular fluid. On average, blood volume in an adult accounts for about 7% of a person's body weight, or about 5 L. Blood volume is distributed between plasma (60% of blood plasma) and red blood cells (40%). When these levels are challenged during prolonged training sessions and competition, they will singly or collectively result in reduced performance and in some cases may cause serious injury, medical emergency, or even death. The sequence of physiologic events affecting the loss of water is via breathing, sweating, feces, and urine output. During prolonged performance, most water is lost in sweat especially during high environmental temperatures. About 580 kcal is lost for every liter of sweat that is evaporated.² Loss of body fluid can be determined by changes in body weight resulting from exercise. Each kilogram of body weight loss accounts for about 1 L of fluid loss. Development of sports drinks with appropriate and adequate concentrations of electrolytes and CHOs promotes maintenance of homeostasis, prevents injuries, and maintains optimal performance.³ Water balance in the body is regulated by various means. Changes in osmotic pressure or circulating blood volume stimulate the osmoreceptors in the hypothalamus and baroreceptors in heart and blood vessels. Water balance also is regulated by several hormones. The renin-angiotensin-aldosterone system regulates sodium retention, and vasopressin (antidiuretic hormone) regulates water retention in kidneys. Vasopressin also participates in thermoregulation in hypohydrated subjects. Atrial natriuretic peptide secreted by the heart participates in water balance regulation. Atrial natriuretic peptide does not participate or only minimally participates in water balance regulation during cold exposure at 10°C to 12°C. However, exposure to a –20°C environment while wearing warm clothing elicits a two-fold increase in atrial natri-

Correspondence to: Serge P. von Duvillard, PhD, FACSM, Director, Human Performance Laboratory, Department of Health, Kinesiology, and Sports Studies, Texas A&M University-Commerce, P.O. Box 3011, Commerce, TX 75429, USA. E-mail: serge_vonduvillard@tamu-commerce.edu

uretic peptide. Cold-stimulated atrial natriuretic peptide release has been found to be inhibited by a 3% level of dehydration.⁴

ELECTROLYTE BALANCE, PLASMA VOLUME, AND FLUID SHIFT DURING EXERCISE

Numerous investigators have reported changes in plasma electrolyte concentrations, plasma volume changes, fluid shifts, delayed fatigue, thermoregulation, and hormonal and catecholamine responses during short, prolonged, and low-, moderate-, and high-intensity exercise.^{4–32} Prolonged exercise may induce Na^+ and K^+ losses and excretion of electrolyte free water in subjects with otherwise normal water balance.³³ Sanders et al.²⁵ investigated sodium replacement and fluid shifts during prolonged exercise and found that there is an increase in Na^+ concentration and that most water is lost in the form of sweat that comes from extracellular fluid and intracellular fluid, causing an increase in plasma osmolality. An increase in osmolality and a reduction in plasma volume cause a reduction in skin blood flow and thus directly induce hyperthermia.²⁵ Malhotra et al.³⁴ examined the effect of restricted K^+ intake and physiologic response during heat exposure. They found that in a hot environment the major loss in K^+ was through sweat. As much as 7 to 8 L of sweat may be lost on a hot summer day in a tropical environment. They further stated that urinary output during these types of summer days is very small and reduction in K^+ may not be attributed to urinary loss alone. They suggested that K^+ intake needs to be adequate to reduce deficiency in K^+ excretion via urine and sweat because there is no metabolic conservation mechanism in place to control for excessive K^+ loss as there is in the case of Na^+ .

The effect of acute plasma volume expansion on body temperature response during exercise performance in the heat was studied by Sawka et al.²⁷ They reported that plasma volume expansion is an important factor in the heart rate reduction response observed in their study of 4 d of heat acclimatization; however, there was no reduction in core temperature and no increase in performance in the albumin infusion trial. Dann et al.³⁵ addressed the issue of fluid intake on renal function during exercise in the cold. They found that when exercising in the cold less fluid is taken in, resulting in greater dehydration, decreased glomerular filtration rate, reduced osmotic clearance, and reduced urine volume. When fluids were consumed, these effects were eliminated. They also suggested that a person of average weight may require about 150 mL/h of fluid intake when exercising in the cold. Rintamäki et al.⁴ also studied water balance during physical performance in the cold. Disturbances in water balance when exercising in the cold may be due to the body's metabolic increase. These are due mostly to heavy clothing, cost of movement in snow, increased heat production caused by external cooling, and eating and drinking habits.

Water loss in sport and during weight control was reported by Naghii.² He found that during heat exhaustion the thermoregulatory mechanisms are working, but that individuals cannot dissipate heat well enough due to reduced blood flow to the skin. This may be accompanied by an increase in core temperature, weakness, fatigue, headache, vomiting, diarrhea, and muscle cramps. It is not unusual for elite endurance athletes to lose 1.5 L/h of fluid from sweat during training and/or competition when the rate of gastric emptying is only about 1.0 L/h. Therefore, endurance event-trained athletes should be encouraged to take in fluids before, during, and after training or competition.

But taking in only water may be problematic for exercise durations exceeding several hours that produce high sweat rates. Twerenbold et al.³⁶ examined the effect of different sodium concentrations in replacement fluids during prolonged exercise in women. Based on their findings they recommended a sodium intake of at least 680 mg/h for endurance exercises lasting 4 h or longer in women who are in a state of fluid overload to minimize

the risk of hyponatremia. In addition, they recommended a fluid intake of less than 1 L/h for women during prolonged exercise because consuming 1 L/h during a 4-h run was sufficient to cause fluid overload in most of the subjects in their study. Vrijens and Rehrer³⁷ investigated sodium-free fluid ingestion and the effect it may have on plasma sodium during exercise in the heat. They determined that, even with a lack of fluid overload, decreased plasma sodium concentration and increased risk of hyponatremia can occur during prolonged performance exercise in the heat when only sodium-free fluids are consumed to replace sweat losses. When a beverage containing low sodium is consumed instead of water alone in this situation, the relative sodium deficit can be minimized.

The influence of hydration level on body fluids and exercise performance in the heat was examined by Sawka et al.²⁸ They addressed the issues of hypo- and hyperhydration and their effects on performance. Their results indicated a small thermoregulatory advantage to hyperhydration that may have been affected by the protocol-induced hypervolemia. Van Nieuwenhoven et al.³⁸ studied gastrointestinal function during exercise by comparing water, sports drinks, and sports drinks plus caffeine. They reported that gastrointestinal function associated with exercise is not well known; however, they cited that one of the most intriguing theories may be the exercise-induced reduction in gastrointestinal blood flow. It is very difficult to measure gastrointestinal blood flow during exercise and to assert that at maximal exercise intensity the flow may be reduced to 20% of the resting value in trained and untrained people. They reported that caffeine enhances endurance performance, even below the International Olympic Committee limits. Therefore, supplementation of sports drinks with caffeine may be desirable. In this regard, many current sports drinks are supplemented with 150 mg/L caffeine. They concluded that moderate amounts of caffeinated sports drinks do not affect gastrointestinal function. They further reported that caffeine inhibits the cholinergic innervation of the striated muscle component of the esophagus, leading to lower peristaltic pressure in the midesophagus, and that caffeine stimulates glucose uptake in the small bowel. Shirreffs and Maughan³⁹ addressed the issue of replacement of water and sodium losses after exercise-induced volume depletion. They reported that loss of potassium in sweat is small relative to that of sodium. Subjects in their study were depleted by $1.89 \pm 0.17\%$ of their body mass before starting their trials. Forty minutes after exercise subjects started to consume drinks containing 0, 25, 50, and 100 mM/L of sodium. The participants consumed virtually no potassium with a beverage in any trial. However, trials with 100 mM/L of sodium resulted in a large secretion of potassium over the 6-h recovery period relative to the other trials. They attributed this electrolyte excretion (high K^+ and low Cl^-) to metabolic alkalosis as a result of acetate metabolism. The subjects were deficient in potassium throughout the recovery period, not due to the loss of potassium in sweat during exercise but to the loss in urine during the recovery period. They concluded that 102 mM/L of sodium drink appears to maximize the acute restoration of fluid balance, but its consequences on potassium levels must be considered unfavorable in terms of whole-body electrolyte balance. Stachenfeld et al.³⁰ investigated fluid balance and renal response after dehydrated exercise in well-trained men and women. They reported that, after the dehydrating exercise, well-trained men and women had a similar response for the early (<2 h) part of recovery. The women had a significantly greater rate of reabsorption during the last 2 h of the 4-h recovery period. The women also had slightly elevated plasma arginine vasopressin levels relative to baseline throughout recovery which may in part explain their greater water reabsorption. In addition, the women had a more rapid recovery of serum aldosterone, which was consistent with their lower sodium reabsorption. The sex differences in renal fluid and sodium regulatory function may have been due to estrogen effects on fluid-regulating hormones and water retention. Despite these small differences, the overall fluid balance during exercise and recovery were similar between men and women. Sanders et

al.²⁶ examined water and electrolyte shifts with partial fluid replacement during exercise. They reported that endurance athletes seldom drink more than 0.5 L/h of fluid during competition and that the ensuing dehydration leads to potential increases in plasma sodium and a decrease in plasma volume. They further stated that, when athletes replace only about half of their fluid losses during prolonged endurance performance, they should drink water to maintain their plasma osmolality and thermoregulation rather than attempt to replace their sodium losses. Their results showed that water ingestion maintains plasma sodium levels and that saline ingestion increases plasma sodium levels to values similar to those found in athletes performing a test without fluid intake.

The effect of intravenous fluid administration on recovery after running a marathon was investigated by Polak et al.⁴⁰ They studied two groups of marathon runners. One group received an intravenous infusion of 2.5 L of a 2.5% glucose and 0.45% NaCl solution. The other group received a placebo infusion of 0.9% NaCl. They found that the group that received 2.5-L infusion required 10.2 d versus 9.2 d for the placebo group to recover. The group receiving 2.5 L of saline also reported more muscle pain and stiffness. They further reported that, although these differences were not significant, they were consistent. However, the group receiving 2.5 L of saline was faster than the placebo group and arrived at the finish line at an average of 172 min versus 181 min for the placebo group. Their findings suggested that faster athletes need more time to recover and have muscle pain and stiffness for a longer period.

Nielson et al.²¹ evaluated cardiovascular, hormonal, and body fluid changes during prolonged exercise in a group of athletes who cycled and swam for 90 min. They observed a gradual upward drift in heart rate after 10 min. They also reported that this secondary rise in heart rate may be due to a reduction in stroke volume caused by reduced filling of the heart that depends on hemodynamic pressure and blood volume. The activities of cycling and swimming differ with regard to hydrostatic pressure and to water loss due to sweating. They also differ as a consequence of an upright position during cycling versus a horizontal position during swimming. These resulted in greater cardiac output and stroke volume during swimming. In addition, plasma volume decreased by 5% to 6% within the first 5 to 10 min of exercise for both exercise modes and remained unchanged throughout the 90 min of exercise. Sweat loss during cycling was four times greater than that during swimming. Swimming also induced diuresis resulting in only 2.5% less loss in total water compared with cycling. Despite differences in sweating and peripheral pooling due to hydrostatic forces, the gradual secondary increase in heart rate was the same during cycling and swimming tests. In addition, the rise in heart rate was positively related to the increase in plasma catecholamines, which occurred as exercise progressed. In a different study Nielsen et al.⁴¹ investigated fluid balance in exercise dehydration and rehydration with different glucose and electrolyte drinks. In their study subjects lost 3% of body weight after exercise. During a 2-h recovery period they administered one of four different beverages containing water, high potassium, high sodium, or high sugar every 15 min. They administered submaximal (30°C for 2 h at 50% of maximum oxygen consumption [$\text{VO}_{2\text{max}}$]) and supramaximal (105% of $\text{VO}_{2\text{max}}$) tests before dehydration and then after rehydration. Dehydration reduced plasma volume by 16%. This process was reversed during recovery even before fluid ingestion was administered due to release of water from exercising muscles. They found that the greatest increase in plasma volume was found after the sodium-rich drink. The potassium-rich drink produced the smallest and slowest increase in plasma volume. The investigators determined that the sodium-rich drink favored filling the extracellular water compartment, whereas the potassium-rich and high-sugar drinks favored the intracellular water compartment. Heart rate during the submaximal exercise test was significantly higher when the test was performed after exercise dehydration and subsequent rest and rehydration than the test before dehydration. These were found even though the plasma volume was higher than

normal after the rehydration period. The work capacity was reduced by 20% after a supramaximal performance test (105% $\text{VO}_{2\text{max}}$) after dehydration and even after 2 h of recovery and rehydration. The reduction was similar regardless of the composition of the drink solution. The researchers suggested that this decrease may also be due to glycogen depletion.

The interaction between sodium content and fluid volume and its effect on rehydration and restoration of fluid spaces and cardiovascular function were investigated by Mitchell et al.¹⁸ Subjects in this study completed four exercise trials in a hot environment (35°C) until they were dehydrated (2.9% of body weight). Four rehydration drinks were administered: a high or low volume of fluid replacement and/or a low or high sodium content. For whole-body rehydration, they found no benefit in adding sodium above 25 mM/L. For fluid compartment restoration, there did not appear to be an interaction between sodium and volume in relation to intracellular space. Cardiovascular response was restored after 3 h of rehydration regardless of fluid composition. They concluded that a minimum level of fluid may be necessary to restore cardiovascular function, especially if it is accompanied by a complete plasma volume restoration. Moquin and Mazzeo²⁰ reported on the effect of dehydration on the lactate threshold and performance to exhaustion in women. They studied seven moderately trained young women who performed two incremental tests. One test was conducted during a euhydrated state and the other during a dehydrated state. They reported that dehydration was associated with a decrease in performance time to exhaustion. They did not observe any significant changes in $\text{VO}_{2\text{max}}$ in either test. However, they did observe an early inflection in blood lactate during the dehydrated state and postulated that this may be due to greater acid-base disturbance in the muscles. However, the peak lactate between the two trials did not differ. They concluded that the decrease in time to exhaustion was highly correlated for the dehydration group and that there was a significant time reduction to exhaustion. Maughan et al.⁴² examined the effects of postexercise rehydration with fluid alone or with a meal plus fluid in eight healthy subjects. Subjects were dehydrated (2.1% of body mass) before intermittent cyclic exercise in a warm (34°C) and humid environment (55% relative humidity). For 60 min starting 30 min after exercise, subjects consumed commercially available sports drinks containing sodium, potassium, and chloride during two trials (A and B). During a different trial (C) they consumed a standard meal containing CHO, fat protein, sodium, and potassium plus a drink containing small amounts of sodium and potassium. Blood and urine samples were collected at intervals throughout the study. Blood was analyzed for hematocrit, hemoglobin concentration, serum osmolality, Na^+ , K^+ , and Cl^- concentrations, and plasma angiotensin II concentration. In urine they measured osmolality and electrolyte concentration. Dehydration resulted in 5.2% reduction in plasma volume and only osmolality was higher in trial B than in trial A. There were no differences in any other parameter. They concluded that postexercise fluid replacement can be achieved by ingestion of water consumed in sufficient volume with a meal that contains significant amount of electrolytes. Melin et al.⁴³ reported on the effect of passive heat and exercise-induced dehydration on renal water and electrolyte excretion and several hormones. They found that during exercise sympathoadrenal activation plays a major role by causing a marked decrease in urine flow and sodium excretion compared with passive heat exposure. The antidiuresis was not due to renal concentrating ability even in the presence of high plasma vasopressin concentration. After dehydration, the effect of vasopressin was effective in restoring renal concentrating ability, regardless of previous dehydrating events. They also reported on the hydration status and hormonal response during moderate exercise in the heat. They found that catecholamine response decreases significantly during exercise in a rehydrated state. In addition, rehydration corrected hypovolemia, assisted in establishing better hemodynamic response, and reduced sympathetic activity that was observed in the dehydrated state.⁴⁴

CARBOHYDRATE AND ELECTROLYTE FLUID INTAKE DURING EXERCISE

Many studies have been conducted with sports drinks, CHO and electrolyte solutions, and their effects on hydration/dehydration status, plasma volume changes, gastric emptying, and performance times to name a few.^{10,36,38,41,45–67} Murray et al.⁶⁰ investigated the effect of CHO content on exercise. They reported that beverages containing too much CHO (8% to 10%) delayed gastric emptying, reduced fluid absorption, and compromised physiologic function. However, they also reported that beverages containing 6% of sucrose increased performance after 60 min of exercise. These have been attributed to sporting events and training sessions that last longer than 90 min, resulting from reduced muscle and liver glycogen stores. They suggested that water and beverages containing low CHO (<2.5%) be consumed during shorter exercise sessions and that CHO intake beyond 45 g/h may not increase exercise performance and may result in decline in exercise or performance. Wong et al.⁶⁶ investigated the effects of a large volume of CHO and electrolyte solution on rehydration during recovery followed by another bout of exercise. They stated that dehydration and depletion of CHO are the two most important factors on an athlete's endurance capacity. They found that a positive fluid balance can be achieved when athletes consume a 6.9% CHO and electrolyte solution or an artificially sweetened placebo. They also found that the CHO and electrolyte solution is more effective in restoring endurance capacity than the same volume of placebo solution. Yaspelkis and Ivy⁶⁷ studied the effect of CHO supplement and water on exercise metabolism in the heat. They found that fluid replacement drinks containing 8.5% CHO can regulate body temperature and maintain fluid homeostasis as effectively as water during prolonged low-intensity exercise in the heat. They further reported that an 8.5% CHO supplement provides a sufficient amount of CHO to prevent a decline in CHO oxidation and may slow the rate of muscle glycogen depletion.

Tsintzas et al.⁶⁴ studied the influence of CHO supplementation early in exercise on endurance running capacity in men. Their subjects ingested only water or a 5.5% or 6.9% CHO and electrolyte solution during the first hour before the treadmill test. This was followed by a treadmill run to exhaustion (70% of $\dot{V}O_{2max}$). During the treadmill test only water was consumed. In their study the ingestion of a 6.9% of CHO and electrolyte solution did not significantly improve the time to exhaustion. Their study disagreed with the findings of others. These investigators reported that a 7.0% CHO solution can delay the onset of fatigue during prolonged running. However, they reported that numerous participants experienced gastrointestinal discomfort with the 6.9% CHO and electrolyte solution compared with very few when the 5.5% CHO and electrolyte solution and water were ingested. In addition, they reported that gastric emptying rate at rest between the 5.5% and 6.9% CHO and electrolyte solutions were similar (about 60 min). However, when using the same amount of water, the gastric emptying rate appeared to be shortened to approximately 30 min. They suggested that the ingestion of 5.5% CHO and electrolyte solution during the first hour of exercise improves time to exhaustion compared with water. There were no statistical differences between the 5.5% and 6.9% CHO and electrolyte solutions, although more subjects exhibited an improved endurance capacity when ingesting the 5.5% CHO and electrolyte solution. These authors concluded that sparing of muscle glycogen, rather than maintenance of blood glucose and CHO oxidation rate toward the end of exercise, may have been responsible for the improvement of endurance running capacity.

Tsintzas et al.⁶⁵ also examined the effect of CHO and electrolyte drinks on marathon running performance. They found that ingestion of a 5.5% CHO and electrolyte solution in comparison with ingestion of the same volume of water before and during a marathon treadmill run improves endurance performance. They

reported that their runners were able to maintain their running speed when consuming the 5.5% CHO and electrolyte solution compared with more concentrated (6.9%) CHO and electrolyte drink or water. Shi et al.⁶⁸ studied gastric emptying of cold beverages. They found that 6.0% CHO and electrolyte solutions containing one or two CHOs in single or bound forms empty at similar rates in humans and rats. Differences in CHO type, number of transportable CHOs, and beverage osmolalities within the range of 250 to 434 mOsm/kg H_2O did not influence gastric emptying rate. Intragastric temperature quickly returned to near normal within 5 min after beverage ingestion, suggesting that, if cold beverage does affect gastric emptying, the effects are likely to be small and transitory.

Sproule²⁹ studied the influence of no fluid or CHO and electrolyte fluid ingestion and the hot versus thermoneutral environment on running economy after prolonged high-intensity exercise. After prolonged running at 80% of $\dot{V}O_{2max}$ for 60 min, he found that a significant decrease ($>3.0 \text{ mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$) in running economy occurs at the common speed of 10.8 km/h (65% $\dot{V}O_{2max}$). This negative change in running economy after prolonged high-intensity running appeared to happen to the same extent irrespective of whether fluid was ingested or not, regardless of whether the fluid contained CHO (6.0%) and electrolytes or just electrolytes, and without regard for environment, thermoneutral or hot and humid.

Ray et al.²³ investigated the effect of sodium in a rehydration beverage when consumed as a fluid or meal. Thirty male and female subjects were studied during 2 h of rehydration after an initial 2.5% body weight loss. They administered water, chicken broth, a CHO and electrolyte drink, and a chicken noodle soup. Their subjects exhibited greater plasma volume recovery and lower urine volumes when they ingested chicken broth and chicken noodle soup containing high concentrations of sodium compared with those consuming water and CHO and electrolyte solution. These differences were present despite the ingestion of only 350 mL of each beverage at the onset of hydration. The composition of a fluid consumed immediately after heat- and exercise-induced dehydration contributed to body fluid restoration and should be considered if rapid rehydration is the objective. Consuming a meal such as soup has the advantage of providing fluid and electrolytes and minimizing the hunger commonly experienced after exercise. Passe et al.⁶⁹ studied the effect of beverage acceptability (6.0% CHO and electrolyte solution) on fluid intake during exercise. They reported that beverages that are often disliked during sedentary conditions increase in acceptance (are more palatable) and are often preferred over water, although water was the preferred drink during sedentary conditions. They also reported that carbonated drinks lose their acceptability in favor of water and CHO and electrolyte solutions during exercising conditions. Minehan et al.⁷⁰ studied the effect of flavor and awareness of energy content of drinks on preference and fluid balance in nine training sessions of female players of netball and basketball. They found that subjects were better able to maintain fluid balance when consuming flavored drink than water alone. Whether the drink contained calories did not matter with regard to promotion of fluid intake.

Nassis et al.⁶¹ studied the effect of a CHO and electrolyte drink on endurance capacity during prolonged intermittent high-intensity running in nine subjects who ran to exhaustion on two separate occasions. Subjects consumed water placebo or a 6.9% CHO and electrolyte solution immediately before the run (3 mL/kg of body weight) and every 20 min thereafter (2 mL/kg of body weight). Runners in this study performed $265 \times 15\text{-s}$ repeated bouts of fast running equal to 80% of $\dot{V}O_{2max}$ and low-intensity running, separated by 10 s. They found that performance times were not different between the two trials for the water placebo or the CHO and electrolyte solution. They concluded that ingestion of water or a CHO and electrolyte solution during repeated bouts of submaximal intermittent high-intensity running does not delay the onset of fatigue.

Montain and Coyle¹⁹ investigated the timing of fluid ingestion of thermoregulation during exercise and heat stresses in seven

endurance-trained cyclists who performed four separate tests of 140 min of cyclic ergometer exercise at 62% to 66% of $\dot{V}O_{2\max}$ in a hot environment (33°C). The subjects drank 1173 mL of the CHO and electrolyte beverage at 0, 40, and 80 min of exercise or they consumed the same total volume in small aliquots throughout the exercise. The exercise produced 1.2 L of calculated sweat loss and a body weight loss of 2.9% after 140 min of exercise. This investigation changed the timing of fluid ingestion during exercise and heat stresses to determine whether this would affect the thermoregulatory and cardiovascular responses. They found that increases in temperature and heart rate closely follow hydration. These effects were evident by decreased blood volume, increased serum osmolality, and increased serum sodium concentration. Beginning fluid ingestion at the onset of exercise initially attenuated the increase in core temperature and heart rate when subjects waited until 40 and 80 min to drink the same volume of fluid. These differences no longer existed after 140 min of exercise. They concluded that fluid consumption before the exercise provides no thermoregulatory advantage over waiting to drink later in the exercise.

MEDICAL REASONS FOR FLUID REPLACEMENT DURING EXERCISE

Noakes⁷¹ historically and very eloquently described medical reasons for fluid replacement during marathon running. He addressed several crucial factors that determine the risk of heatstroke, stating that heatstroke is not associated with the levels of dehydration during exercise but, more importantly, with the rate at which the athlete produces heat and the capacity of the environment to absorb that heat. He further reported that several factors more important than dehydration are responsible for heat stress, heat illness, or heatstroke. One of these factors is determination of when the rate of heat production exceeds the rate of heat loss. The rate of heat production is determined by the athlete's rate of energy expenditure, which is a function of the athlete's mass and intensity of effort or running speed. Noakes further explained that the risk of heatstroke is likely to be greater in athletes who run 10-km races than in marathon runners because the 10-km race pace is faster than the marathon race pace. Thus, marathon athletes should drink ad libitum and aim for ingestion rates of about 800 mL/h. Heavier athletes are also at greater risk for heat-related conditions than are lighter athletes when both run at the same speed. In a different study Noakes⁷² addressed the etiology of hyponatremia in distance runners and fluid and sodium balance during exercise. A clinical condition was described in which altered cerebral function was associated with very low serum sodium concentrations (<127 mM/L). Noakes attributed the condition to fluid overload as a result of voluntary overdrinking and the only factor responsible for hyponatremia of exercise. Severe hyponatremia may cause edema of vital organs, brain, and lungs. Noakes pointed out that the cause of hyponatremia is not the ingestion of large quantities of sodium contained within drinks most athletes consume during exercise but the overdrinking that may develop and induce the cerebral edema. It is cerebral edema and not the sodium concentration that causes symptoms of this condition. High rates of sodium ingestion during exercise reduce the rate of urine production, thereby perhaps increasing the possibility that fluid overload will develop when voluntary overdrinking is combined with high rates of sodium ingestion. Dangers of dehydration during exercise was further addressed by Noakes.⁷³ He disputed the fact that dehydration is the cause for heatstroke in all cases of collapse in endurance athletes, as has been alluded to historically. He further described that there is good evidence that even mild levels of dehydration impair performance. Much greater levels of dehydration are required to produce renal failure or even death. He suggested that athletes can safely maintain low levels of dehydration by drinking enough but not too much during exercise. Athletes should be aware that very

high rates of fluid ingestion (>1.5 L/h) sustained for many hours can lead to hyponatremia with a potentially fatal outcome. Excessive water intake may evoke signs and symptoms of hyponatremia. Hyponatremia is usually caused by increased intake and retention of dilute fluids concurrent with large losses of sodium through sweat.⁷⁴

CONCLUSION

Exercise, athletic competition, prolonged workouts, and long training sessions in hot, hot and humid, or cold environments challenge physiologic function. Dehydration, thermoregulation, fluid balance, rehydration, electrolyte changes, plasma volume, and cardiovascular challenges, to name a few, accompany most physical activities, exercise, training, and competition. This is especially true during prolonged endurance exercise and competition. Loss of body fluids inherently leads to a performance decrease, especially if the exercise is performed in hot environment. Thus, it is recommended that all individuals who exercise, train, and/or compete attempt to rehydrate and replace fluids and electrolytes that have been lost during exercise, mostly as a result of sweating. Maintaining proper hydration is not only a physiologic necessity but also adds to a performance advantage and reduces risks of medical problems or injury due to fluid losses.^{75–82}

REFERENCES

1. American College of Sports Medicine. Position stand on exercise and fluid replacement. *Med Sci Sports Exerc* 1996;28:i
2. Naghii MR. The significance of water in sport and weight control. *Nutr Health* 2000;14:127
3. Powers SK, Lawler J, Dodd S, Tulley R, Landry G, Wheeler K. Fluid replacement drinks during high intensity exercise: effects on minimizing exercise-induced disturbances in homeostasis. *Eur J Appl Physiol* 1990;60:54
4. Rintamäki H, Mäkinen T, Oksa J, Latvala J. Water balance and physical performance in cold. *Arch Med Res* 1995;45(suppl 2):32
5. Bilzon JLJ, Allsopp AJ, Williams C. Short-term recovery from prolonged constant pace running in a warm environment: the effectiveness of a carbohydrate-electrolyte solution. *Eur J Appl Physiol* 2000;82:305
6. Buono MJ, Wall AJ. Effect of hypohydration on core temperature during exercise in temperate and hot environment. *Pflugers Arch Eur J Appl Physiol* 2000;440:476
7. Dengel DR, Weyand RG, Black DM, Cureton KJ. Effects of varying levels of hypohydration on ratings of perceived exertion. *Int J Sports Nutr Metab* 1993;3:376
8. Epstein Y, Armstrong LE. Fluid-electrolyte balance during labor and exercise: concepts and misconceptions. *Int J Sports Nutr Metab* 1999;9:1
9. Galloway SDR, Maughan RJ. The effects of substrate and fluid provision on thermoregulatory, cardiorespiratory and metabolic responses to prolonged exercise in a cold environment in man. *Exp Physiol* 1998;83:419
10. Gore CJ, Scroop GC, Marker JD, Catchside PG. Plasma volume, osmolarity, total protein and electrolytes during treadmill running and cycle ergometer exercise. *Eur J Appl Physiol* 1992;65:302
11. Gowrishankar M, Chen C, Mallie JP, Halprin ML. What is the impact of potassium excretion on the intracellular fluid volume: importance of urine anions. *Kidney Int* 1996;50:1490
12. Jentjens RLP, Wagenmakers AJM, Jeukendrup AE. Heat stress increases muscle glycogen use but reduces the oxidation of ingested carbohydrates during exercise. *J Appl Physiol* 2002;92:1562
13. Kachadorian WA, Johnson RE. Renal responses to various rates of exercise. *J Appl Physiol* 1970;28:748
14. Latzka WA, Sawka MN, Montain SJ, et al. Hyperhydration: thermoregulatory effects during compensable exercise-heat stress. *J Appl Physiol* 1997;83:860
15. Lindinger MI, Graham TE, Spriet LL. Caffeine attenuates the exercise-induced increase in plasma [K⁺] in humans. *J Appl Physiol* 1993;74:1149
16. 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;22:477
17. Maughan RJ, Bethell LR, Leiper JB. Effects of ingested fluids on exercise capacity and on cardiovascular and metabolic responses to prolonged exercise in man. *Exp Physiol* 1996;81:847

18. Mitchell JB, Philips MD, Mercer SP, Baylies HL, Pizza FX. Postexercise rehydration: effect of Na^+ and volume on restoration of fluid spaces and cardiovascular function. *J Appl Physiol* 2000;89:1302
19. Montain SJ, Coyle EF. Influence of fluid ingestion on temperature regulation during exercise. *J Appl Physiol* 1993;75:688
20. Moquin A, Mazzeo RS. Effect of mild dehydration on the lactate threshold in women. *Med Sci Sports Exerc* 2000;32:396
21. Nielson B, Sjogaard G, Bonde-Petersen F. Cardiovascular, hormonal, and body fluid changes during prolonged exercise. *Eur J Appl Physiol* 1984;53:63
22. Nose H, Takamata A, Mack GW, et al. Water and electrolyte balance in the vascular space during graded exercise in humans. *J Appl Physiol* 1991;70:1757
23. Ray ML, Bryan MW, Ruden TM, Baier SM, Sharp RL, King DS. Effect of sodium in a rehydration beverage when consumed as a fluid or meal. *J Appl Physiol* 1998;85:1329
24. Sagawa S, Miki K, Tajima F, et al. Effect of dehydration on thirst and drinking during immersion in men. *J Appl Physiol* 1992;72:128
25. Sanders B, Noakes TD, Dennis SC. Sodium replacement and fluid shifts during prolonged exercise in humans. *Eur J Appl Physiol* 2001;84:419
26. Sanders B, Noakes TD, Dennis SC. Water and electrolyte shifts with partial fluid replacement during exercise. *Eur J Appl Physiol* 1999;80:318
27. Sawka MN, Hubbard RW, Francesconi RP, Horstman DH. Effects of acute plasma volume expansion on altering exercise-heat performance. *Eur J Appl Physiol* 51:303
28. Sawka MN, Francesconi RF, Young AJ, Pandolf KB. Influence of hydration level and body fluids on exercise performance in the heat. *JAMA* 1984;252:1165
29. Sproule J. The influence of either no fluid or carbohydrate-electrolyte fluid ingestion and the environment (thermoneutral versus hot and humid) on running economy after prolonged, high-intensity exercise. *Eur J Appl Physiol* 1998;77:536
30. Stachenfeld NS, Gleim GW, Zabetakis PM, Nicholas JA. Fluid balance and renal response following dehydrating exercise in well-trained men and women. *Eur J Appl Physiol* 1996;72:468-477
31. Verburg E, Hallén J, Sejersted OM, Vollestad NK. Loss of potassium from muscle during moderate exercise in humans: a result if insufficient activation of the Na^+-K^+ pump? *Acta Physiol Scand* 1999;165:357
32. Zorbas RG, Ichinose MN, Sakagami MB. Fluid electrolyte changes in physically healthy subjects during prolonged restriction of motor activity and daily hyperhydration. *Mater Med Pol* 1993;25:97
33. Mallié JP, Ait-Djafer Z, Saunders C, et al. Renal handling of salt and water in humans during exercise with or without hydration. *Eur J Appl Physiol* 2002;86:196
34. Malhorta MS, Sridharan K, Venkataswamy Y, et al. Effect of restricted potassium intake on its excretion and on physiological response during heat stress. *Eur J Appl Physiol* 1981;47:169
35. Dann EJ, Gillis S, Burstein R. Effect of fluid intake on renal function during exercise in the cold. *Eur J Appl Physiol* 1990;61:133
36. Twerenbold R, Knechtle B, Kakebeeke TH, et al. Effects of different sodium concentrations in replacement fluids during prolonged exercise in women. *Br J Sports Med* 2003;37:300
37. Vrijens DMJ, Rehrer NJ. Sodium-free fluid ingestion decreases plasma sodium during exercise in the heat. *J Appl Physiol* 1999;86:1847
38. Van Nieuwenhoven MA, Brummer RJM, Brouns F. Gastrointestinal function during exercise: comparison of water, sports drinks, and sports drink with caffeine. *J Appl Physiol* 2000;89:1079
39. Shirreffs SM, Maughan RJ. Volume repletion after exercise-induced volume depletion in humans: replacement of water and sodium losses. *Am J Appl Physiol* 1998;274(5 pt 2):F868
40. Polak AA, van Linge B, Rutten FLPA, Stijne T. Effect of intravenous fluid administration on recovery after running a marathon. *Br J Sport Med* 1993;27:205
41. Nielsen B, Sjogaard G, Ugelvig J, Knudsen B, Cohlmann B. Fluid balance in exercise dehydration and rehydration with different glucose-electrolyte drinks. *Eur J Appl Physiol* 1986;55:318
42. Maughan RJ, Leiper JB, Shirreffs SM. Restoration of fluid balance after exercise-induced dehydration: effects of food and fluid intake. *Eur J Appl Physiol* 1996;73:317
43. Melin B, Koulmann N, Jimenez C, et al. Comparison of passive heat or exercise-induced dehydration on renal water and electrolyte excretion: the hormonal involvement. *Eur J Appl Physiol* 2001;85:250
44. Bellow PR, Mora-Rodríguez R, González-Alonso J, Coyle EF. Fluid and carbohydrate ingestion independently improve performance during 1 h of intense exercise. *Med Sci Sports Exerc* 1995;27:200
45. 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* 1997;76:320
46. Bilzon JIJ, Murphy JL, Allsopp AJ, Wootton SA, Williams C. Influence of glucose ingestion by humans during recovery from exercise on substrate utilization during subsequent exercise in a warm environment. *Eur J Appl Physiol* 2002;87:318
47. Chrysanthopoulos C, Williams C, Wilson W, Asher L, Hearne L. Comparison between carbohydrate feedings before and during exercise on running performance during a 30-km treadmill time trial. *Int J Sports Nutr* 1994;4:374
48. Chrysanthopoulos C, Hennessy LCM, Williams C. The influence of pre-exercise glucose ingestion on endurance running capacity. *Br J Sports Med* 1994;28:105
49. Cunningham JJ. Is potassium needed in sports drinks for fluid replacement during exercise? *Int J Sports Nutr Metab* 1997;7:154
50. Davis JM, Burgess WA, Slentz CA, Bartoli WP, Pate RR. Effects of ingestion 6% and 12% glucose/electrolyte beverages during prolonged intermittent cycling in the heat. *Eur J Appl Physiol* 1988;57:563
51. Fallowfield JL, Williams C, Singh R. The influence of ingesting a carbohydrate-electrolyte beverage during 4 hours of recovery on subsequent endurance capacity. *Int J Sports Nutr* 1995;5:285
52. Fallowfield JL, Williams C. Carbohydrate intake and recovery from prolonged exercise. *Int J Sports Nutr Metab* 1993;3:150
53. Febbraio MA, Murton P, Selig SE, et al. Effect of CHO ingestion on exercise metabolism and performance in different ambient temperatures. *Med Sci Sports Exerc* 1996;28:1380
54. Galloway SDR, Wootton SA, Murphy JL, Maughan RJ. Exogenous carbohydrate oxidation from drinks ingested during prolonged exercise in a cold environment in humans. *J Appl Physiol* 2001;91:654
55. Glace BW, Murphy CA, McHugh MP. Food intake and electrolyte status or ultramarathoners competing in extreme heat. *J Am Coll Nutr* 2002;21:553
56. Glace BW, Murphy CA, McHugh MP. Food intake and electrolyte status of ultramarathoners competing in extreme heat. *J Am Coll Nutr* 2002;21:553
57. Horswill CA. Effective fluid replacement. *Int J Sports Nutr* 1998;8:175
58. Koulman N, Melin B, Jimenez C, Charpenet A, Savourey G, Bittel J. Effects of different carbohydrate-electrolyte beverages on the appearance of ingested deuterium in body fluids during moderate exercise by humans in the heat. *Eur J Appl Physiol* 1997;75:525
59. Murray R. Fluid needs ion hot and cold environments. *Int J Sports Nutr* 1995;5(suppl):S62
60. Murray R, Seifert JG, Eddy DE, Paul GL, Halaby GA. Carbohydrate feeding and exercise: effect of beverage carbohydrate content. *Eur J Appl Physiol* 1989;59:152
61. Nassis GP, Williams C, Chisnall P. Effect of a carbohydrate-electrolyte drink on endurance capacity during prolonged intermittent high intensity running. *Br J Sports Med* 1998;32:248
62. Oliver SK, Tremblay MS. Effects of a sport nutrition bar on endurance running performance. *J Strength Cond Res* 2002;16:152
63. Ormerod JK, Elliott TA, Scheett TP, vanHeest JL, Armstrong LE, Maresh CM. Drinking behavior and perception of thirst in untrained women during 6 weeks of heat acclimation and outdoor training. *Int J Sport Nutr Metab* 2003;13:15
64. Tsintzas OK, Williams C, Wilson W, Burrin J. Influence of the carbohydrate supplementation early in exercise on endurance running capacity. *Med Sci Sports Exerc* 1996;28:1373
65. Tsintzas OK, Williams C, Singh R, Wilson W, Burrin J. Influence of carbohydrate-electrolyte drinks on marathon running performance. *Eur J Appl Physiol* 1995;70:154
66. Wong SH, Williams C, Adams N. Effects of ingesting a large volume of carbohydrate-electrolyte solution on rehydration during recovery and subsequent exercise capacity. *Int J Sport Nutr Metab* 2000;10:375
67. Yaspelkis BB, Ivy JL. Effect of carbohydrate supplements and water on exercise metabolism in the heat. *J Appl Physiol* 1991;71:680
68. Shi X, Bartoli W, Horn M, Murray R. Gastric emptying of cold beverages in humans: effect of transportable carbohydrates. *Int J Sport Nutr Metab* 2000;10:394
69. Passe DH, Horn M, Murray R. Impact of beverage acceptability on fluid intake during exercise. *Appetite* 2000;35:219
70. 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 Sports Nutr Metab* 2002;12:81
71. Noakes T. Fluid replacement during marathon running. *Clin J Sport Med* 2003;13:309
72. Noakes T. Hyponatremia in distance runners: fluid and sodium balance during exercise. *Curr Sports Med Rep* 2002;1:197
73. Noakes TD. Dehydration during exercise: what are the real dangers? *Clin J Sport Med* 1995;5:123
74. Frizzell RT, Lang GH, Lowance DC, Lathan R. Hyponatremia and ultramarathon running. *JAMA* 1986;225:772