ABSTRACT

The objective of this article is to provide a review of the fundamental aspects of body fluid balance and the physiological consequences of water imbalances, as well as discuss considerations for the optimal composition of a fluid replacement beverage across a broad range of applications. Early pioneering research involving fluid replacement in persons suffering from diarrheal disease and in military, occupational, and athlete populations incurring exercise- and/or heat-induced sweat losses has provided much of the insight regarding basic principles on beverage palatability, voluntary fluid intake, fluid absorption, and fluid retention. We review this work and also discuss more recent advances in the understanding of fluid replacement as it applies to various populations (military, athletes, occupational, men, women, children, and older adults) and situations (pathophysiological factors, spaceflight, bed rest, long plane flights, heat stress, altitude/cold exposure, and recreational exercise). We discuss how beverage carbohydrate and electrolytes impact fluid replacement. We also discuss nutrients and compounds that are often included in fluid-replacement beverages to augment physiological functions unrelated to hydration, such as the provision of energy. The optimal composition of a fluid-replacement beverage depends upon the source of the fluid loss, whether from sweat, urine, respiration, or diarrhea/vomiting. It is also apparent that the optimal fluid-replacement beverage is one that is customized according to specific physiological needs, environmental conditions, desired benefits, and individual characteristics and taste preferences. © 2014 American Physiological Society. Compr Physiol 4:575-620, 2014.

Introduction

Body water is a large constituent of the human body and is important for optimal physiological function and health. In general, humans drink adequately to maintain body water balance, that is, fluid replacement to offset losses, under normal resting, nonstressful conditions. However, situations often arise in which perturbations in fluid balance occur as a result of large fluid losses from the body. For example, heat exposure in an occupational setting or exercise for competitive sport or recreation can induce significant increases in thermal sweat loss. Other conditions, such as cold and/or altitude exposure may increase body water loss through respiration and/or urination. Upon exposure to microgravity, either due to spaceflight or bed rest, plasma volume is significantly contracted. In addition, individuals suffering from diarrheal disease can become severely dehydrated from fecal water loss. Fluid replacement in all of these cases is important to prevent or at least minimize the detrimental effects of body water deficits and the only way to replace fluid loss is by drinking. One form of fluid replacement is plain drinking water. However, oftentimes the optimal fluid replacement beverage includes carbohydrate, electrolytes, and/or other ingredients to improve palatability, stimulate thirst, speed intestinal fluid absorption, and promote fluid retention. Optimal composition may depend upon the source of the fluid loss, whether from sweat, urine, respiration, or diarrhea/vomiting with additional consideration for the population and environmental conditions. While the main objective of a fluid replacement beverage is to replace water losses, the beverage may also serve as a vehicle for the provision of nutrients or compounds to augment physiological function.

The purpose of this article is to review the basic scientific principles of fluid replacement and provide insight regarding the optimal composition of a fluid replacement beverage across a broad range of applications. Specifically, this article reviews: (i) the early pioneering research involving fluid replacement in humans; (ii) the basic physiology of body fluid balance, including its composition, distribution, homeostatic regulation, and physiological effects of a deficit; (iii) sources and rates of water loss from the body, both at rest and as a result various physiological and environmental stressors; (iv) the physiological processes involved in fluid replacement, including thirst and voluntary fluid intake, intestinal fluid absorption, and fluid retention; (v) common ingredients of a fluid replacement beverage and their potential benefits; and...
(vi) beverage composition considerations for specific applications and populations.

**Historical Roots of Fluid-Replacement Beverages**

**Pioneering work for military needs**

Some of the earliest reports of the effect of hydration on work capacity are from military combats. Military personnel are often exposed to extreme environmental conditions, such as hot and dry desert conditions or hot and humid tropical and subtropical regions (3). In these hot weather operations the battles could be decided by the availability of water to combat troops. Several authors have commented on the impact of heat illness on military campaigns and how wars have been won or lost by blocking access to water supplies (230). Although exact numbers were difficult to track, hypohydration-induced heat stroke was believed (according to intelligence reports) to account for a very high number of deaths in several wars, including 11 per 10,000 troops per week in the desert area of the Persian Gulf Command in the Middle Eastern Theater in 1943 (510), 378 per 10,000 troops in the month of May during the Vietnam war (482), and 20,000 Egyptian soldier deaths during the 1967 Six-Day War with Israel (230). These causality numbers are striking and perhaps preventable. There are also likely incidences of heat illness not severe enough to cause death, but influence combat effectiveness and impact on the success of a military campaign (230, 323). While several factors are involved in the etiology of heat illness, including environmental conditions and level of physical activity (which are difficult to control since these factors are dictated by the tactical situation), fluid replacement is also an important factor in body temperature regulation, and risk for heat illness (3).

The 1940s marked a time when the military devoted a significant amount of time and energy to better understand the fluid replacement needs of soldiers operating in desert environments as well as how to assist soldiers when trapped with limited water. In 1944, Pitts et al. (375) were the first to experimentally compare the progressive changes in physiological function when men marched on a treadmill in the heat with fluid replacement to match sweat loss, *ad libitum* fluid replacement, or no fluid replacement (see Fig. 1). The main findings from their work were that subjects only voluntarily drank about two-thirds of sweat loss, drinking *ad libitum* resulted in lower heart rates and rectal temperatures compared to drinking nothing, and drinking water, a 0.2% saline, or ∼3% glucose solution in a volume to match sweat losses resulted in even lower rectal temperatures and heart rates than *ad libitum* drinking. The main conclusion by the authors was that the best performance is achieved by replacing water loss in a volume to match sweat (375).

A few years later Adolph and associates (3) published a comprehensive report on man’s physiological responses to marching in the desert. With U.S. warfare beginning in the African deserts in 1941, the need for scientific investigation arose. The work of Adolph and associates began in 1942 to address the following basic questions from military leaders: what are man’s water needs in the desert and what happens if they are not met (2)? Adolph and associates’ 1947 report was the first to address these questions. Many important insights were gained as a result of this pioneering work conducted.

![Figure 1](Image)

**Figure 1** Effect of no water vs. *ad libitum* water intake vs. water intake to match sweat losses on rectal temperature during marching in the heat (37.8 °C, 35%-45% relative humidity) in 1 male subject. Reprinted (with permission) from Pitts et al. (375).
at the Armored Medical Research Laboratory in the desert area of Freda, California and the Desert Laboratory Unit at the University of Rochester. Here, they confirmed the findings of incomplete water replacement when drinking ad libitum [termed “voluntary hypohydration” by Rothstein et al. (400)], that hypohydration results in early onset of fatigue, and that fluid replacement improved thermal and cardiovascular function and delayed the onset of fatigue during prolonged marching in the desert (62, 399). In addition, in 1947, it was found that drinking a sodium-containing fluid improved ad libitum fluid intake and reduced renal water excretion (400). Fluid intake was also improved by cooling and flavoring the water. They also characterized the physiological and psychological effects of a water shortage, mostly due to inadequate circulation, with exhaustion from hypohydration occurring at 5-6% body weight deficit (62, 399). Their work also helped dispel the widespread belief among the military that man could be trained to require less fluid intake during heat exposure (3).

**Occupational settings**

Observations on fluid loss and replacement in occupational settings also contributed significantly to the early development of the field. Extensive literature (primarily from the 1920s and 1930s) described the sweating rates, sweat composition, and dietary intake of workers, as well as the physiological consequences of labor, in extreme environmental conditions. Of greatest importance was the observation that profuse sweating (>1 L/h, but as high as ≥2.5 L/h) by the workers in extreme heat resulted in loss of water and sodium chloride which was associated with mild to severe, debilitating muscle cramps (“heat cramps”) (332, 479, 480). One of the earliest reports of heat cramps in the occupational setting was in 1878, from the gold mines in Virginia City, Nevada, where miners worked in environmental temperatures as high as 48 to 54°C (276). Many other reports of heat cramping among miners, stokers, iron or steel workers, and agricultural workers followed (102, 136, 151, 332, 370, 480). Importantly, included in many of these reports was the observation that the ingestion or intravenous administration of sodium chloride solution was a highly successful therapeutic agent in resolving heat cramps (151, 479, 480). Moreover, the importance of daily sodium chloride intake to replace that lost in sweat was well-recognized; as workers were often provided with salted drinking water, saline, fresh cow’s milk, barley water, or salted beer or encouraged to liberally salt their food (313, 479, 480).

**Survival from diarrheal illness**

Another important step in the understanding of the optimal formulation of a fluid replacement beverage came with research in 1950s and 1960s showing that the cotransport of glucose and sodium accelerated water absorption in the small intestine (277). This was groundbreaking in the fight against diarrheal-induced hypohydration (from cholera) in developing countries. Survivability from diarrheal disease was likely if intravenous fluids were given promptly. However, Darrow (126) suggested that an orally administered electrolyte solution with glucose could be given to treat patients when intravenous fluids were unavailable. This solution proved very practical and effective and is considered an important medical advancement in the treatment of illnesses involving diarrhea and vomiting (277, 278). The mechanism (sodium transport and glucose transport are coupled so glucose accelerates the absorption of solute and water) was later discovered by investigations in the 1950s and 1960s. This was first observed in the guinea pig small intestine in 1958 (390) and in humans in the early 1960s (277, 423). The first detailed description of the mechanism was proposed as the sodium-glucose cotransport process by Bob Crane in 1960 at the Symposium on Membrane Transport and Metabolism in Prague (120). This discovery led to a standardized oral replacement solution by the World Health Organization; but can also be applied to formulation of all fluid replacement beverages as intestinal fluid absorption is a key process involved in rehydration (discussed in more detail later).

**Sports performance**

Another application for fluidreplacement beverages is for athletes participating in prolonged heavy exercise that induces sweat loss. This work was pioneered by a series of studies by Cade et al. in the early 1970s (74, 75). In 1971, they reported the effects of exercise in a hot/humid environment on body fluid changes in ten players of the University of Florida football team during a vigorous 2 h practice session with no fluid intake (74). They found that body weight, extracellular fluid volume, and plasma volume decreased by an average of 2.9%, 11%, and 7% respectively. This work was followed by a study in 1972 (75) to determine whether the fluid deficits affected performance and whether fluid replacement could prevent the disturbances in physiology and performance. Cade et al. (75) found that performance during a standardized walk-run test (7 mile course) at an ambient temperature of 32 to 34°C was best when ~1.0 L of a glucose (3%)electrolyte (17 mmol/L sodium, 3.5 mmol/L K, and 12 mmol/L chloride) solution was consumed, intermediate when the athletes drank 0.1% saline (1 L), and poorest when they drank nothing. Cade et al. (75) concluded that the effects of water and carbohydrate were striking. This early work of Cade et al. eventually led to the invention of sports drinks. Since the publication of these seminal studies in football players considerable insight has been gleaned from research testing the effect of beverage formulation on the delivery of fluid, electrolytes, and carbohydrate energy to the body during exercise. In the discussion that follows, water, sodium, and carbohydrate will be the primary topics covered, but we also discuss other beverage composition factors that have been hypothesized to impact physiological function or physical/cognitive performance.
Physiological Review of Fluid Replacement

Body water

Water functions as a solvent for organic and inorganic materials and provides a medium for biochemical reactions and for transportation of solutes throughout the body among various tissues, supplying nutrients and removing waste. Water accounts for approximately 60% of total body mass in the average adult, but ranges from 45% to 75% depending on body composition, age, and sex (13). The variation due to body composition is because fat-free mass has a much higher water content (~70%-80%) than adipose tissue (~10%) (496). Total body water can be divided into two compartments—the intracellular water and the extracellular water. The intracellular compartment accounts for approximately 55% to 65% of total body water, while the extracellular compartment accounts for the remaining 35% to 45% (239, 299). The extracellular space can be further divided into the interstitial and intravascular fluid (~7.5% of total body water) compartments (147, 299). Because water is a major component of vascular volume, [blood volume is about 55%-65% water (plasma) and 35%-45% red blood cells] hydration also plays a critical role in cardiovascular function and body temperature regulation. Figure 2 illustrates the body fluid distribution in a 70 kg human.

Sodium and its conjugate anions (chloride and bicarbonate) comprise the most osmotically active components of the extracellular fluid. Consequently, sodium balance plays a key role in governing the size of the extracellular fluid compartment and passive water movement according to osmotic gradients between the intracellular and extracellular water spaces (299). The most abundant cations in the intracellular water are potassium and magnesium, while the primary anions are proteins. The imbalance of sodium and potassium across the fluid compartments is maintained by the Na-K pump. Maintenance of this distribution of electrolytes between the intracellular and extracellular fluid is critical for cell function and electrical communication throughout the body.

Daily fluid requirements

Daily fluid requirements are determined by total body water loss, with the goal of intake approximating daily water losses. The United States Department of Agriculture’s Adequate Intake for total water, based on the median total water intake from the U.S. National Health and Nutrition Examination Survey data, is 3.7 and 2.7 L/d for young adult (19–30 years) men and women, respectively (239). The European Food Safety Authority defines Adequate Intake for total water as 2.5 L/d for men and 2.0 L/d for women (154). Daily fluid requirements are higher in individuals who are extremely active, exposed to environmental stress from heat or altitude, or losing fluid through vomiting or diarrhea.

When there is a mismatch between fluid intake and fluid loss this imbalance leads to a body water deficit or surplus. Throughout this paper, the term “euhydration” refers to maintenance of “normal” baseline body water content, while the terms “hypohydration” and “hyperhydration” refer to body water deficits and excesses beyond euhydration, respectively. The term “dehydration” is defined as the process of the dynamic loss of body water or the transition from euhydration to hypohydration.

To assess an individual’s acute change in hydration status their body mass can be compared to baseline or control values. For example, 3% hypohydration is defined as a water deficit equal to 3% of body mass. Acute body mass change (e.g., from before to after exercise) represents approximately 1 mL of water loss per 1 g of body mass loss. This method of hydration assessment provides the simplest index in real time (21) and is referred to frequently throughout this paper. However, it is important to note that a small portion of body mass loss during activity occurs due to substrate oxidation, that is, nonwater mass. Therefore, estimations in water loss based on change in body mass should be corrected for this nonwater mass loss during exercise lasting several hours (e.g., > 3 h) (414). The reader is referred to papers that discuss the topic of hydration assessment in greater detail (21, 311, 414). Euhydration cutoff values for various biomarkers of hydration status are provided in Table 1.

Sources and Composition of Fluid Loss

Body water loss can be categorized as insensible or sensible. Insensible water loss is evaporative water loss through respiration and water diffusion through the skin. Under normal conditions, respiratory water loss is approximately 250 to 350 mL/d (229) but can be higher in dry climates and when respiration rate is increased, such as during exercise or at altitude. Loss of water via diffusion through the skin is approximately 450 mL/d (275). All other water loss, including urination and thermoregulatory sweating is termed sensible.

### Figure 2

Body fluid compartments that comprise 42 L of total body water in a 70 kg human, and sources of fluid gain or loss. Reprinted (with permission) from Armstrong (21).
Table 1  Biomarkers of Hydration Status

<table>
<thead>
<tr>
<th>Practicality</th>
<th>Validity</th>
<th>Euthydration cut-off</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total body water</td>
<td>Low</td>
<td>Acute and chronic</td>
</tr>
<tr>
<td>Plasma osmolality</td>
<td>Medium</td>
<td>Acute and chronic</td>
</tr>
<tr>
<td>Urine specific gravity</td>
<td>High</td>
<td>Chronic</td>
</tr>
<tr>
<td>Urine osmolality</td>
<td>High</td>
<td>Chronic</td>
</tr>
<tr>
<td>Body weight</td>
<td>High</td>
<td>Acute and chronic*</td>
</tr>
</tbody>
</table>

*Potentially confounded by changes in body composition during very prolonged assessment periods. Reprinted (with permission) from Sawka et al. (414).

because the person is aware of the loss as it is occurring. Urine production is the main avenue of body water loss under normal circumstances. Renal fluid output can vary considerably, as it is primarily a function of water intake. Obligatory urine loss (needed to excrete end products, such as creatinine and urea; and needed to excrete electrolytes to maintain electrolyte balance) is approximately 500 mL/d (5). However, urine output generally averages 1 to 2 L/d. Other factors that affect urine output include exercise, heat stress (decrease loss), cold, and altitude exposure (increase loss). Gastrointestinal (fecal) water loss in a healthy adult is small, approximately 100 to 200 mL/d (345). Table 2 lists estimated minimum daily water losses through respiration, urination, the gastrointestinal tract, and the skin.

During exercise and/or exposure to a hot environment thermoregulatory sweat is the main source of water loss from the body. Evaporation of sweat secreted onto the skin surface by eccrine sweat glands is the primary avenue of heat loss during exercise and/or heat stress. Radiation (heat exchange between the body and the environment in the form of infrared rays), conduction (transfer of heat to or from the body through direct contact with an object), and convection (heat exchange between the body and surrounding moving air (wind) or body fluids (blood)) are other potential avenues of heat loss. However, when ambient temperature is greater than skin temperature, evaporation of sweat is the only means of body heat loss; which is important to attenuate the increase in body core temperature. With sweating, heat is transferred from the body to water (sweat) on the surface of the skin. When this water gains sufficient heat, it is converted to a gas (water vapor), thereby removing heat from the body. Evaporation of 1 kg of sweat from the skin will remove 580 kcal of heat from the body (508). It is important to note that sweat dripping from the body is wasted water loss because sweat must evaporate to allow effective cooling.

Metabolic heat production is directly proportional to exercise intensity. When exercise is performed, a large amount of heat is produced by the contracting muscles. In fact, less than 25% of all the energy produced by contracting muscles is used to perform work, with the remaining 75% converted to heat in the muscles. Thus sweating rates increase in proportion to work intensity. However, heat acclimatization, higher fitness levels, clothing, and higher ambient temperatures also increase an individual’s sweating rate. By contrast, wet skin (from high humidity) can reduce sweating rate (189, 418, 419). Figure 3 illustrates predicted daily water

Table 2  Estimation of Minimum Daily Water Losses and Production*

<table>
<thead>
<tr>
<th>Reference</th>
<th>Source</th>
<th>Loss (mL/d)</th>
<th>Production (mL/d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hoyt and Honig (229)</td>
<td>Respiratory loss</td>
<td>250 to 350</td>
<td></td>
</tr>
<tr>
<td>Adolph (5)</td>
<td>Urinary loss</td>
<td>500 to 1000</td>
<td></td>
</tr>
<tr>
<td>Newburgh et al. (345)</td>
<td>Fecal loss</td>
<td>100 to 200</td>
<td></td>
</tr>
<tr>
<td>Kuno (275)</td>
<td>Insensible loss</td>
<td>450 to 1900</td>
<td></td>
</tr>
<tr>
<td>Hoyt and Honig (229)</td>
<td>Metabolic production</td>
<td>250 to 350</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>1300 to 3450</td>
<td>250 to 350</td>
</tr>
<tr>
<td></td>
<td>Net loss</td>
<td>1050 to 3100</td>
<td></td>
</tr>
</tbody>
</table>

*Assuming conditions in which there is minimal water loss from sweating. Reprinted (with permission) from Institute of Medicine (239).
required as a function of daily energy expenditure and air temperature.

Because sweating plays a critical role in attenuating increases in body core temperature, it is apparent that sufficient hydration (via drinking) is needed to maintain sweating, especially in extreme heat (7). Early observations have shown that if water supply is adequate, healthy humans can withstand and even thrive in extremely hot environments (provided that evaporation of sweat is not impeded by high ambient humidity or by the wearing of impermeable clothing) (7, 233). For instance, in 1910, healthy European men, observed during a very hot (≥45°C) and dry spell of weather, consumed ≥13.6 L of water per day and were able to walk and perform a considerable amount of physical exercise without difficulty (233).

In general, women typically exhibit lower sweating rates than men, primarily due to smaller body mass and lower metabolic rate achieved during activity (414). However, when expressed relative to body surface area, mean sweating rates are similar between sexes in temperate and hot-dry conditions (429). In hot-wet conditions, however, sweating rate per m² surface area is lower in women than men (30, 429). The greater suppression of sweat in response to wetted skin results in less wasted sweat. By having a lower sweating rate in this condition women are losing less fluid and therefore minimizing hypohydration. On the other hand, men drip more sweat from their bodies (i.e., wasted water since it is not readily evaporated and does not contribute significantly to cooling) in humid conditions and become more dehydrated (30, 417, 429). However at the same level of hypohydration (5%), women exhibit similar physiological responses (e.g., increases in heart rate and body core temperature) to exercise-heat stress in both hot-dry and hot-wet conditions compared to men when matched for age, fitness, and percent body fat (417).

The loss of water due to thermoregulatory sweating is accompanied by loss of electrolytes. Sodium is the predominant electrolyte lost in sweat. The total amount of sodium lost depends on sweating rate and duration as well as sweat sodium concentration. Average sweat sodium concentration measured using the “gold standard” whole-body washdown procedure has been reported to be approximately 40 mmol/L, but ranges from as low as 15 mmol/L to as much as 90 mmol/L (35). Even those athletes with low or average sweat sodium concentration, can accrue a substantial sodium deficit by virtue of large sweat losses due to high sweating rates (≥2 L/h) or extended periods of strenuous exercise (two-a-day practices or ultraendurance events). The wide range is a result of the myriad of factors that influence sweat sodium concentration, including genetics, diet, heat acclimatization status, sweating rate, and hydration status (414). Sodium and chloride are reabsorbed in the duct of the sweat gland, thus sweat sodium concentration is lower than that of plasma. However, as sweating rate increases, the sodium secretion rate increases proportionally more than the rate of sodium reabsorption, thus sweat sodium concentration increases linearly with increases in sweating rate (68). Heat acclimatization improves sodium chloride reabsorption, thus resulting in lower sodium chloride concentration (>50% reduction) for any given sweating rate (10). Studies have found that moderate (~3.5-4 g/d) to high dietary sodium (~8-9 g/d) intake results in significantly higher sweat sodium concentration compared to that of low sodium diets (~1-2 g/d) (11, 23, 221). Increased sweat sodium chloride concentration can also result from hypohydration (330), but neither sex nor aging seem to have a significant effect (331). Figure 4 illustrates predicted daily sodium...
requirements as a function of daily energy expenditure and air temperature. In addition to sodium, several other electrolytes are lost in sweat. These include, but are not limited to, chloride (≈30 mmol/L), potassium (≈5 mmol/L), calcium (≈0.5 mmol/L), and magnesium (≈0.1 mmol/L) (152, 414).

There are primarily two different types of hypohydration, depending on the route of water loss and the amount of osmolytes (electrolytes) lost in association with the water. Isoosmotic hypohydration (isotonic hypovolemia) occurs when fluid loss is iso-osmotic with plasma, that is, loss of water and osmolytes occurs in equal proportions. This type of body water deficit is associated with fluid losses induced by cold, altitude, diuretics, and secretory diarrhea. For example, fluid (urine) losses induced by administration of a diuretic, such as furosemide, will cause the intravascular and interstitial fluid compartments to decrease proportionally. Thus the end result is a state of hypohydration with no change in plasma osmolality. On the other hand, hypohydration induced by sweat loss due to exercise and/or heat stress results in a decrease in the extracellular compartment size and an increase in plasma osmolality (1, 273). This is because sweat is hypotonic compared to the plasma. An increase in plasma osmolality initiates fluid movement from the cellular compartment into the plasma to maintain osmotic balance. This results in cellular hypohydration, that is, cell shrinkage and hypertonicity. This is known as hyperosmotic hypohydration and occurs when loss of water is greater than the loss of osmolytes. Hyperosmotic hypohydration can also occur as a result of osmotic diarrhea. The effect on blood osmolality has important implications to cardiovascular and thermoregulatory physiology because hyperosmolality increases the temperature threshold for sweating and cutaneous vasodilation during exercise in the heat (172, 339).

Sources of fluid replacement

Daily fluid requirements can be met from a combination of drinking water, water in beverages, and water that is in food. In the U.S. approximately 81% of the water is consumed in fluids (drinking water and beverages), while foods account for the remaining 19% of water intake. However, in other countries with higher intake of fruits and vegetables, such as Greece and South Korea, water intake from foods is higher (287, 329).

According to the 1994 to 1996 U.S. Continuing Survey of Food Intakes by Individuals (aged 20-64 years), drinking water is the main source of fluid water intake, with coffee, tea, carbonated drinks, juice, and milk being some of the other beverages contributing to fluid water intake in the U.S. (222). Table 3 shows the water content of various foods and beverages. Other sources of fluid water intake include sports drinks and oral rehydration solutions. These beverages, which have specific applications, are discussed in greater detail later in this article.

It is important to note that water gain also occurs through metabolic water production. Water is a byproduct of oxidative phosphorylation and its rate of formation is primarily dependent upon energy expenditure and to a lesser extent on the type of substrate oxidized. This has been estimated to be approximately 250 to 350 mL/d for sedentary persons and up to 500 to 600 mL/d for the physically active (229).

Regulation of fluid balance

Body water is regulated by various physiological mechanisms to minimize fluctuations in body water content and
artery and veins sense the decrease in central venous pressure located in the chambers of the heart and the pulmonary arterial pressure. Cardiopulmonary (or low pressure) baroreceptors increases sympathetic nervous activity to vasoconstrict compared to blood pressure. Both neural and humoral effectors can act as efferent arms of the baroreflexes. During hypohydration losses (urine flow rate and sweat losses), and fluid intake (thirst). The most rapid adjustments are initiated by neural reflexes that control vascular resistance (fluid distribution). If the perturbation to fluid balance is prolonged (>20 min), vascular volume/pressure and plasma osmolality are maintained by circulating hormones that modify renal salt and water excretion (299, 404).

Baroreceptors are the pressure sensing reflexes in the heart and vascular system that function to minimize perturbations to blood pressure. Both neural and humoral effectors can act as efferent arms of the baroreflexes. During hypohydration venous return is decreased due to a reduction in plasma volume. Thus, hypohydration results in a decrease in central blood volume or central venous pressure and left ventricular stroke volume. These vascular changes (decrease in transmural pressure) result in unloading of baroreceptors, which increases sympathetic nervous activity to vasoconstrict compliant beds to protect central venous pressure and mean arterial pressure. Cardiopulmonary (or low pressure) baroreceptors located in the chambers of the heart and the pulmonary artery and veins sense the decrease in central venous pressure with hypohydration and cause increased peripheral vascular resistance (especially in skin and muscle). Arterial (or high pressure) baroreceptors located in the carotid artery and arch of the aorta sense the reduction in arterial pressure (and/or aortic pulse pressure) with dehydration and elicit an increase in heart rate and vascular resistance of the splanchnic circulation (299, 404). The role of baroreflexes in maintaining blood volume is depicted in Figure 5.

The kidneys are crucial in regulating water balance. Changes in body fluids trigger humoral responses that act on the kidneys to modulate urinary water losses, with the goal of maintaining a tight range of plasma osmolality between ~280 and 295 mOsm/kg (159). The main role of the kidneys is to filter plasma to remove metabolic wastes from the body. This process begins with glomerular filtration, which is the movement of water and solute from the circulation into the renal tubule at the glomerular capillary. The functional unit of the kidney, the nephron, consists of an extensive system of tubules which interact with the systemic circulation (peritubular capillaries) to allow movement of water/solute between the circulatory and renal tubule compartments. In the nephron, water and solutes (such as sodium chloride) are reabsorbed back into circulation. Thus, the excretion of water via urination is the net effect of glomerular filtration versus renal tubular reabsorption.

Arginine vasopressin (or antidiuretic hormone) plays an important role in the maintenance of vascular volume and does so by increasing the renal reabsorption of water. Sweating-induced dehydration causes an increase in plasma osmolality, which leads to the movement of fluid from cells into the plasma to maintain osmotic balance. This results in cellular hypohydration or cell shrinkage. Shrinkage of osmoreceptors in the hypothalamus and heart stimulate the synthesis of vasopressin in the supraoptic and paraventricular nuclei of the hypothalamus. Vasopressin increases renal water reabsorption by binding to V2 receptors on the basolateral membrane of cells of the distal tubule and collecting duct of the kidneys, stimulating aquaporin transport of water across these cells (from lumen to blood/basolateral side). Hyperosmolality also stimulates thirst which would increase fluid intake and contribute to the maintenance of vascular volume (299, 404).

The renin-angiotensin-aldosterone system also plays an important role in the maintenance of vascular volume and exerts its effects primarily on the renal system to conserve sodium and water. Renin is released in response to increased sympathetic nervous system activity, decreased blood pressure, decreased blood sodium concentration, or decreased renal blood flow. In response to these stimuli the juxtaglomerular apparatus cells of the kidneys release the enzyme renin into the blood. Renin then converts circulating Angiotensinogen to Angiotensin I. When Angiotensin I travels through the pulmonary circulation Angiotensin Converting Enzyme cleaves Angiotensin I to form Angiotensin II. Angiotensin II can affect vascular volume by directly constricting smooth muscle of arterioles (especially the splanchnic and renal circulation). In addition, Angiotensin II stimulates aldosterone synthesis and release from the adrenal

<table>
<thead>
<tr>
<th>Percentage</th>
<th>Food item</th>
</tr>
</thead>
<tbody>
<tr>
<td>100%</td>
<td>Water</td>
</tr>
<tr>
<td>90%-99%</td>
<td>Fat-free milk, cantaloupe, strawberries, watermelon, lettuce, cabbage, celery, spinach, pickles, squash (cooked)</td>
</tr>
<tr>
<td>80%-89%</td>
<td>Fruit juice, yogurt, apples, grapes, oranges, carrots, broccoli (cooked), pears, pineapple</td>
</tr>
<tr>
<td>70%-79%</td>
<td>Bananas, avocados, cottage cheese, ricotta cheese, potato (baked), corn (cooked), shrimp</td>
</tr>
<tr>
<td>60%-69%</td>
<td>Pasta, legumes, salmon, ice cream, chicken breast</td>
</tr>
<tr>
<td>50%-59%</td>
<td>Ground beef, hot dogs, feta cheese, tenderloin steak (cooked)</td>
</tr>
<tr>
<td>40%-49%</td>
<td>Pizza</td>
</tr>
<tr>
<td>30%-39%</td>
<td>Cheddar cheese, bagels, bread</td>
</tr>
<tr>
<td>20%-29%</td>
<td>Pepperoni sausage, cake, biscuits</td>
</tr>
<tr>
<td>10%-19%</td>
<td>Butter, margarine, raisins</td>
</tr>
<tr>
<td>1%-9%</td>
<td>Walnuts, peanuts (dry roasted), chocolate chip cookies, crackers, cereals, pretzels, taco shells, peanut butter</td>
</tr>
<tr>
<td>0%</td>
<td>Oils, sugars</td>
</tr>
</tbody>
</table>

Table 3  The Water Content Range for Selected Foods

Reprinted (with permission) from Popkin et al. (377).
cortex, which in turn stimulates renal sodium chloride reabsorption. Angiotensin II also regulates body water by acting on the central nervous system to stimulate thirst and water and sodium ingestion (299, 404).

Some hormone-mediated differences in the renal handling of water and electrolytes exist between sexes and within women across different phases of the menstrual cycle. For example, in response to a water load, women have a higher rate of water turnover, particularly during the luteal phase of the menstrual cycle (101). Estrogens and progesterone increase renal water and electrolyte retention (463, 465, 466). Furthermore, body core temperature is elevated by up to 0.6°C during the luteal phase. Despite these hormonal effects, there is no evidence that phase of the menstrual cycle significantly impacts exercise performance, perceived exertion, or risk for heat illness during exercise (301) or renal water and electrolyte retention with fluid replacement after exercise (308).

More detailed summaries of body water and electrolytes, including factors governing water volume, distribution (147, 299), and movement between compartments (468, 469) can be found in other reviews.

**Physiology of fluid replacement**

Replacement of fluid losses is a process involving several steps that starts with ingestion and culminates in fluid being absorbed into the blood stream and distributed to the intra- and extracellular fluid spaces of the body. In this section we review these processes and discuss the physiological, and in some cases psychological, factors involved in fluid replacement.

**Thirst and voluntary fluid intake**

The first step in fluid replacement is the act of drinking water or other fluids. As discussed previously, the renal system effects fluid balance by limiting water loss through urination; however, this system has no ability to restore lost water. Therefore, the replacement of a fluid following a deficit is ultimately dependent upon fluid intake. As simple as this sounds thirst and fluid intake are actually very complex and
dictated by multiple mechanisms (6). The consumption of fluids occurs in response to physiological, psychological, and environmental stimuli.

Physiological (or regulatory) thirst is stimulated independently by cellular and extracellular hypohydration. Increases in cellular tonicity (cellular hypohydration) are sensed by osmoreceptors in the central nervous system, while decreases in extracellular fluid volume (extracellular hypohydration) are sensed by the cardiopulmonary (low pressure) baroreceptors. The sensory information from the osmoreceptors and baroreceptors regarding plasma tonicity and extracellular fluid volume, respectively, feed into higher brain regions to stimulate thirst. The areas of the brain involved in the consciousness of thirst include the anterior cingulate region and specific sites in the middle temporal gyrus and periaqueductal gray area (134).

The stimulation of thirst is delayed compared to other physiological indicators of hypohydration. For example, the threshold for the release of vasopressin and renal water conserving mechanisms occurs at a lower plasma osmolality than does thirst. The osmotic threshold for vasopressin secretion is approximately 286 mOsm/kg whereas the average threshold for thirst is 295 mOsm/kg (394). The stimulation of physiological thirst is also modified by aging and sex hormones (discussed elsewhere in this article).

Thirst and fluid intake are influenced by a complex interaction of numerous other factors. Afferent signals arising from the oropharyngeal region influence thirst. For instance, the sensation of a dry mouth drives thirst and initiates drinking. However, dry mouth is a perceived sensation of thirst rather than a physiological signal of hypohydration. Oropharyngeal factors can also provide signals to terminate drinking. The act of swallowing produces a sudden inhibition of osmotically stimulated thirst. Also, a process called oropharyngeal metering acts to limit the overall rate of fluid ingestion (163). Gastrointestinal factors such as gastric distension can also provide sensory input to terminate drinking.

Other nonregulatory factors include cultural/social factors/preferences, beverage availability or proximity, and organoleptic properties of beverage (temperature, flavor, sweetness, saltiness, texture, and aftertaste) (365, 395) and are discussed in more detail later. Figure 6 illustrates the multiple factors involved in thirst and voluntary fluid intake.

In general, humans drink adequately to offset losses on a day-to-day basis. Body hydration status may fluctuate throughout the day, but any fluid deficit is typically replaced with fluid intake during meals and ad libitum drinking between meals. Intakes of food and water are directly related (15) and food has a water-retaining effect (108). However, ad libitum drinking during and/or after periods of fluid loss (e.g., in workers or athletes losing sweat while physically active or exposed to heat stress) usually results in incomplete fluid replacement, a concept known as “voluntary hypohydration” (213, 400). For example, in 1947 men in the desert only replaced about 50% of losses when active, but when eating food and/or at rest, the men drank enough to restore body water balance (3). More recent studies have confirmed this phenomenon (306). When underdrinking occurs over a prolonged period of time (e.g., ~75 min of running in Ref. 364, but will vary depending on sweating rate) body weight deficits of ≥~2% during or after exercise and/or heat-stress have been reported (213, 364, 400). Thus, the optimal fluid

![Figure 6](image_url)  
**Figure 6** Diagram illustrating the multiple stimulating and attenuating factors involved in thirst and voluntary fluid intake.
replacement beverage would be one that is palatable enough so as not to impede drinking and perhaps even promote drinking when individuals would otherwise wish to avoid it (e.g., extreme, prolonged loss of appetite and desire to drink due to sickness, altitude, or cold stress).

Gastric emptying and intestinal absorption

The second major step in fluid replacement is the process of absorption into the bloodstream. This process involves both the emptying of fluid from the stomach and transport of water across the intestinal epithelium. Very little absorption of water and solutes takes place in the stomach, thus the ingested fluid must be emptied from the stomach and delivered to the lumen of the small intestine before it can enter the circulation. The gastric emptying rate of liquids is faster than that of solids and solutions with lower energy density empty faster than those of higher energy density (236). Gastric emptying of liquids is regulated by the interaction of gastric volume and feedback inhibition related to the nutrient content of the small intestine (234, 235, 333). Gastric emptying can be maintained at a high rate (15 to more than 20 mL/min) by maintaining a high gastric volume with ingestion of either water or a dilute carbohydrate solution.

Absorption of water and solutes occurs primarily in the proximal small intestine (duodenum and jejunum). The structure of the epithelium in the small intestine allows water and solute to pass into the bloodstream by both paracellular (via tight junctions between cells) and transcellular (across the epithelial cell membrane) processes. Absorption of solute from the intestinal lumen occurs by diffusion along electrochemical gradients and by specific transport mechanisms in the brush border membrane of intestinal epithelial cells. Water absorption follows solute absorption; that is, water uptake is a passive process, dependent on an osmotic gradient which is created by absorption of solutes (333, 436). Figure 7 illustrates the proposed mechanisms of water and solute absorption.

Several factors can impact the rate at which gastric emptying and fluid absorption occurs, including various types of stressors. For example, hypohydration ≥3% is associated with impaired gastric emptying (344, 381, 491) and exercise intensity > ∼70% to 75% slows gastric emptying and intestinal water absorption (112, 168). Beverage composition, particularly energy (carbohydrate) content and osmolality, also has a significant influence on the rate at which these processes occur. In general, the higher the energy density and osmolality of the ingested beverage the slower the rate of gastric emptying and intestinal fluid absorption, respectively (334, 436). When both energy provision and fluid replacement are important (e.g., exercise in a warm environment), the optimal beverage would be formulated to deliver nutrients to the body without impeding gastric emptying and intestinal absorption of water. However, when sweat losses are low (e.g., exercise in very cool weather) or high rates of carbohydrate delivery...
Table 4  The Relative Roles that Physiological Processes Play in Whole-Body Fluid Balance, during Different Life Scenarios

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Renal regulation of fluid-electrolyte balance</th>
<th>Thirst and drinking behavior</th>
<th>Sweat gland secretion of hypotonic fluid</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sedentary daily activities (16 h)</td>
<td>Normal</td>
<td>Normal</td>
<td>Negligible</td>
<td>Normal hormonal and CNS regulation</td>
</tr>
<tr>
<td>Brief, intense exercise (&lt;5 min)</td>
<td>Negligible</td>
<td>Negligible</td>
<td>Minor</td>
<td>Volume of fluid loss is small</td>
</tr>
<tr>
<td>Prolonged, strenuous exercise (5-30 min)</td>
<td>Minor</td>
<td>Minor to moderate</td>
<td>Minor to moderate</td>
<td>Volume of fluid loss is minor when compared to TBW</td>
</tr>
<tr>
<td>Prolonged endurance exercise (0.5-5 h) at moderate intensity</td>
<td>Minor to moderate</td>
<td>Minor to large</td>
<td>Moderate to large</td>
<td>Large water turnover due to sweating and drinking</td>
</tr>
<tr>
<td>Continuous or intermittent exercise, or labor at low intensity (5-24 h)</td>
<td>Minor to large</td>
<td>Minor to large</td>
<td>Large</td>
<td>Fluid and electrolyte losses may exceed daily dietary intake</td>
</tr>
<tr>
<td>Consecutive days of activities, labor, or exercise (1-180 d)</td>
<td>Normal</td>
<td>Normal</td>
<td>Varied, depending on labor and exercise</td>
<td>Adequate dietary fluid and electrolyte consumption is essential</td>
</tr>
</tbody>
</table>

Reprinted (with permission) from Armstrong (21).

is necessary (e.g., >2 h of exercise) more concentrated beverages may be acceptable. These topics are discussed in more detail later. Also, the reader is referred to other reviews that discuss the idea of potential trade-offs between carbohydrate and fluid ingestion during exercise (115, 119).

Fluid distribution and retention

Finally, once the ingested fluid enters the bloodstream, a sufficient volume of the fluid needs to be retained to rehydrate and offset losses incurred through sweating, respiration, and/or urination. Thus, the optimal fluid-replacement beverage would be formulated to facilitate renal water reabsorption (described in detail above) as opposed to stimulating diuresis. In addition, the beverage should promote retention of fluid in the compartment (intracellular or extracellular) that has incurred the fluid deficit. For example, in the case of significant hypovolemia, the aim would be to promote fluid retention in the vascular space. The relative roles that various physiological processes (renal regulation, thirst and drinking behavior, and sweat secretion) play in determining whole-body fluid balance during different life scenarios is described in Table 4.

Effect of a body fluid deficit on human physiological responses

Survival

High levels of hypohydration (~10% body mass deficit) alone do not significantly increase the risk of death. However, when severe hypohydration is combined with other stressors, such as illness or environmental/physical stress, body water deficits can contribute to death (4, 239, 505). Reports from humans in desert survival situations suggest that hypohydration exhaustion occurs at 5% to 10% body mass deficit, thus it has been suggested that ~10% hypohydration could be fatal unless medical assistance is available for recovery and rehydration (4). In the summer of 1877, soldiers of the U.S. Cavalry wandered into the arid “Staked Plains” near Fort Concho, Texas while scouting for Indians and found themselves without water supply for 3.5 days. In a brief account of the ordeal, King (270) described the sufferings from deprivation of water and reported that 4 of the men died by the time the troop managed to get back to the Supply Camp. The longest period of time that any person has been documented to survive without water is 18 days (516).

No experimental data on the effects of water restriction on mortality are available in humans, for obvious reasons. Survival studies with dogs and cats exposed to heat stress suggest that death from water restriction occurs with body mass loss of 10% to 20%, due to a rapid rise in body core temperature, with death consistently occurring at 41.6 to 43°C (4). From the work conducted by Adolph and associates in the desert, the authors speculated that body mass deficits of 15% to 25% would be fatal in humans (4). The environmental conditions influence the level of hypohydration that is fatal. As little as 15% hypohydration could be fatal at ambient temperatures above ~30°C, while more severe hypohydration would be required at cooler temperatures (4).

Cardiovascular and thermoregulatory systems

A reduction in body water is associated with impaired circulatory and thermoregulatory function. Hypohydration causes a
decrease in plasma volume and, therefore, a decrease in stroke volume and a compensatory increase in heart rate (by 3-5 bpm per 1% body mass deficit) (195, 325, 411) to maintain a given cardiac output. Hypohydration delays the onset (i.e., increases the body core temperature threshold) and decreases the sensitivity (i.e., slope of the relation between sweating rate or skin blood flow relative to the change in body core temperature) of the sweating and skin blood flow response to hyperthermia (169, 172, 269, 326). Both hypovolemia and hyperosmolality mediate these hypohydration-induced adjustments. For example, studies (169, 339) found that hypovolemia per se (via diuretic administration) increased the esophageal temperature threshold for cutaneous vascular conductance by $\sim 0.4^\circ C$ (slope of relation not affected) and reduced the slope of the relation between sweating rate and esophageal temperature (threshold not affected). Fortney et al. (172) then found that hyperosmolality per se elevated the esophageal temperature thresholds for both cutaneous vasodilation and sweating. Thus, hypohydration results in an increased core temperature during exercise and an increased risk for heat exhaustion (3, 315, 421) and heat stroke (79, 153, 196, 384). The magnitude of hyperthermia ranges from approximately 0.1 to 0.2$^\circ C$ per 1% body mass deficit (325, 420) and likely varies with ambient conditions and exercise intensity. The impact of various amounts of fluid intake on cardiovascular function, body core temperature, and rating of perceived exertion during exercise are illustrated in Figures 8, 9, and 10, respectively.

Heat acclimatization and endurance training increase the sweating and skin blood flow responses to exercise in the heat (509). These responses augment heat dissipation and therefore minimize the rise in body core temperature during exercise/heat stress. However, the improvements in thermoregulatory function conferred by heat acclimatization and aerobic training are negated by hypohydration (73, 417).

**Medical conditions**

Low habitual fluid intake has been reported, mostly in epidemiological studies, to be associated with a number of chronic medical conditions, including urinary tract infections, blood clots, asthma, urolithiasis (kidney stones), cholelithiasis (gallstones), constipation, cardiovascular disease, diabetic hyperglycemia, and some cancers (239, 300, 377). There is evidence that increased fluid intake reduces the risk of kidney stones, particularly in the prevention of recurrence in individuals that have already had stones (239). For example, Borghi et al. (56) tested the effects of increasing water intake in 199 individuals with idiopathic calcium nephrolithiasis. The treatment group increased fluid intake such that 24-h urine volume increased from $\sim 1$ to 2.6 L, whereas the control group did not change fluid intake (24-h urine volume remained at $\sim 1$ L). Upon follow-up 5 years later, recurrent stones had occurred in 27% of the control group, but only 12% of the treatment group. Similarly, increasing fluid intake has been shown to decrease recurrence of infections in women with a history of urinary tract infections (146, 374). Increasing fluid intake is

![Figure 8](image-url) Cardiac output, heart rate, stroke volume, and forearm blood flow during 120 min of cycling (62%-67% VO\(_{2}\)max) in the heat (33$^\circ C$, 50% rh) when no fluid or small (0.58 L), moderate (1.42 L), or large (2.38 L) volume of fluid was ingested, which induced 4.2%, 3.4%, 2.3%, and 1.1% hypohydration, respectively. Values are means ± SE for 8 different endurance-trained cyclists. *Significantly different from no fluid, P < 0.05. † Significantly different from small volume of fluid, P < 0.05. § Significantly different from moderate fluid volume of fluid, P < 0.05. Reprinted (with permission) from Montain and Coyle (325).
also commonly recommended for the treatment of constipation. However, the few research studies available on this topic suggest that increased fluid intake is only effective in dehydrated individuals and is not useful in mitigating constipation in euhydrated individuals (28). The relation between daily water intake and cancer (bladder and colon) has also been evaluated. Some case-control studies suggest a link between higher rates of fluid intake and decreased colon and bladder cancer risk (239, 320, 428); however, others have failed to demonstrate a significant association (239, 451).

Acute hypohydration may also be a precipitating factor in some acute medical conditions. For example, hypohydration is thought to be a risk factor for delirium in the elderly (284, 499). Poor hydration status has also been linked to an increased risk of infection, especially in elderly individuals (161). Increased mortality is commonly observed during heat waves. Although unusually hot weather is the primary culprit, failure to increase water intake would exacerbate the effects of heat strain (303). Another acute condition thought to benefit from provision of water is headache, including migraine. Water deprivation and hypohydration have been shown to increase self-reported headache (443) and trigger and prolong migraine (54, 55). In individuals with headaches caused by water deprivation, ingestion of water provided relief from headache within 30 min to 3 h (55). However, there is insufficient evidence to suggest that fluid intake is an effective prophylaxis against headache (457). Finally, one study (420) has reported that severe levels of hypohydration (5% to 7%) resulted in numerous premature ventricular contractions in healthy young adults exercising in the heat for over 2 h. It is important to recognize that only associations and not direct causal relations have been demonstrated between hydration status and most of these acute and chronic medical conditions.

It has been suggested that rhabdomyolysis, which is syndrome observed with novel strenuous exercise and manifested as release of skeletal muscle contents leading to acute renal insufficiency or failure, is exacerbated by hypohydration. Specifically, when rhabdomyolysis is accompanied by hypohydration, there is an increased likelihood or severity of acute renal failure (66, 422). Thus, the combination of novel training, heat stress, and fluid restriction is especially dangerous and potentially fatal (196).

### Physical performance

It is widely accepted that hypohydration negatively affects cardiovascular and thermoregulatory function, the combined effect of which can increase perceived effort and impair performance during activity which is greatly dependent upon these two systems, that is, prolonged aerobic exercise (239, 414, 444). Hypohydration >2% body mass can degrade aerobic exercise performance in temperate and warm/hot environments (81, 92, 239, 414). The greater the level of hypohydration and heat stress, the greater the degradation in aerobic exercise performance (239, 414). Hypohydration only marginally degrades aerobic exercise performance in cold environments.
enced with hypohydration is likely attributed to a decrease in cerebral blood flow velocity. When subjects moved from a seated to a standing position, cerebral blood flow velocity was significantly reduced by prior heat exposure and further reduced by 3% hypohydration compared to when subjects were euhydrated. The hemodynamic response to orthostatic stress has been found to improve with water ingestion (77, 298, 426). For instance, acute water intake of 500 mL blunted the increase in heart rate and decrease in stroke volume during head-up tilt with lower body negative pressure and improved orthostatic tolerance (time to syncope) in healthy young adults (426). Also, Ando et al. (16) found that 300 mL fluid ingestion can prevent vasovagal reaction in blood donors who are at a high risk of postdonation syncope. The beneficial effect of 300 to 500 mL water ingestion on orthostatic tolerance occurs without significant changes in blood volume (77). Instead, the mechanism of action responsible for these improved hemodynamic responses is likely due to the stimulatory effects of drinking on the sympathetic nervous system to increase peripheral resistance (426).

Adverse effects of overconsumption

When someone overdrinks (drinks more fluid than they have lost through sweating, urination, etc.) he or she can become hypervolemic (overall increased volume of plasma), and hypo-osmotic (dilution of plasma contents). Excessive consumption of fluids (especially sodium-free fluid, such as water) over a prolonged period of time can lead to the dilution of sodium concentration in the blood. This rare, but potentially dangerous condition is called hyponatremia. The plasma sodium concentration of those with symptoms of hyponatremia is typically less than 130 mmol/L. Normal resting plasma sodium concentration ranges from 135 to 145 mmol/L. The reduction in solute concentration in plasma promotes movement of water from the plasma into cells (327). Symptoms of mild to moderate hyponatremia may include headache, nausea, dizziness, and muscle weakness, while severe hyponatremia (typically plasma sodium concentration <125 mmol/L) is characterized by pulmonary edema, cardiorespiratory arrest, cerebral edema, seizures, and/or coma (31, 327). The rapidity, with which the serum sodium concentration declines, as well as the absolute change, impacts the severity of the symptoms. In a 70-kg man, approximately 5.1 L increase in total body water is required to decrease serum sodium concentration to 125 mmol/L from an initial concentration of 140 mmol/L (239).

Hyponatremia can occur in anyone partaking in overzealous fluid consumption, including accidental water intoxication or forced drinking in children (18, 264), in social situations (166), in athletes (127, 225, 350, 456) or military recruits (180, 355) during prolonged exercise, in occupational situations (332), or in psychiatric patients (particularly those with schizophrenia) who have psychogenic polydipsia (129, 239). Acute water intoxication usually occurs as a result of rapid consumption of large quantities of fluid that greatly exceed the kidney’s maximal excretion rate (∼1.0 L per h) (239). Factors

Brain and cognition

Hyponatremia can also have detrimental effects on cognitive performance (short-term memory, attention, and visual-motor tracking) and ratings of mental fatigue and mood, especially when the body water deficit is combined with environmental heat stress (96, 97, 198, 430). In general, hypohydration >2% of body mass loss, typically induced by exercise and/or heat stress, degrades cognitive function. However, milder levels of hypohydration have also been suggested to adversely affect some aspects of mood and cognitive performance (24, 179, 292). For example, Ganio et al. (179) found that 1.6% hypohydration degraded visual vigilance and visual working memory and increased ratings of fatigue and tension/anxiety in healthy young men. Furthermore, there is some evidence that cognitive performance is degraded in a dose-dependent manner with graded levels of hypohydration (198, 292). These effects have the potential to negatively impact the capacity to perform work involving mentally demanding or skilled tasks in everyday life as well as in occupational, military, and sports settings.

Another negative effect and potential safety hazard of hypohydration related to the brain is an increased risk of orthostatic intolerance (postural hypotension) in the heat. Upon standing, fluid displacement from the thorax to the lower extremities leads to a transient fall in mean arterial blood pressure, sometimes leading to syncope. In 1947, Adolph et al. reported that dehydrated subjects felt “dizzy” upon standing and “may faint if asked to stand still” (4, 62). Recently, Carter et al. (78) reported that the orthostatic intolerance experienced with hypohydration is likely attributed to a decrease
which decrease or impair renal water excretion can put someone at a higher risk for hyponatremia. Exercise and/or heat stress reduce urine volume. Also, nausea reduces urine output by stimulating vasopressin secretion. Hospitalized patients who develop hyponatremia often exhibit inappropriate secretion of vasopressin during fluid overload (184).

The development of hyponatremia during exercise is usually associated with excessive overconsumption of fluid (in excess of sweat losses) over a period of activity that is greater than 4 to 6 h, such as during endurance events (327). Exercise-associated hyponatremia has also been reported in American football and tennis players (138, 223) and in recreational exercisers (31, 401, 447). In addition, women and children are more susceptible to hyponatremia because their smaller total body water and extracellular fluid volume requires less overdrinking than men to dilute serum sodium concentration (239).

Symptomatic exercise-associated hyponatremia tends to occur more commonly in women than men (12, 224, 414). The reason is not fully understood, but a variety of psychosocial and/or biological factors may be involved. Studies have found that women overdrink relative to body weight compared to men (34, 224). Other factors that may increase a woman’s risk for overdrinking includes lower body mass and total body water (467) as well as longer marathon race times (12). A recent prospective study comparing women with and without a history of hyponatremia suggests that female sex hormones may also play a role in the development of hyponatremia during exercise. Stachenfeld et al. (467) found that, compared to women with no history, women susceptible to hyponatremia retained more fluid (in response to a fluid overload) and lost more sodium when both estradiol and progesterone were elevated. The higher severity of cerebral edema symptoms (i.e., morbidity and mortality) reported in women may be related to how the brain handles water and electrolyte imbalances, as some animal studies have shown impaired Na-K-ATPase pump activity in the female brain during AVP-induced hyponatremia (175, 176).

**Components of a Fluid-Replacement Beverage**

**Objectives of a fluid-replacement beverage**

The main objective of a fluid-replacement beverage is to replace water lost from the body. However, depending on the objective and target population, fluid-replacement beverages are often formulated with other ingredients, especially for beverages intended to improve physical performance.

Beverage composition can have a substantial impact on fluid ingestion, gastric emptying, intestinal fluid absorption, fluid distribution, and fluid retention. Therefore, when fluid replacement is the main objective, the beverage should be formulated to optimize these processes. Moreover, the optimal composition of the beverage depends upon the source of the fluid losses. For example, the beverage should be formulated differently to replace fluid losses from secretory diarrhea compared to a beverage intended to replace losses incurred through thermoregulatory sweating.

A fluid-replacement beverage can also act as a vehicle to provide various nutrients or compounds to aid physiological processes unrelated to hydration. Some examples include carbohydrate for energy provision, caffeine for stimulation of the central nervous system, and protein to promote postexercise muscle recovery. Many of these added ingredients can promote ergogenic effects to physical and mental performance; if properly formulated, can do so without hindering hydration and in some cases even promote the rehydration process.

**Overview of potential ingredients**

In this section, we introduce ingredients commonly found in fluid-replacement beverages and summarize the general effects of these ingredients on fluid replacement, provision of energy, or augmenting physiological function. The relevance and efficacy of these ingredients to specific populations will be discussed in detail later.

**Carbohydrate**

Carbohydrate is included in fluid-replacement beverages in part because of its impact on the rate of water absorption. The cotransport of glucose and sodium facilitate the passive absorption of water across the intestinal mucosa. To improve water absorption, the minimum glucose concentration needed in a beverage is 0.9% (185). In addition, carbohydrate intake is important for maintaining blood glucose concentrations and high rates of carbohydrate oxidation, especially when endogenous carbohydrate stores are being depleted, such as during physical activity (247, 251).

As will be discussed in more detail later, both the type and amount of carbohydrate impacts the rate of fluid and solute absorption from a beverage at rest and during exercise. This is related to the fact that different transport mechanisms are utilized by different carbohydrate types. Glucose (derived from a glucose source or hydrolysis of maltose, maltodextrin, glucose polymers, or starch) and galactose are transported across the intestinal mucosa via the energy-dependent sodium-glucose link transporter (SGLT1), whereas fructose utilizes GLUT5, and sucrose can either be hydrolyzed into glucose and fructose or utilize its own disaccharide transporter SCRT (160, 265, 319). In addition, carbohydrate type greatly impacts the osmolarity of a beverage, with maltodextrin and starch having lower osmolality than mono- and disaccharides.

Carbohydrate amount and type also impact the sweetness and thus the palatability of fluid replacement beverages. For example, compared to sucrose (table sugar, relative sweetness rating of 100) solutions that contain crystalline fructose (rating of 180) or high fructose corn syrup (rating 105-130) have higher relative sweetness whereas glucose (rating of 50-70) and maltose (rating 50) taste less sweet. Moreover, complex
carbohydrates such as maltodextrin and starch have very low sweetness levels (44, 337).

**Electrolytes**

The presence of sodium in a fluid-replacement beverage enhances palatability and stimulates the physiological drive to drink. By contrast, consumption of plain water decreases plasma osmolality and sodium concentration, which reduce the drive to drink, oftentimes before body water volume has been fully restored (351, 478). It is important to note that very high sodium concentrations (≥50 mmol/L) decrease drink palatability (507), which could hinder ad libitum fluid intake. However, the unpalatable salty taste from high concentrations of sodium chloride (the typical source of sodium) can be decreased by substituting other anions (such as citrate) for chloride (440). The increase in serum sodium concentration and osmolality with sodium ingestion stimulates renal water reabsorption. Furthermore, because sodium is the primary extracellular osmolyte, ingestion of sodium helps maintain extracellular fluid volume, including plasma volume.

Potassium is the major cation in the intracellular fluid compartment. The balance of potassium in the extracellular versus intracellular space has important effects on neural transmission, muscle contraction, and vascular tone. Potassium is often included in fluid replacement beverages in relatively small amounts to replace losses due to sweating or diarrhea. Furthermore, potassium influences the concentration of sodium in the blood. This is because plasma sodium concentration is a function of the mass balance of sodium, potassium, and water (148, 346, 361).

Chloride is usually included as the major anion in most fluid-replacement beverages. This is due in part to chloride being the anion lost in the greatest amount in sweat. There is limited information available about the effect of a fluid-replacement beverages’ anion content on intestinal water and solute absorption. One study has investigated the absorption rate of a test solution with various anion compositions while holding sodium and glucose concentrations constant. Using the triple-lumen catheter technique, Fordtran (167) perfused a solution with 80 mmol/L of sodium and 65 mmol/L of glucose with either chloride, bicarbonate, or sulfate as the anion to sodium. The author reported that maximal water and sodium absorption in the jejunum was attained with chloride, followed by bicarbonate, and then sulfate.

**Protein**

Protein is included in postexercise fluid-replacement beverages to promote muscle protein synthesis and thus aid in the recovery process after physical activity (373). There are also recent data on the role that protein may play in rehydration and hydration-related physiological outcomes. For instance, ingestion of milk has been studied for its efficacy in promoting fluid retention during the postexercise rehydration process (244, 245). Furthermore, the promotion of albumin synthesis with protein ingestion after repeated days of exercise in the heat has been shown to enhance plasma volume expansion and thermoregulatory adaptations in both young adults and older individuals (199, 357). These studies are discussed in more detail in the competitive sport and exercise section below.

Amino acids have been investigated for their effects on intestinal water and solute absorption, primarily in the oral rehydration from diarrheal disease literature. Theoretically, amino acids could improve fluid absorption because they utilize sodium-coupled transporters independently of the sodium-hexose cotransporter. Thus, combining amino acids with glucose in a fluid replacement beverage provides separate but additive sodium cotransport systems (424). The addition of glutamine to glucose-based oral rehydration solutions has been shown to improve sodium chloride absorption in the piglet jejunum (385, 386). However, because glutamine (and other nitrogen-containing compounds) negatively affect beverage palatability and stability, it is difficult to formulate oral rehydration solutions with glutamine (424).

**Osmotically active solutes**

Glycerol is an osmotically active solute that is reported to be evenly distributed among all fluid compartments. Scientific evidence supports the efficacy of glycerol for inducing a temporary hyperhydrated state when ingested with additional volumes of water. Glycerol promotes hyperhydration by inducing an osmotic gradient that enhances renal water reabsorption. Thus, when glycerol (typically 1 g of glycerol per kg body mass) is ingested with water (typically ~20 mL per kg body mass), subjects retain more fluid (due to lower free water clearance) compared to when they ingest a placebo with water (341). Although glycerol can be used to retain fluid, the physiological and performance advantages with hyperhydration are inconsistent and the side effects often outweigh the potential advantages (341, 414, 492). For a more complete overview of the literature on glycerol hyperhydration the reader is referred to recent review papers (341, 492).

**Compounds that have central effects**

Some beverages contain compounds that affect neurotransmitter systems and are consumed for their potential to prevent central fatigue and improve aspects of mood, cognitive function, or physical performance. Some of these compounds include caffeine, branched-chain amino acids, and tyrosine.

Caffeine’s central effects are likely mediated by the blocking of adenosine receptor sites. Adenosine is a neurotransmitter-inhibitor with sedative-like properties, thus blocking the action of adenosine results in a stimulatory effect on the sympathetic nervous system. Caffeine is a relatively nonspecific adenosine antagonist, but seems to have the highest affinity for the A1 receptor subtype, which is located in several regions of the brain involved in arousal (165, 177). Caffeinated beverages are routinely consumed...
for their beneficial effects on mood, alertness, cognition, and physical performance. Also, contrary to popular belief, several studies have shown that caffeinated fluids contribute to hydration in a similar manner to noncaffeinated fluids (26, 133, 202). To determine the effects of caffeinated beverages on hydration status, Grandjean et al. (202) had 19 to 39 year old free-living men (participating in light exercise only) consume various combinations of caffeinated and noncaffeinated beverages, including water only; water and caffeinated cola; water, caffeinated cola, and instant coffee; or water and noncaffeinated citrus soft drink; in a counterbalanced, crossover manner for one 24-h period. The subjects’ diets were standardized and total fluid intake was controlled at 35 mL/kg/d (clinical practice guideline) to avoid over- and underdrinking. There were no significant differences in urinary output or change in body weight among beverage treatments, suggesting that caffeinated beverages do not hinder hydration.

Through their potential effects on brain serotonin synthesis, branched-chain amino acids (BCAA; including leucine, isoleucine, and valine) have been proposed as a nutritional countermeasure to central fatigue (128). Changes in brain serotonin are known to affect mood, arousal, and sleepiness. Brain serotonin synthesis increases when the ratio of plasma free tryptophan-to-BCAA rises, thus ingestion of BCAA has been hypothesized to reduce the concentration of serotonin in the brain and mitigate central fatigue.

Tyrosine is a dietary precursor for catecholamine (dopamine and norepinephrine) synthesis and has been purported to mitigate some adverse behavioral, cognitive, and physiological effects of acute stress. It has been hypothesized that central catecholamine neurons are unable to synthesize sufficient neurotransmitter (particularly norepinephrine) during acutely stressful situations (e.g., sleep deprivation, emotional/mental stress, or exposure to cold, heat, or altitude in military applications) (519). Administration of tyrosine (a catecholamine precursor) is thought to enhance the ability of neurons to release neurotransmitter, potentially preventing the cognitive deficits that typically occur with stress (219, 521).

The literature regarding the efficacy of caffeine, BCAA, and tyrosine ingestion on mood, cognition, and physical performance, such as for military and/or sport applications, are discussed in more detail below.

Other important characteristics of a fluid-replacement beverage

A major determinant of the amount of fluid consumed is the palatability of the available drink. Beverage palatability plays an important role in the stimulus of drinking behavior and involves a complex interaction of perceptual and physiological cues that drive the detection of sensory characteristics like taste, flavor, texture, temperature, and thirst. Palatability can also be affected by time of day (52), previous experience with the drink (376), and cultural background (409). Changes in beverage preference with environment and activity may also affect intake (366, 454). For example, in a classic study, Sohar et al. (454) showed that men marching in hot climates preferred cooled, noncarbonated, citrus-flavored water over what they would normally prefer during leisure (beer, cola, coffee, tea, and milk). Most individuals, whether active or at rest, drink more lightly sweetened and flavored beverages compared to nonflavored beverages or water (366, 396, 476, 512).

The temperature of a beverage has a substantial impact on palatability and voluntary fluid intake. As early as 1947, Rothstein et al. (400) found that soldiers replaced more of their sweat losses after walking for 2 h in 39°C ambient conditions when the available water was cool (13°C) versus warm (28°C). Several subsequent studies involving exercise in the heat supported Rothstein et al.’s original findings—that cool (10-15°C) drinks are more preferred and attenuate involuntary hypohydration better than warm (20-40°C) drinks (57, 231, 454, 476). In one study (57), 140 mountain patrol guards were given water ranging from 0 to 50°C (in 5°C increments) in a between groups manner, after first dehydrating by mountain climbing for a half day without food or water. The study also tested the fluid intake of 260 patients who had first dehydrated by sitting in a spa-like room (40°C). Fluid intake was maximized for both subject populations at a water temperature of 15°C (57). The effect of beverage temperature on palatability is also impacted by exercise state and beverage temperature expectations. Palatability of cool fluids increases during exercise (412) compared to control conditions. Also, the palatability of some beverages decreases when they are served at a temperature that is not “expected” or “appropriate” (e.g., coffee is expected to be served warm/hot, white wine is expected to be served chilled) (525).

Beverage Composition Considerations for Specific Applications

There are several applications for fluid-replacement beverages, from maintenance of general health and occupational safety to augmentation of sport performance; and there are unique challenges that each group of individuals face in meeting their fluid replacement needs. This section provides a detailed summary of the literature related to expected fluid losses and fluid-replacement beverage composition and intake strategies for health, competitive sport, recreational exercise, occupational and military settings, and exposure to microgravity or altitude as well as special considerations for age and pathophysiological factors.

Oral rehydration from diarrheal disease

Diarrheal disease is a common cause of death and disability worldwide. In fact it accounts for 16% of deaths among
children less than 5 years of age (518). It is particularly problematic in developing countries, where hygiene, sanitation, and access to safe drinking water is poor and thus enteric infectious diseases are more prevalent. Oral rehydration solutions are formulated to replace fluid and electrolyte losses associated with diarrhea- and vomiting-induced hypohydration (29). The discovery of oral rehydration solutions and scientific establishment of their usefulness in correcting hypohydration and reducing mortality was a medical breakthrough in the management of diarrheal diseases (29, 277, 278). A key step in the development of oral rehydration solutions was the finding that glucose and sodium transport is coupled in the small intestine and this process is unaffected by the pathologies that induce water secretion into the gut (29, 37, 158).

Since the use of the standard World Health Organization oral rehydration solution started in the 1960s, there has been a decrease in the mortality associated with acute diarrheal illnesses in children in both developing and developed countries (29). Globally, the proportion of diarrheal episodes treated with oral rehydration therapy increased from less than 15% in 1984 to approximately 40% in 1993 (495). This increased use of oral rehydration therapy is thought to be responsible for some of the decrease in mortality rates over the past two decades (5.6 to 4.9 per 1000 per year in children under 5 years of age in developing countries), especially from acute dehydrating diarrhea (272).

In 1975, the World Health Organization recommended that the standard oral rehydration solution contain 90 mmol/L of sodium, 20 mmol/L of potassium, 80 mmol/L of chloride, and 10 mmol/L citrate. Additionally, the standard World Health Organization oral rehydration solution contained a small amount of glucose (111 mmol/L or 4.7 g per 8-oz or 237 ml serving) to facilitate intestinal absorption of fluid and electrolytes (29). The overall beverage osmolarity of this formulation was 311 mOsm/L. This formula was designed to replace water and electrolytes lost in stools; however, it did not decrease patients’ diarrhea duration or fecal volume. Thus, the World Health Organization developed a lower osmolarity (245 mOsm/L) version of the standard oral rehydration solution, consisting of 75 mmol/L sodium, 20 mmol/L potassium, 65 mmol/L chloride, 10 mmol/L citrate, and 75 mmol/L glucose (517). According to a meta-analysis of studies conducted with the reduced-osmolarity oral rehydration solution, the use of this formula resulted in lower likelihood of unscheduled intravenous therapy, and significantly reduced stool output and vomiting compared with the standard oral rehydration solution in children with acute diarrhea (217). In 2002, the World Health Organization started recommending the reduced osmolarity oral rehydration solution for the treatment of acute noncholera diarrhea in children (517). The World Health Organization also recommended zinc supplementation to offset losses incurred through diarrhea. The substitution of rice powder for glucose in oral rehydration solutions has been proposed; although some studies report beneficial results (242), further research is needed prior to a change in formulation (see Ref. 29 for discussion). For the treatment of acute diarrhea due to cholera in children and adults, a recent analytical review of the literature reported little differences in unscheduled intravenous infusion, stool output, vomiting, and duration of diarrhea between ≤ 270 mOsm/L versus ≥ 310 mOsm/L oral rehydration solutions (338). Notably, blood sodium concentrations less than 130 mmol/L were more common with the lower osmolarity oral rehydration solutions (≤ 270 mOsm/L), but no symptoms of hyponatremia were reported (338).

The prescribed dosage of oral rehydration solution depends on the level of hypohydration incurred from diarrheal water losses. For 3% to 5% hypohydration, the recommended dosage is 50 ml/kg consumed over a period of 2 to 4 h. For more severe levels of hypohydration (6%-9%), the dosage should be increased to 100 ml/kg over 2 to 4 h. Bellemare et al. (42) found that oral rehydration was as effective as intravenous therapy for treating hypohydration secondary to acute gastroenteritis in children. However, if hypohydration is ≥ 10%, intravenous fluids should be infused initially, followed by 100 mL/kg oral rehydration solution over a 4 h period when the patient is able to drink (29).

Most of the research and recommendations from the World Health Organization have been made for children. Oral rehydration solutions have been underused and understudied in adults, but it is reasonable to speculate that the successful results in studies with children can be extrapolated to adults (29). Oral rehydration solutions are thought to be useful in the treatment of travelers’ diarrhea, although research in this area is limited. Finally, oral rehydration solutions may decrease intravenous fluid requirements in patients with short bowel syndrome who require parenteral nutrition (29). Patients with a reduced length of jejunum ending in the stoma have a reduced capacity to absorb sodium and water, thus may require parenteral nutrition (347). Some studies indicate that ingestion of isotonic oral rehydration solutions containing high concentrations of sodium (≥ 90 mmol/L) result in a positive sodium balance and are better tolerated than salt capsules (290, 348).

Oral rehydration solutions and sports drinks are commonly considered to be interchangeable. While there are some similarities in their composition, oral rehydration solutions and sports drinks are formulated for two distinct purposes. Oral rehydration solutions are formulated to replace fluid and electrolyte losses in individuals suffering from diarrhea- and vomiting-induced hypohydration. Conversely, sports drinks are formulated for rehydration, replenishment of sweat electrolyte losses, and provision of energy during/after exercise. The differences in electrolyte concentration in these two types of beverages reflect the differences in electrolyte losses in diarrhea and vomit versus sweat. The main formulation differences between sports drinks and oral rehydration solutions are summarized in Table 5. This table also includes a comparison with sodium loading beverages designed to counteract expected changes in plasma volume with exposure to microgravity, bed rest, or exercise/heat stress.
Microgravity

Spaceflight

The weightlessness experienced during spaceflight presents unique challenges to body fluid regulation, culminating in changes in fluid distribution and fluid/electrolyte balance that impair orthostatic tolerance and physical performance of astronauts upon return to earth. These perturbations to fluid/electrolyte homeostasis where observed during early studies of manned space flights. Subsequent experimental research in the 1960s and 1970s played an important role in elucidating how beverage composition impacts fluid replacement and mitigation of the detrimental effects of hypovolemia.

Almost immediately upon insertion into microgravity, fluid is displaced from the lower to the upper body as indicated by the reduction of thigh and leg girths and puffiness in the head and face of astronauts (164, 484). In addition, studies have reported body water deficits and plasma volume contraction within the first two days of spaceflight (204). Across several Gemini, Apollo, and Skylab missions, an average body mass deficit of 3.16 ± 0.85% accrued in these 2 to 84 day missions (204). The body water reduction during the first 2 days is thought to be mainly from decreased fluid intake (irrespective of motion sickness), not from diuresis/natriuresis (285) or evaporative water loss (286). These early spaceflight studies of manned space flights. This is because blood volume is an important component of blood pressure regulation. Tolerance to orthostasis and acceleration forces (hydrostatic pressure changes that force blood to legs and from blood into interstitial tissue spaces)

<table>
<thead>
<tr>
<th>Table 5</th>
<th>Composition of Various Types of Fluid Replacement Beverages</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sports drinks</td>
</tr>
<tr>
<td>Carbohydrate</td>
<td>Moderate (~60-80 g/L)</td>
</tr>
<tr>
<td>Sodium</td>
<td>Low to moderate (~10-35 mmol/L)</td>
</tr>
<tr>
<td>Chloride</td>
<td>Low (~10-12 mmol/L)</td>
</tr>
<tr>
<td>Potassium</td>
<td>Low (~3-5 mmol/L)</td>
</tr>
<tr>
<td>Osmolality</td>
<td>~280-380 mOsm/kg</td>
</tr>
<tr>
<td>Other potential ingredients</td>
<td>Minerals, protein, caffeine, others</td>
</tr>
</tbody>
</table>

Sports Drinks composition partially from Maughan and Murray (309), WHO ORS 2002 composition from Atia and Buchman (29), AstroAde composition from Greenleaf et al. (212) and Fortney et al. (171).
Optimal Composition of Fluid-Replacement Beverages

is greatly dependent upon an individuals’ ability to maintain adequate mean arterial blood pressure to the brain and retinal arteries.

To mitigate these issues, scientists have used high sodium beverages to provide an osmotic impetus for fluid movement into the extracellular fluid compartment. Some of the first work done in this area was with bed rest studies. One to two weeks of bed rest has similar effects as microgravity in that it results in a significant decrease in plasma volume, although the underlying mechanisms are different (increased central venous pressure and diuresis; discussed in more detail below). Like astronauts during reentry, bed rest and the accompanying hypovolemia results in significantly impaired tolerance to acceleration forces (simulated via centrifugation of human subjects up to ~4 G). Therefore, Greenleaf et al. (214) tested the effects of rehydrating subjects, who had been on bed rest for 2 weeks, with a solution containing 143 mmol/L of sodium and 31 mmol/L potassium (620 mOsm/L total) on plasma volume and centrifugation tolerance. The drink was given over a 3-h period before centrifugation in a volume equivalent to the calculated extracellular fluid deficit (1.0-1.9 L). Rehydration restored plasma volume up to ~5.5% compared to the original 11.9% loss after 2 weeks of bed rest. Furthermore, acceleration tolerance was significantly increased after rehydration, albeit not completely restored to control values (before bed rest). Other supporting studies followed, including one that found oral rehydration with 800 mL of 0.9% saline to be as effective as blood infusion in restoring acceleration tolerance (207).

The unequivocal support for this countermeasure resulted in the recommendation to take 0.1 or 0.4 g NaCl in 15 to 30 mL water per kg body mass in 3 to 4 portions beginning 8 to 24 h before and ending 2 to 3 h before the gravitational exposure (216). After testing this rehydration protocol in simulation studies, crewmembers of the Salyut space station program used these recommendations in spaceflight. The cosmonauts’ orthostatic tolerance was reported to be greatly improved post flight compared to previous missions when not using the fluid/sodium replacement protocol (182, 216). The saline loading countermeasure was also used in U.S. Space Shuttle flights. In a parallel group study by Bungo et al. (67), 17 crew members consumed various amounts of salt and water (up to eight 1-g salt tablets with ~1 L of water according to personal preference) 2 h prior to the reentry phase of Space Shuttle flights. Nine other astronauts who did not consume any water or salt 2 h prior to reentry served as control subjects. Orthostatic tolerance during a passive standing test was assessed in each astronaut 1 to 2 h after landing. Bungo et al. (67) found that the group using the salt + water countermeasure experienced significantly better cardiovascular response to orthostatic stress than the control group, including an amelioration of the decline in mean blood pressure (+2 mmHg in the countermeasure group vs. −7 mmHg in the controls). The results of this study led to the official adoption of fluid and salt ingestion as an operational procedure during Space Shuttle flights as a countermeasure to microgravity-induced hypovolemia. Various methods of salt and water ingestion have been employed, including salt tablets with water, as in the Bungo et al. study (205) as well as customized sodium loading beverages (AstroAde, Shaklee Corporation) (209, 210). In addition, bouillon has been used successfully to restore plasma volume and orthostatic tolerance in a 15-d bed rest study to simulate weightlessness (258).

It has been recommended that the sodium beverage is consumed shortly before reentry to maximize fluid retention in the vascular space. Ingestion of the high-sodium beverage is not recommended throughout the duration of spaceflight as high sodium intake may exacerbate calcium loss and bone turnover. For this reason, the recommended upper limit for daily sodium intake is 3500 mg/d. The daily water intake recommendation is 2 L (280). Salt tablets are preferred by some crew members, but not generally recommended since it is possible that they may fail to drink an appropriate volume of water with the salt tablets. Insufficient water intake with the salt could cause gastric upset and water secretion into the gastrointestinal tract, exacerbating the hypovolemia. On the other hand, if insufficient salt is consumed water diuresis could ensue, making for ineffective fluid replacement (209, 211).

Bed rest

Patients are commonly put on prolonged bed rest by their physicians to facilitate rehabilitation from injury or illness. Confinement to a horizontal resting position is often a necessary part of the recovery process; however, it also has unwanted physiological effects. Bed rest studies indicate that the weightlessness of bed rest imparts some plasma volume changes similar to that of astronauts and microgravity, albeit through disparate mechanisms, and for which similar fluidreplacement strategies would apply.

Unlike the microgravity-effects of spaceflight where astronauts experience no change in urinary output, bed rest is associated with significant diuresis. Increased urine volume starts on day 1 of horizontal bed rest, with no compensatory increase in thirst and voluntary fluid intake (170, 203). Total body water declines by approximately 600 mL by day 2 and by approximately 1500 mL after 12 to 14 days of horizontal bed rest (243). This loss of total body water is primarily from the extracellular fluid compartment. In a study involving head down (~5°) bed rest, plasma volume contracted by ~5% after 24 h (349). Longer term confinement to bed rest results in a chronic decrease in plasma volume; reaching the lowest point after 4 days of horizontal bed rest (approximately −8% to −11% with exercise) or a continual decline (~15%) with no remedial exercise (206). The increased diuresis is accompanied by significant losses of sodium and potassium during the first 24 h and leads to a decreased serum sodium concentration during the first 3 days of horizontal bed rest (170). The body fluid and electrolyte changes outlined above may be exacerbated when bed rest is in a slight head down position (~4° to ~8°) (170).
Countermeasures to plasma volume contraction during bed rest are similar to that recommended to astronauts during spaceflight. Lower body negative pressure training, aerobic exercise training, and/or water intake with salt supplementation have been effective strategies for attenuating the decrease in plasma volume during bed rest and improving orthostatic responses following bed rest (as discussed above in the spaceflight section) (214, 258). More details on physiological mechanisms mediating body fluid and electrolyte changes during short- and long-term bed rest can be found in previous reviews (170, 203).

**Competitive sport or exercise**

The physiological demands and environment of a sport influence the optimal composition of a fluid-replacement beverage for athletes. For most sports, maintaining hydration and provision of energy are probably the most important challenges in the prevention of fatigue. Another possible mechanism of fatigue during exercise or sports training/competition includes central fatigue, which could be involved in cognitive and/or motor performance impairments. Fluid-replacement beverages targeted to athletes, such as sports drinks, are often formulated to mitigate one or more of these sources of fatigue. Sports drinks have received an abundance of research attention since the early pioneering work of Cade and associates in the early 1970s (74, 75).

The most recent guidelines by the American College of Sports Medicine (414) state that hypohydration of more than 2% of body mass should be prevented but also warns against drinking in excess of sweating rate to prevent hyponatremia. Sweating rates can vary from less than 0.5 to over 2.5 L/h depending upon exercise intensity, environmental conditions, amount and type of clothing or equipment, heat acclimatization state, fitness level, and body size (382, 413, 414). The range of sweating rates that have been measured across various sports and environmental conditions are shown in Table 6.

This table also includes sweating rates experienced in cold weather conditions. It is important to note that wearing heavy or impermeable clothing while exercising in cold weather can result in high sweating rates (414).

It is common for individuals to voluntarily replace only about 50% of their sweat losses and incur ≥ 2% hypohydration during training or competition (51, 364, 413). To avoid excessive fluid/electrolyte imbalances and performance decrements during prolonged exercise the ideal hydration practice for athletes is to consume fluids at a rate (to avoid body mass gain and ≥ 2% body mass deficit) and composition approximating that of their sweat losses (33, 340). However, formulating a beverage to approximate sweat losses is difficult, because sweat sodium concentration varies widely among individuals. In addition, beverage palatability and voluntary drinking declines when sodium concentration is too high. Thus, the ideal fluid replacement beverage would strike a balance.

---

**Table 6: Observations of Sweating Rates in Various Sports**

<table>
<thead>
<tr>
<th>Sport</th>
<th>Condition</th>
<th>Mean</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water polo (113)</td>
<td>Training (males)</td>
<td>0.29</td>
<td>0.22-0.35</td>
</tr>
<tr>
<td></td>
<td>Competition (males)</td>
<td>0.79</td>
<td>0.69-0.88</td>
</tr>
<tr>
<td>Netball (60)</td>
<td>Summer training (females)</td>
<td>0.72</td>
<td>0.45-0.99</td>
</tr>
<tr>
<td></td>
<td>Summer competition (females)</td>
<td>0.98</td>
<td>0.45-1.49</td>
</tr>
<tr>
<td>Rowing (69)</td>
<td>Summer training (males)</td>
<td>1.98</td>
<td>0.99-2.92</td>
</tr>
<tr>
<td></td>
<td>Summer training (females)</td>
<td>1.39</td>
<td>0.74-2.34</td>
</tr>
<tr>
<td>Basketball (60)</td>
<td>Summer training (males)</td>
<td>1.37</td>
<td>0.90-1.84</td>
</tr>
<tr>
<td></td>
<td>Summer training (females)</td>
<td>1.60</td>
<td>1.23-1.97</td>
</tr>
<tr>
<td>Soccer (441)</td>
<td>Summer training (males)</td>
<td>1.46</td>
<td>0.99-1.93</td>
</tr>
<tr>
<td>Soccer (312)</td>
<td>Winter training (males)</td>
<td>1.13</td>
<td>0.71-1.77</td>
</tr>
<tr>
<td>American football (191)</td>
<td>Summer training (males)</td>
<td>2.14</td>
<td>1.1-3.18</td>
</tr>
<tr>
<td>Tennis (49)</td>
<td>Summer competition (males)</td>
<td>1.60</td>
<td>0.62-2.58</td>
</tr>
<tr>
<td>Tennis (46)</td>
<td>Summer competition (cramp-prone males)</td>
<td>2.60</td>
<td>1.79-3.41</td>
</tr>
<tr>
<td>Squash (63)</td>
<td>Competition (males)</td>
<td>2.37</td>
<td>1.49-3.25</td>
</tr>
<tr>
<td>Half marathon running (71)</td>
<td>Winter competition (males)</td>
<td>1.49</td>
<td>0.75-2.23</td>
</tr>
<tr>
<td>XC-running (191)</td>
<td>Summer training (males)</td>
<td>1.77</td>
<td>0.99-2.55</td>
</tr>
</tbody>
</table>

Values are mean, plus range of ±95% reference range. Adapted (with permission) from Sawka et al. (414).
between palatability and physiological efficacy. The optimal fluid replacement beverage composition for athletes may also depend upon whether the drink is consumed before, during, or after training/competition.

**Before exercise**

Preexercise sodium loading to induce hyperhydration has been studied in athletes. Starting exercise in a hyperhydrated state could effectively delay the amount of time it takes an athlete to reach a level of hypohydration that impairs cardiovascular and thermoregulatory function and decreases performance. Thus, the strategy of sodium loading and plasma volume expansion prior to reentry into the Earth’s atmosphere after spaceflight (cardiovascular challenge) was applied to endurance exercise performance research. Preexercise ingestion of a high sodium beverage to expand plasma volume prior to exercise has been tested as a preemptive measure to counteract the anticipated plasma volume contraction associated with exercise, particularly exercise in the heat, when sweat losses may be large. Subsequent to the series of studies conducted by Greenleaf et al. in the 1990s (209, 211, 212), others later confirmed the finding of plasma volume expansion and improved performance by sodium loading and extended the benefit to moderately trained nonheat-acclimatized male runners/cyclists (105, 450) and well-trained nonheat-acclimatized female cyclists (449) with either no changes (105) to or improved concomitant thermoregulation (449, 450). It is worth noting however, that while increasing plasma volume (which can also be achieved via dextran infusion) can result in performance advantages for moderately active individuals, this response is less apparent in well-trained and/or heat-acclimatized endurance athletes (see Ref. 352 for discussion).

Preexercise hyperhydration with glycerol has also been tested for its effects on physiological function and performance, but results have been mixed. Several studies have found that glycerol plus fluid ingestion prior to exercise significantly increases total body water compared to ingestion of fluid without glycerol (341). However only half of the studies showed an expansion of plasma volume prior to exercise and/or an attenuation of the decline in plasma volume during exercise as a result of glycerol ingestion (341). Furthermore, there is no clear advantage of hyperhydration over euhydration for cardiovascular or thermoregulatory function or performance during subsequent exercise (263, 282, 283, 341, 414).

It is important to note that some investigators have reported side effects such as nausea, vomiting, and headache as a result of glycerol ingestion; although, the occurrence of these side effects seems to be related to the ingestion of a highly concentrated glycerol dose (≥ 10%) (341). In addition, hyperhydrating before exercise increases the likelihood of having to void during exercise or competition (178, 353). Preexercise hyperhydration with water or glycerol could also increase the risk of dilutional hyponatremia, especially if excessive fluid intake is continued during exercise (324).

**During exercise**

The recommended amount of sodium and potassium to be included in a fluid-replacement beverage during exercise (as communicated by The American College of Sports Medicine) is continued during exercise (324).
Medicine and the Institute of Medicine) is \(\sim 20\) to 30 and \(\sim 2\) to 5 mmol/L, respectively (238, 414). This is primarily because the presence of \(\sim 20\) to 30 mmol/L sodium in a fluid-replacement beverage has been shown to stimulate physiological thirst and improve beverage palatability and voluntary fluid intake (351, 414, 478, 512). In addition, ingestion of \(\sim 20\) to 30 mmol/L of sodium and \(\sim 2\) to 5 mmol/L of potassium from a fluid-replacement beverage helps replace sweat electrolyte losses incurred during exercise (414). Sodium intake may be especially important when sweat sodium losses are large. Some types of exercise-associated muscle cramping may be associated with large sweat sodium losses; and cramp-prone athletes can benefit from sodium intake to prevent or offset muscle cramping (45-47, 149, 470). Furthermore, a sodium-containing beverage helps slow the decline in blood sodium concentration during prolonged exercise, with higher concentrations being more effective at offsetting losses compared to plain water (14, 33, 324, 490, 500). Chloride is typically the primary anion included in sports drinks, since it is the anion lost in the greatest amount in sweat. In addition, a small amount of potassium (\(\sim 3\) mmol/L) is usually included to replace sweat potassium losses. Despite the common perception that magnesium and/or potassium are implicated in the etiology of exercise-associated muscle cramping, there are little to no experimental data to support this notion (440).

Carbohydrate is often included in sports drinks to provide a source of energy. The provision of carbohydrate energy has been shown to postpone fatigue and improve performance (discussed in greater detail later). However, high carbohydrate concentrations can impair the fluid absorption process by slowing gastric emptying. This is because the energy density (i.e., carbohydrate concentration) of an ingested beverage is an important factor in determining gastric emptying rate (61). In general, relatively dilute carbohydrate solutions (e.g., up to 6% or 60 g/L) are emptied from the stomach at a similar rate as an equal volume of water (333, 335, 336, 383). By contrast, beverages with carbohydrate concentrations \(\geq 8\%\) have been found to significantly impair gastric emptying (illustrated in Fig. 11) and increase gastrointestinal discomfort compared to water during exercise (335, 435). Further increases in beverage carbohydrate concentration (15%-18%) have been shown to cause further delays in gastric emptying (380, 383). However, not all studies have followed this pattern. Small but significant decreases in gastric emptying rates have been found with 4% to 5% carbohydrate solutions compared to water (112, 497). Also, some studies have found no differences between solutions of 10% versus 0% carbohydrate (362, 522). These inconsistent results are likely due to methodological differences among studies (fluid volume, fluid intake frequency, gastric emptying measurement techniques, and rest versus exercise) (288, 333).

Relative to the significant impact that energy density has on gastric emptying, the role of beverage osmolality is less important (61, 305, 335, 336). When comparing isoenergetic (50-100 g/L) solutions of different osmolality (by using glucose polymer versus glucose monomer-containing beverages) most investigations have found little or no difference in gastric emptying rates (61, 288, 362). However, the impact of beverage osmolality may depend on the concentration range of the carbohydrate solutions tested (455, 498). One study showed that a 15% maltodextrin solution emptied faster than a 15% glucose solution, whereas there were no differences between maltodextrin and glucose solutions at lower ranges of carbohydrate concentration (5% and 10%) (455).

The effect of carbohydrate type on gastric emptying has also been investigated. Shi et al. (434) measured the effect of multiple transportable carbohydrates on the rate of gastric emptying of four isoenergetic 6% carbohydrate solutions ingested at rest and found no differences between glucose, fructose, glucose + fructose, and sucrose. However, recently Jeukendrup and Moseley (256) found that during moderate intensity exercise, ingestion of an 8.6% glucose + fructose solution (in a 2:1 ratio) increased gastric emptying and fluid delivery (measured via deuterium accumulation of ingested beverages in the plasma) compared with an 8.6% carbohydrate solution containing only glucose. Taken together, the results of these studies suggest that the formulation of beverages with multiple transportable carbohydrates may

![Figure 11](https://example.com/figure11.png)

**Figure 11** Gastric emptying characteristics of test beverages with various % carbohydrate. *Significantly different from all other beverages. Reprinted (with permission) from Murray et al. (335).
improve gastric emptying when the total carbohydrate intake is relatively high.

Carbohydrate amount and type also affects the rate of intestinal fluid absorption (436). This is likely related to the impact of carbohydrate concentration on beverage osmolality. The osmolality of a beverage increases linearly with increases in carbohydrate and electrolyte concentration; and intestinal water absorption is inversely proportional to beverage osmolality. Thus, intestinal water absorption is greater with hypotonic solutions than isotonic or hypertonic solutions. However, formulating a beverage with multiple transportable carbohydrates seems to offset some of the negative effect of beverage hyperosmolality as Shi et al. (437) and Gisolfi et al. (186) reported no differences in water absorption at rest or exercise among carbohydrate-electrolyte solutions ranging from 186 to 417 mOsm/kg. The effect of the interaction between beverage osmolality and multiple transportable carbohydrates on intestinal fluid absorption is shown in Figure 12. Some studies have even reported greater intestinal water absorption rates with isotonic carbohydrate-electrolyte solutions compared with distilled water (188, 289) despite the differences in solution osmolality. Furthermore, Gisolfi et al. (187) found that water absorption was faster with an isotonic carbohydrate-electrolyte solution than isotonic saline. This is likely because passive water absorption is dependent upon active solute absorption in the small intestine.

As mentioned above, the type of carbohydrate impacts the rate of a beverage’s intestinal fluid and solute absorption during exercise. Because individual carbohydrate types are transported across enterocytes via different mechanisms (passive diffusion vs. facilitated diffusion vs. active transport) their
Carbohydrate delivery is important because muscle glycogen and blood glucose are the primary substrates for the contracting muscle during most competitive situations (397). Fatigue during prolonged exercise is often associated with muscle glycogen depletion, diminished total carbohydrate oxidation, and/or reduced blood glucose concentrations (251). Maintaining carbohydrate oxidation through carbohydrate feeding has been shown to be an effective strategy to delay fatigue. Classic studies in the 1980s were conducted by Coggan and Coyle (103, 104, 116-118). Coyle et al. (117) demonstrated that carbohydrate feeding during exercise at 70% VO_2max prevents the drop in blood glucose concentration that was observed when water (placebo) was ingested. Carbohydrate feeding was also associated with higher rates of carbohydrate oxidation and a 33% improvement in endurance capacity. Interestingly, when exercised to exhaustion and rested for a short period, they were able to continue for longer when glucose was ingested or infused intravenously (118). This research showed the importance of plasma glucose as a substrate during exercise. Since these early studies, many others have confirmed these findings and several reviews have discussed the ergogenic effects of carbohydrate ingestion during exercise in more detail (85, 248, 251-253, 255, 262).

In brief, performance improvements have been observed with the ingestion of small quantities of carbohydrate (as little as 20 g) (162). However, during prolonged exercise (> 2 h) there appears to be a dose-response relation between carbohydrate intake and exercise performance, such that greater carbohydrate delivery is associated with improved performance. In one recent study, endurance performance and fuel selection were measured during prolonged exercise while ingesting 15, 30, or 60 g/h glucose (453). Subjects cycled for 2 h at 77% VO_2peak followed by a 20-km time trial and the results suggested a relation between the dose of glucose ingested and improvements in endurance performance. Another study (452) investigated the relation between 0 and 120 g/h carbohydrate and exercise performance during a 20-km time trial preceded by a 2-h constant load ride in cyclists and triathletes. They found a curvilinear relation between 0 and 120 g/h carbohydrate ingestion and performance, such that ingestion of small amounts of carbohydrate (~10-60 g/h) provided a small benefit, the optimal range was estimated to be 68 to 88 g/h, but higher carbohydrate ingestion rates (>~78 g/h) had diminishing returns. A meta-analysis showed very similar results (493). Data from Ironman Hawaii, one of the most challenging ultraendurance events (lasting between 8 and 16 h), suggest that higher ingestion rates (up to 120 g/h) may be beneficial in longer races when athletes are accustomed to such intakes (369), which is in line with suggestions that the gut can adapt to high carbohydrate intakes (114, 255).

As discussed previously, different carbohydrates ingested during exercise may be utilized at different rates and the rate of intestinal carbohydrate absorption can be increased with the presence of multiple transportable carbohydrates (252). In general, carbohydrates can be divided in two categories: those that can be oxidized at rates up to 60 g/h and those that are oxidized at much lower rates (up to about 40 g/h). The faster oxidized carbohydrates include glucose, maltose, sucrose, maltodextrins, and amylopectin starches. The slower oxidized carbohydrates include fructose, galactose, isomaltulose, trehalose, and insoluble (amylose) starches (as reviewed in ref. 252). Exogenous carbohydrate oxidation is mainly limited by the intestinal absorption of carbohydrates and this is most likely related to the saturation of the SGLT1 transporter at ingestion rates of 60 g/h or more. A series of studies attempting to determine the maximal rate of exogenous carbohydrate oxidation confirmed that multiple transportable carbohydrates utilizing both the SGLT 1 and GLUT5 resulted in (up to 75%) higher oxidation rates than carbohydrates that use the SGLT1 transporter only (247, 252). At very high intakes (144 g/h, which may be difficult to achieve in competition) it was demonstrated that exogenous carbohydrate oxidation from a glucose:fructose mix could be as high as 105 g/h. These studies provide indirect evidence that saturation of the SGLT1 carbohydrate transporter does indeed occur. There does not seem to be an optimal ratio of carbohydrates but it is of course important to provide as much glucose (or another fast carbohydrate that uses SGLT1) to saturate the glucose transporter (60-70 g/h), plus additional fructose. Studies suggest that fructose oxidation increases with increasing rates of ingestion. The “optimal” ratio may therefore be determined by what is practical. Because athletes are generally able to ingest 90 g carbohydrate per hour, the recommendation often is 60 g/h glucose plus 30 g/h fructose (giving a 2:1 ratio of glucose:fructose) (248).

There is also evidence that ingesting multiple transportable carbohydrates during prolonged (> 2-2.5 h) exercise confers better performance, lower ratings of perceived exertion, and lower gastrointestinal distress than ingesting isocaloric beverages composed of a single carbohydrate (glucose) (123, 257, 408, 487). However, these effects may only become apparent when exercise duration is long enough (> 2.5 h) and intakes are relatively high (> 60 g/h) (232).

During prolonged exercise (i.e., > 2 h), the benefits of carbohydrate are mainly metabolic in nature. However, carbohydrate ingestion during exercise has also been demonstrated to improve performance when the exercise
is of high intensity (>75% VO₂max) and relatively short duration (~1 h) (43, 249, 343). The underlying mechanisms for the ergogenic effect during this type of activity may reside in the central nervous system. This is because emerging research has indicated that rinsing the mouth with a carbohydrate-containing drink is associated with improvements in performance (254). Thus carbohydrate’s ergogenic effect on exercise performance may be due in part to its influence on the brain via carbohydrate-sensitive receptors in the mouth. The oral exposure to a 6.4% glucose or maltodextrin solution has been shown in functional magnetic resonance imaging studies to activate regions of the brain associated with reward and motor control (86). The receptors in the oral cavity have not yet been identified and the exact role of various brain areas is not clearly understood, thus further research is warranted. Carbohydrate feedings may also have an ergogenic effect on intermittent high-intensity exercise performance as well as cognition and motor skill performance in team sports (9, 141, 506, 515). However, more research, employing valid, sensitive, and reliable team/stop-and-go sports protocols, measuring the efficacy of carbohydrate intake on skill performance is needed. Carbohydrate intake recommendations for athletes based on the research findings discussed above are shown in Table 7.

Flavor and sweetness in sports drinks help improve beverage palatability (hedonic ratings such as liking and acceptability) and increase ad libitum fluid intake compared to water. This has been repeatedly demonstrated in both adult and youth athletes (365-367, 391, 395). Oftentimes, one of the major deterrents to drinking adequate fluid volumes to avoid hypohydration is beverage palatability, thus the addition of flavoring components, sweetness, and sodium to stimulate consumption is a major aspect of a sports drinks efficacy (111). It is important to note that altering carbohydrate type and amount will also impact the drinks’ taste characteristics and mouth feel, so a properly formulated fluid-replacement beverage strikes a balance between palatability and physiological efficacy in providing fuel and hydration.

### After exercise

The facilitation of rapid fluid restoration is important in the case of severe hypohydration (4-5% body mass), when food is not available or desired, or when athletes need to participate in subsequent competition in a relatively short timeframe (<24 h, e.g., tournaments, two-a-day practices). In most other situations, water and sodium can be consumed with normal eating and drinking practices with no urgency (444).

The presence of sodium in a fluid replacement beverage helps stimulate more complete rehydration after an athlete incurs exercise-induced hypohydration. This includes both better plasma volume restoration and whole-body fluid balance compared to ingestion of plain water (194, 304, 310, 442, 507). The increase in serum sodium concentration and osmolality with sodium ingestion stimulates renal water reabsorption; and as illustrated in Figure 13, urine output is inversely related to the sodium content of the ingested fluid (304).

There is also an interaction between the volume and the sodium content of fluids ingested. Shirreffs et al. (445) gave subjects either a 23 or 61 mmol/L sodium solution in a volume equivalent to 50%, 100%, 150%, or 200% of body mass loss incurred during previous exercise. Six hours after fluid ingestion, net fluid balance was completely restored only when the fluid volume was greater than fluid lost during exercise (i.e., >100%); however, there was no clear advantage to drinking 200% compared to 150%. Furthermore, net fluid balance was higher (less negative) with the 61 mmol/L than the 23 mmol/L sodium beverage at intake volumes of 100% or more (see Fig. 14). Thus, expert panels recommend that to achieve rapid and complete recovery from hypohydration athletes should drink ~1.5 L of a sodium-containing fluid for each kg of fluid lost during exercise.

### Table 7: Recommendations for Carbohydrate Intake during Different Endurance Events

<table>
<thead>
<tr>
<th>Event</th>
<th>Carbohydrate required for optimal performance and minimizing negative energy balance</th>
<th>Recommended intake</th>
<th>Carbohydrate type</th>
<th>Glu</th>
<th>Glu+Fru</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;30 min</td>
<td>No CHO required</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>30-75 min</td>
<td>Very small amounts</td>
<td>Mouth rinse</td>
<td>Most forms of CHO</td>
<td>•</td>
<td>•</td>
</tr>
<tr>
<td>1-2 h</td>
<td>Small amounts</td>
<td>Up to 30 g/h</td>
<td>Most forms of CHO</td>
<td>•</td>
<td>•</td>
</tr>
<tr>
<td>2-3 h</td>
<td>Moderate amounts</td>
<td>Up to 60 g/h</td>
<td>CHO that are rapidly oxidized (glucose, MD)</td>
<td>○</td>
<td>•</td>
</tr>
<tr>
<td>&gt;2.5 h</td>
<td>Large amounts</td>
<td>Up to 90 g/h</td>
<td>Only multiple transportable CHO</td>
<td>•</td>
<td>•</td>
</tr>
</tbody>
</table>

• indicates optimal, ○ indicates ok, but perhaps not optimal. CHO, carbohydrate; MD, maltodextrin.

These guidelines are intended for serious athletes, exercising at a reasonable exercise intensity (>4 kcal/min). If the (absolute) exercise intensity is below this, the figures for carbohydrate intake should be adjusted downward.
body mass lost (414, 444). The additional volume compensates for the diuresis stimulated by rapid consumption of large volumes of fluid. Consuming fluid with sufficient sodium (as discussed above) and/or at a more gradual rate over time also helps maximize fluid retention (414).

There is some emerging evidence that the inclusion of carbohydrate in a fluid replacement beverage may also have an impact on fluid retention following thermal and exercise-induced hypohydration. Osterberg et al. (360) tested the effects of five different beverages on fluid retention after a 90-min bout of exercise in the heat that induced 2% to 3% hypohydration. The athletes consumed water, placebo, or a 3%, 6%, or 12% carbohydrate (3.25% glucose and 2.75% fructose) solution in a volume to replace 100% of fluid losses incurred during exercise. The placebo and carbohydrate solutions also included 18 mmol/L sodium, 3 mmol/L potassium, and 11 mmol/L chloride. At the end of a 240-min rehydration period, fluid retention was significantly greater with all carbohydrate-containing beverages compared with water, but there was no significant difference between water and placebo. In addition, the 12% carbohydrate solution elicited significantly greater fluid retention than placebo. Similarly, Evans et al. (155) compared the effects of drinks with the same electrolyte content but different carbohydrate concentrations (0%, 2%, and 10%) on fluid retention in subjects who were previously dehydrated by 1.9% of body mass by cycle ergometer exercise in the heat. Significantly more of the ingested fluid was retained with the 10% carbohydrate solution (46 ± 9%) than with the 0% carbohydrate solution (27 ± 13%).

The effect of carbohydrate on fluid retention after exercise could be due to a number of factors. One mechanism to consider is the passive association of water with solute related to glycogen storage. Glucose transport into liver and muscle cells draws water along with the substrate, which can increase intracellular fluid retention and total body water; although the amount of water stored with glycogen is inconclusive (varying across studies from 1 to 4 g of water per g of glycogen) (183, 358, 433). Carbohydrate could also affect fluid retention by delaying gastric emptying or intestinal absorption (from the increased energy density and/or osmolality of the higher carbohydrate beverages), which would effectively delay the appearance of fluid in the bloodstream. The delayed absorption of fluid and/or the higher plasma osmolality elicited by...
the carbohydrate drink would attenuate renal water excretion. An alternate mechanism of action may be related to the insulin response to carbohydrate intake. Infusion of insulin has been associated with acute antinatriuresis in humans (131, 379) and in vitro studies in animals have shown that insulin binds directly to proximal and distal segments of nephrons to enhance renal sodium reabsorption (132), which would in turn promote water retention. In a recent study, Kamijo et al. (261) fed subjects a carbohydrate-free placebo, 3.3% carbohydrate beverage, or 6.5% carbohydrate beverage (all with 21 mmol/L sodium, 5 mmol/L potassium, 16.5 mmol/L chloride, and 10 mmol/L citrate) in volumes equivalent to fluid loss after exercise and heat-induced hypohydration to approximately ~2.3% body mass. Their results suggested that accumulated urine volume was smallest, and renal sodium reabsorption was greatest with the 6.5% carbohydrate beverage. At this time plasma vasopressin and aldosterone concentrations were not significantly different among trials, thus were unlikely to be involved in the enhanced renal sodium reabsorption rate. On the other hand, serum insulin concentration was significantly higher in the 6.5% carbohydrate trial vs. the placebo and 3.3% carbohydrate trials. Furthermore, they found that serum insulin concentration was significantly correlated with renal sodium reabsorption rate.

Protein is included in sports drinks to promote muscle protein synthesis and aid in the postexercise recovery process. The optimum timing for protein ingestion is after exercise, specifically as soon as possible after exercise, particularly if optimum muscle adaptation and performance are a high priority. Consumption of high quality protein (i.e., one that provides all of the essential amino acids) after exercise at a rate of 20 to 25 g stimulates muscle protein synthesis and possibly lowers the rate of muscle protein breakdown. Higher rates of protein intake after exercise do not confer additional benefits (328). It appears that the amino acid leucine, in particular, is important for this response. These recommendations apply to both strength-trained and endurance trained athletes (373).

Recent studies have shown that protein may enhance postexercise retention of ingested fluids, with milk being as effective (245) and in some cases more effective (244, 446, 504) than carbohydrate-electrolyte drinks. Watson et al. (504) compared the postexercise rehydration efficacy of skimmed milk and a commercially available sports drink. Recreational athletes first exercised intermittently at 55% VO\textsubscript{2}peak in the heat (35°C, 60%-70% relative humidity) until they reached 2.0% body mass loss. Thirty min after exercise, they consumed either skimmed milk or a carbohydrate-electrolyte sports drink equivalent to 150% body mass lost. At the end of the 3 h recovery period, the subjects had excreted more cumulative urine in the carbohydrate-electrolyte trial (861 ± 396 mL) than the milk trial (525 ±118 mL); equal to a net fluid balance difference of 326 mL or 0.4 ± 0.5% body mass.

The mechanisms by which protein influences rehydration are unclear since differences between milk and carbohydrate-electrolyte solutions have been reported even when matched for electrolyte composition (244) and/or osmolality (244, 504). It has been suggested that the increased energy density as well as the clotting of the casein in the milk-based products delays gastric emptying (244, 245) and slows intestinal fluid absorption compared to whey protein (76) or glucose drinks (72). A delay in fluid entering the bloodstream would consequently attenuate the reduction in serum osmolality and therefore prolong the stimulus for renal water reabsorption. A few recent studies provide indirect support for these purported biological mechanisms. First, Seifert et al. (427) found that a 6% carbohydrate + 1.5% whey protein beverage was retained to a greater extent than a 6% carbohydrate drink. Then, James et al. (244) compared a 6.5% carbohydrate beverage with a 4% carbohydrate + 2.5% milk protein beverage and found that milk protein significantly improved postexercise fluid retention. However, in a subsequent study where carbohydrate only and carbohydrate + protein beverages matched for electrolyte content and energy density were compared, the protein source was whey protein isolate. In this study there were no differences between 5% carbohydrate + 1.5% protein vs. 6.5% carbohydrate beverages in postexercise rehydration (245). Taken together these results suggest that energy density differences between beverages and/or casein per se (when beverages are energy-matched) and associated delays in gastric emptying/fluid absorption may explain the difference in fluid retention between milk and traditional carbohydrate drinks found in some studies.

Recent studies suggest that plasma volume expansion (which is one of the physiological adaptations that occur after aerobic training and heat acclimation (109, 110)) can be further enhanced by ingestion of a protein-carbohydrate supplement immediately after repeated days of aerobic exercise in the heat (199, 356). In one study with recreationally active college students, resting plasma volume and stroke volume were twofold higher after 5 days of aerobic training with postexercise ingestion of a protein-carbohydrate supplementation (0.36 g/kg protein and 0.47 g/kg carbohydrate) than with a nonprotein, low calorie (only 0.09 g/kg carbohydrate) placebo (199). Due to the expanded plasma volume after training, protein-carbohydrate supplementation conferred a thermoregulatory benefit—attenuating the rise in heart rate and esophageal temperature during a 30 min cycling test (65% VO\textsubscript{2}peak) compared to placebo. The plasma volume expansion was attributed to increased total protein and albumin content influencing total plasma water retention (199). Improvements in cardiovascular and thermoregulatory function with protein-carbohydrate supplementation have also been observed in older men during an 8 week aerobic training regimen (356).

Sometimes rehydration is achieved through the administration of fluid intravenously instead of orally. However, the oral intake of fluid for purposes of rehydration is often preferred by clinicians because it is more practical and is potentially safer than administering intravenous fluids, particularly in a sporting context (80, 82). Administration of intravenous fluids requires trained personnel and increases
the risk of infection due to venipuncture. However, another relevant consideration is whether intravenous vs. oral fluids confers any physiological advantage. One study compared oral and intravenous rehydration after a 4% reduction in body mass and demonstrated that restoration of plasma volume, plasma osmolality, plasma sodium concentration, and fluid regulatory hormones were similar regardless of the route of fluid administration. Moreover, there were no cardiovascular, thermoregulatory, or performance advantages of intravenous vs. oral fluid administration during exercise in the heat (267). Therefore, there are generally no differences when similar volumes and compositions of fluid are delivered either orally or intravenously (80, 83, 267). However, there are times when oral intake of fluids is neither possible nor practical, and would be contraindicated (i.e., trauma, nausea, vomiting). In these instances, intravenous fluid administration remains the primary route for rapid rehydration.

Recreational exercise

Many people engage in exercise on a recreational level because of the potential health and social benefits. Recreational exercise can include numerous types of activities, including gardening, aerobics, walking, hiking, running, or cycling; and is usually conducted at a lower intensity and/or duration than competitive athletes. Thus, aggressive fluid replacement is typically not necessary, as Kenefick and Cheuvront (266) predicted that fluid losses seldom reach \( \geq 2\% \) body mass at recreational running paces in temperate weather conditions (22\(^\circ \)C). However, when exercise is of high-intensity, longer duration (\( \geq 1\) h), or performed in a hot environment, fluid replacement with carbohydrate and electrolytes at a rate sufficient to prevent \( \geq 2\% \) hypohydration can be advantageous (discussed in detail in competitive exercise section above).

Recreational exercisers should employ practical hydration assessment techniques to gauge their fluid needs. Practical markers of hydration status include urine (e.g., color or urine specific gravity, USG), body weight (e.g., fluctuation in morning body weight or change from before to after exercise), and thirst. For example, first morning nude body mass can serve as an indicator of hydration status. When hydration status is stable, morning nude body mass does not fluctuate significantly (25). However, when a first morning nude body mass deviates from normal morning body mass (established by regular measurements over a period of several days) by \( > 1\% \), the individual may be hypohydrated, especially if accompanied by dark urine and thirst.

It is also important that recreational exercisers avoid overdrinking. Dilutional hyponatremia has been reported in recreational hikers/trekkers (31, 401, 447) and recreational runners/cyclists (e.g., \( > 4-5\) h marathoners) (12, 127, 143, 225). For example, seven cases were reported in Grand Canyon hikers, varying in age from 19 to 64 years in 1993 (31). While most reasons for acute collapse associated with physical activity in the heat involve heat exhaustion or other heat illnesses, a small percentage have been associated with hyponatremia (447). Overzealous drinking is typically the cause, thus it is important that individuals determine their individual sweating rates so they can determine appropriate fluid intake rates. In addition, supplementation with sodium-containing foods or fluids may help. However, it is important to note that overdrinking of even sodium-containing beverages should be avoided as consumption of any fluid with sodium concentration less than that of the blood (135-145 mmol/L) can decrease serum sodium concentration if consumed in excess of fluid losses (324).

Occupational

In many occupational settings, workers are faced with environmental conditions that impose heat stress and consequent fluid loss from sweating. When these environmental conditions are combined with physical work and/or impermeable protective clothing (that prevents evaporation of sweat), workers are at risk for hypohydration and hyperthermia. The associated consequences may be impairment of cognitive and physical function that could not only impact work performance but also worker morale and safety. Mining, firefighting, agriculture, logging, construction, landscaping, industrial/plant work, and law enforcement are just some of the examples of occupations that face these unique challenges.

Occupational work is characterized by a variety of types of activity, including aerobic, anaerobic, and/or strength involving the upper and/or lower body, interspersed with rest cycles. This type of work can elicit large sweat losses, especially when combined with protective clothing. Sweating rates above 2 L/h have been observed in simulated work conditions in which industrial workers (53) and firefighters (398) were wearing protective gear. Ruby et al. (410) measured water turnover in wild land firefighters during a 5-d period of arduous fire suppression work. Water turnover during this period of time was 6.7 L/d in the firefighters versus 3.8 L/d in a control group of recreationally-active college students. They also found that the firefighters total body water decreased by 0.9 kg (2\%) and body mass decreased by 1.0 kg (1.4\%), while the control group did not change over the 5 days (410).

To complicate the matter, protective face masks can make fluid consumption difficult and the working conditions may not be conducive to drinking (carrying water load) or excretion. Mean body mass deficits from pre- to postshift have been reported to be approximately 1\% to 3\% in various studies with planters and forestry workers (368, 488). Furthermore, it is well-documented that workers commonly start the workday in a fluid deficit (268). For example, one study (59) reported that 60\% of miners started work in a hypohydrated state and their hydration status did not improve throughout the 10 to 12 h work shift. Biggs et al. (50) observed that 44\% of South African forestry workers had preshift USG above 1.020 and
63% of workers ended their shift with USG above 1.020. In addition, at least 20% of workers experienced >2% to 3% body mass deficit from pre- to postshift. The workers’ hydration status did not vary by sex or season (23°C vs. 29°C).

The importance of hydration on physical performance specific to the work place has not been well studied. However, Cheung and McLellan (88) and McLellan et al. (315) showed that exercise tolerance time in men wearing nuclear, biological, and chemical protective clothing during light (3.5 km/h, 0% grade at 40°C), moderate (4.8 km/h, 0% grade at 35°C), and heavy (4.8 km/h, 4% grade at 40°C) treadmill exercise was significantly reduced by ~2% hypohydration compared to euhydration. One study has experimentally compared the impact of hypohydration vs. euhydration on manual labor productivity. Wasterlund and Chaseling (460, 461) found that forest workers were 12% slower in stacking and debarking 2.4 m³ of pulpwood when they were given limited fluid (resulting in mean body mass deficit of 0.7 kg) versus when they were provided enough fluid to fully replace sweat losses. It is well-documented, however, that mood, fatigue levels, alertness, and cognitive performance can be adversely affected by hypohydration, especially when combined with heat stress (96, 97, 198, 430, 443). Importantly, not only can hypohydration impair job performance, but also worker health and safety. Because orthostatic tolerance is affected by hydration status, job-related accidents from fainting are a potential outcome of working in a hot environment while dehydrated. Additionally, postural balance has been shown to be impaired by hypohydration (135, 139, 181). A direct cause-effect relation between hypohydration and work-related accidents has not been established. However, a classic study by Vernon (494) showed that accident rates were highest in the summer (hot) months (peaking in July and August), when sweating rates and risk for hypohydration is highest, and lowest in the winter (cold) months.

Regarding the composition of a fluid-replacement beverage for workers, the same general concepts discussed for athletes would also apply to workers for maintenance of physical and cognitive function. Carbohydrate is important for maintenance of blood glucose concentration and supplying fuel to the muscles and brain during prolonged work. Cuddy et al. (121) measured the effect of supplemental liquid carbohydrate feedings on work output during wildfire suppression. Subjects were given 200 mL of either a 20% carbohydrate solution or placebo every hour during a 12-h shift in addition to their sack lunch. The group consuming carbohydrate supplementation experienced significantly higher blood glucose concentration and self-selected work rates (activity counts) than the placebo group, particularly during the latter hours of the shift. However, the amount of carbohydrate included in a fluid-replacement beverage should be customized to the workers’ energy demands. The firefighters in this study (121) were performing arduous work, whereas work intensity and therefore carbohydrate intake requirements may be lower in other occupations. For instance, Miller and Bates (322) suggested that a fluid replacement beverage should by relatively low in carbohydrates, to avoid excessive calorie intake since workers exposed to a hot environment can consume a high volume of fluid over a shift.

Inclusion of salt in a fluid-replacement beverage may be important if sweat electrolyte losses are high. Shearer et al. (431) studied South African gold miners who presented with heat disorders during strenuous work in extremely hot and humid conditions at depths up to 3500 m. They reported that the miners who suffered from heat cramps had significantly lower serum sodium concentrations and drank significantly more water than the miners who suffered from collapse. Thus, the authors suggested that miners be provided with electrolyte tablets to reconstitute in their standard water bottles (for a 0.1% saline solution). People are commonly advised to limit salt intake, because of its association with hypertension. However, this can exacerbate a workers risk for hyponatremia, especially when salt avoidance is paired with excessive water intake (50). Moreover, Roberts (393) showed that increased daily sodium intake through consumption of 4.5 L/d (8.4-h shift) of a carbohydrate (333 mmol/L) electrolyte (18 mmol/L sodium, 3 mmol/L potassium) solution or an electrolyte (18 mmol/L sodium, 3 mmol/L potassium) solution by normotensive tree planters for one month had no impact on resting blood pressure compared to workers who drank only water during their shift.

Two studies by Clapp et al. (99, 100) have observed beverage preferences and voluntary fluid intake behavior in an industrial setting. In a parallel-designed study, Clapp et al. (100) provided workers with water or a 6% carbohydrate electrolyte solution during a simulated 4-h work shift (intervals of 30-min moderate intensity followed by 30 min rest) in 18, 23, and 27°C Wet Bulb Globe Temperature (WBGT) conditions. In all conditions, the carbohydrate-electrolyte solution was rated more palatable and consumed at a higher rate than the water. In a follow-up study employing the same simulated work protocol at 33°C WBGT, Clapp et al. (99) provided subjects ad libitum access to lime colored water, lemon-lime placebo, lemon lime 6% carbohydrate solution with 18 mmol/L of sodium, and lemon lime 6% carbohydrate solution with 36 mmol/L sodium in a crossover design. Subjects drank more and tended to experience less body mass deficit in trials in which the 6% carbohydrate electrolyte solution (~0.01% with 18 mmol/L, +0.11% with 36 mmol/L) was provided compared with the water (~0.55%) or placebo beverage (~0.31%).

Fluid intake recommendations from organizations such as Occupational Safety and Health Administration (OSHA), American Conference of Industrial Hygienists (ACGIH), and National Institute for Occupational Safety and Health (NIOSH) are vague and do not take into account variations due to environmental conditions, protective clothing, or work intensity (268). OSHA and ACGIH recommend providing cool nonalcoholic liquids to workers and encourage them to drink about one cup (237 mL) every 20 min (268). NIOSH simply recommends that drinking water should be readily available to workers exposed to the heat (268). Review papers
on fluid replacement guidelines for heat-exposed workers suggest that a beverage with 4% to 8% carbohydrate and 10 to 30 mmol/L sodium may induce greater voluntary intake, aid rehydration, improve work performance, and delay the onset of fatigue (98).

Military

Military personnel are faced with a wide array of challenges posed by the environment, including heat and/or altitude exposure. Because of these environmental stressors and the physical demands of military operations, body mass deficits of 2% to 3% from profuse sweat loss are common among military troops (3, 230). In one study Gopinathan et al. (198) induced 1%, 2%, 3%, and 4% hypohydration (in separate trials) in soldiers by combined water restriction and exercise heat stress and found a significant deterioration in arithmetic ability, short-term memory, and visuomotor tracking at ≥2% hypohydration. Adequate fluid replacement is of utmost importance for maintenance of physical and cognitive performance on the battlefield.

Another threat to soldiers’ hydration status is traveler’s diarrhea. In fact, it is among the most common reasons for clinic visits unrelated to battle injury (58). Although there is some debate as to whether rehydration should be initiated with oral rehydration solutions or intravenous therapy, partly because of the paucity of data on the use of oral rehydration solutions specific to travelers’ diarrhea, both methods are thought to be effective.

Mineral losses can also be substantial in military personnel because of the sweat loss induced by the physical and environmental stressors of training or combat. Sweat mineral concentration in uniformed soldiers (collected/measured using the arm glove technique) is similar to that reported in studies with civilians (27). However, because soldiers are physically active and exposed to environmental extremes for very prolonged periods of time (hours or days at a time) total mineral losses are likely higher than that of the general population. Armstrong et al. (27) demonstrated that fluid and electrolyte (sodium, chloride, potassium, calcium, and magnesium) losses of soldiers in various uniform configurations (temperate battle dress and full military protective posture with or without mask and hood) during intermittent treadmill walking for 6 h in the heat (30°C) exceed that of normal daily intake, thus warranting dietary supplementation in similar conditions.

Potassium deficiencies have also been documented in the military. Knochel et al. (271) measured potassium balance in healthy young Army recruits who were undergoing basic training in Fort Sam Houston, Texas. Total body potassium (exchangeable 42K) as well as potassium intake and output (sweat and urine) were measured during the winter and summer seasons. Total body potassium deficiency developed in the recruits during training in the summer, but not in the winter, suggesting that sweat potassium losses accounted for the deficiency. Moreover, military surveys suggest that soldiers’ mineral intakes may be inadequate, that is, less than Dietary Reference Intakes (240).

It has been suggested that a carbohydrate-electrolyte solution may be necessary for soldiers in some military situations, including when: sweat losses are large, performing > 60 min of exercise, dietary intake at meals is limited due to interruption or heat-induced anorexia, or ill with diarrheal disease (20). In addition to energy provision and water/electrolyte replacement, beverage palatability is also an important formulation consideration. Szlyk et al. (475, 476) completed a series of studies showing the effect of beverage characteristics on ad libitum intake of soldiers during actual or simulated training. For example, in 1989 (476), they reported that either flavoring or cooling (15°C) water enhanced voluntary fluid intake and reduced body mass deficits during 6 h of treadmill exercise in a hot environment, particularly in men who were typically reluctant to drink.

In addition to hypohydration, other stressors such as sleep deprivation, physical fatigue, and psychological stress also jeopardize the troops’ cognitive function and mood. During an observational study, highly trained U.S. Army officers from an elite combat unit participating in a 53-h simulated combat training exercise incurred a body water deficit of 6.3% and slept only 3 h. The multiple stressors resulted in substantial degradations in vigilance, reaction time, attention, memory, and vigor in the soldiers from pre- to postexercise (293).

Several research studies have addressed the potential utility of various substances, including caffeine, carbohydrate, and tyrosine in maintaining cognitive function specific to military applications (291). Lieberman et al. (295) found that, compared to placebo, caffeine significantly improved vigilance, reaction time, and alertness in Navy SEAL trainees after 72 h of sleep deprivation. Similarly, improvements in marksmanship sighting/target detection time (483, 485) and accuracy (316) have been reported with caffeine ingestion compared with placebo during military training involving sleep deprivation and operational and environmental stress. Providing supplemental carbohydrate energy to a military unit during sustained simulated combat operation has been shown to have beneficial cognitive effects. Lieberman et al. (294) randomly divided 143 male soldiers into three groups who received either a placebo beverage, a 6% carbohydrate, or a 12% carbohydrate (primarily maltodextrin) beverage on six occasions during a 10-h test day. They found that auditory vigilance improved with carbohydrate in a dose-related manner; that is, performance was best with 12% carbohydrate (70 kJ/kcal), intermediate with 6% carbohydrate (35 kJ/kg), and worst with placebo (0 kJ/kg).

The ingestion of tyrosine, a dietary precursor for catecholamine synthesis, may have important military application. Tyrosine ingestion in doses of 100 to 300 mg/kg has been successful in offsetting decrements in cognitive function during tasks relevant to military operations. For example, Baner and Lieberman (36) found that during a combined stress of cold and hypoxia, performance on cognitive tests (addition, coding, map/compass, pattern recognition, and reaction
time) was better with tyrosine ingestion compared to placebo. Acute tyrosine administration was also associated with improvements in memory and psychomotor task performance during extended wakefulness (342) and cold exposure (354, 448) in healthy young adults. The discrepancy between these positive findings and the exercise literature (discussed above) may be related to the severity and duration of stress experienced in military versus sport settings. It is possible that the stress experienced in the exercise studies has not been sufficient to deplete catecholamine supply and therefore physical and cognitive performance is unaffected by tyrosine administration in a sporting context (503).

**Altitude exposure**

Exposure to altitude such as during mountain climbing, back-packing, and military training/operations can result in marked fluid losses. Hypohydration in this situation often occurs despite cool ambient temperatures and low sweating rates. At altitude the main source of hypohydration (aside from urination) is from insensible water loss, primarily respiration (125). Two main factors are involved in high respiratory water loss at altitude. First, hyperventilation that is stimulated at altitude increases the rate of water loss. Also, the ambient air becomes drier with increases in altitude, resulting in the inhalation of dry air (in exchange for moist exhaled air). This results in respiratory water losses \(~\sim 200\) mL/day above that at sea level (228). To complicate matters, altitude exposure results in diuresis and natriuresis during the initial days of exposure. This is a normal physiological response to enter the hypobaric/hypoxic environment (228), although it comes at the cost of a reduced blood volume, stroke volume and cardiac output. In fact, plasma volume has been found to decrease by as much as 28% in subjects at 4600 m for 1 to 4 months (378). To further complicate matters, voluntary fluid and sodium intake is lower at altitude because of a decrease in thirst/appetite, limited fluid availability, and/or misjudging of fluid losses because of cool ambient temperatures (378). Field studies have found 1.5 to 2 L decreases in total body water, accounting for about 50% of total body mass loss, by men climbing for a 10 to 12 day expedition at 4300 m (107, 226). In a series of classic studies conducted at more extreme altitudes of 5790 m, Pugh (378) found that whole body water turnover increased from 2.9 L/d at sea level to 3.9 L/d at altitude. During days in which the men climbed 5 to 7 h/d, water turnover further increased to 5.0 L/d. The type of hypohydration experienced at altitude is iso-osmotic hypovolemia, provided that substantial sweat losses do not contribute significantly to body water loss. A more detailed discussion of the physiological mechanisms controlling body fluid volume and sodium and water metabolism during acute and chronic hypoxia can be found in reviews by Hoyt and Honig (227, 228).

While a decrease in total body water is thought to be necessary for successful adaptation to hypoxic environments, the impact of hypohydration on the incidence/severity of acute mountain sickness (symptoms include headache, nausea, vomiting, dizziness, lassitude, and weakness) and physical performance at altitude has not been well studied (228). Throughout the literature, hypohydration has been reported to both alleviate and exacerbate the development/severity of acute mountain sickness. Early reports (173) suggested that diuretics prevented or alleviated symptoms of acute mountain sickness. By contrast, Aoki and Robinson (17) showed that this practice did not affect acute mountain sickness symptoms at a simulated altitude of 14,000 ft (4267 m) for 40 h. Disagreement between reports may be due to differences in acute mountain sickness severity. The former study (173) involved pulmonary edema, therefore it stands to reason that diuretics would be the most rapid and effective treatment. Other studies suggested that hypohydration may worsen acute mountain sickness (41, 122, 387, 388). For example, Richardson et al. (387) tested the effects of euhydration versus progressive hypohydration and found that hypohydration greater than 2% is associated with higher acute mountain sickness symptom scores than euhydration. Castellani et al. (84) were the first to experimentally evaluate the effect of hypohydration on aerobic exercise performance at altitude. Whereas Aoki and Robinson (17) evaluated iso-osmotic hypovolemia (via diuretic-induced hypohydration), Castellani et al. (84) induced hyperosmotic hypovolemia/hypohydration with exercise-heat stress the day prior to experimental trials/altitude exposure. Hypohydration was induced this way to mimic the type of hypohydration commonly experienced by military personnel and recreational climbers/trekkers (as a result of exercise-induced sweat losses). They found that 4% hypohydration and simulated altitude at 3048 m in a warm (27°C) hypobaric chamber reduced cycling time trial performance (total kJ work completed in 30 min preceded by 30 min submaximal steady state cycling) in an additive manner. Compared to performance at sea level in an euhydrated state, hypohydration reduced performance by 19%, altitude reduced performance by 11%, and the combination reduced performance by 34%. However, there was only a tendency for acute mountain sickness prevalence and severity to be higher in the hypohydration trials.

One fluid replacement study at altitude has compared beverages of different compositions. Yanagisawa et al. (520) compared ingestion of a carbohydrate-electrolyte solution versus water on urinary output and plasma volume during the early stage of high altitude training in male university students who were ski training at an altitude of 1800 m. All 16 of the skiers consumed the same meals, but 8 of them were given 2.5 L/d of water and the other 8 skiers were given 2.5 L/d of a carbohydrate-electrolyte beverage (4.7% carbohydrate and 15 mmol/L sodium). After 2 days, total urine volume was significantly lower in the group drinking the carbohydrate-electrolyte beverage, but the change in plasma volume was not different between groups. Performance and acute mountain sickness symptoms were not measured. More work is needed to determine the optimal
composition of fluid replacement beverages during high-altitude exposure.

**Flights**

Air travel, especially long-haul flights, is characterized by prolonged confinement with reduced physical activity and food/fluid intake and increased psychological stress (e.g., anxiety) (208). In addition, air pressure and humidity in the cabin while in flight are lower than on the ground (e.g., at sea-level). These factors can contribute to body fluid shifts and an increased risk for hypohydration during air travel (208). Prolonged periods of sitting are known to result in lower body edema. When the calf “muscle pump” becomes inactive, blood is not propelled up to the heart as quickly as normal. Lower extremity edema is associated with fluid movement into the interstitial space, which results in hypovolemia and hemoconcentration (432). One study measured a ∼6% to 9% decrease in plasma volume in 10 healthy young men after 10-h of simulated air cabin conditions at 2800 m (539 mmHg, 21-23°C, 25%-33% relative humidity, moderate confinement in an altitude chamber) (208). Increased insensible water loss through the skin and respiration (from reduced cabin water vapor pressure) and decreased fluid intake (due in part to the desire to avoid needing to urinate while in flight) are also thought to contribute to in-flight hypovolemia (208). It has been suggested that hypovolemia may contribute to the signs and symptoms associated with “jet lag” (fatigue, malaise, headache, irritability, and general discomfort) (208).

One study has evaluated the efficacy of fluid replacement beverages as a countermeasure to hypovolemia during a simulated long-haul flight at 2800 m. Greenleaf et al. (208) confined 10 healthy young men to an altitude chamber (21-23°C, 25%-33% relative humidity, 539 mmHg) for 12 h. Subjects spent most of the time in a semi-reclining position (reading, watching nonstressful video, or doing computer work), but were allowed to get up and walk around as desired. Dietary intake was controlled during the experiment and consisted of a simulated airline lunch and dinner as well as a total of 960 mL of nonalcoholic fluid. Ten hours into the simulated flight, subjects drank 12 mL/kg of either a high sodium, low carbohydrate drink (185 mmol/L sodium, 0 mmol/L potassium, and 5 mg/dL glucose), a low sodium, high carbohydrate drink (21.6 mmol/L sodium, 4.4 mmol/L potassium, and 1996 mg/dL glucose), or water over a 30 min period. Two hours after beverage ingestion, plasma volume was restored (not significantly different from baseline) with the carbohydrate-electrolyte solutions but was 8% below baseline with water. The restoration of plasma volume with ingestion of the carbohydrate-electrolyte solutions was attributed to lower urinary output compared with ingestion of water. Urine volume during rehydration was not different between the two carbohydrate-electrolyte beverages (208).

Although there is no direct evidence linking hypohydration to the risk or prevention of venous thromboembolism (481, 502), only one study has tested the effect of beverage composition on hydration and blood viscosity during long plane flights. Hamada et al. (218) gave forty young healthy men ∼1.3 L of either a carbohydrate-electrolyte solution or water in five aliquots during a 9-h flight. The men who drank the carbohydrate-electrolyte solution had a lower urine output and less viscous blood than those who drank water. Similarly, Chang et al. (87) found that ingestion of a carbohydrate-electrolyte solution (21 mmol/L sodium, 5 mmol/L potassium, and 66 g/L carbohydrate) resulted in significantly lower blood viscosity in young healthy men during rehydration from 2.2% exercise-induced hypohydration than ingestion of tea or water.

**Special considerations**

**Children**

Physical activity is important for the enhancement and maintenance of children’s health (48). However, physical activity in the heat can place significant strain on the body and increase the risk for heat-related illness or injury. Prepubertal children are anatomically and physiologically unique from adults in that they exhibit lower sweating rates than adults and have a higher body surface area-to-mass ratio. Sweating capacity (sweating rate per unit body surface area and sweat production per gland) has been consistently found to be much lower in boys than men (65, 157, 318). Fewer data are available on female subjects, but sweating rate seems to be similar between girls and women. For example, Brown et al. (65) compared sweating rates of 10 to 12 year old boys and girls to that of adult men and women while running on the treadmill for 1 h in a warm environment. There was a significant difference in male subjects, as sweating rate was 332 ± 184 mL/m²/h versus 896 ± 310 mL/m²/h in boys versus men, respectively. By contrast, there was no significant difference in the sweating rate of girls (403 ± 147 mL/m²/h) vs. women (564 ± 197 mL/m²/h). Rivera-Brown et al. (392) found similar results when comparing the sweating rates of premenarcheal girls (546 mL/m²/h) and young adult women (720 mL/m²/h). Although sweating rate is lower in prepubertal boys than adult men, the magnitude of hypohydration is similar when expressed as percentage change in body mass (142, 317). In a review paper based on six studies comparing sweating rates in children versus adults, Meyer and Bar-Or (317) calculated the percentage hypohydration which would have accrued after 1 h of exercise in the heat without fluid replacement. The level of predicted hypohydration ranged from 0.40% to 2.41% across the six studies, but was similar between children and adults in each study.

Since heat transfer between the environment and the body depends on the surface area of the body exposed to the environment, children absorb heat faster than adults when ambient temperature exceeds skin temperature. Having a higher body surface area and lower sweating capacity means that children rely to a greater extent on radiation (when ambient temperature is lower than skin temperature) and convection rather than evaporation of sweat to dissipate body
heat. Because of these differences, children were traditionally thought to tolerate exercise in the heat more poorly than adults. However, recent studies indicate that there are no age differences in body core temperature or exercise tolerance when direct adult-child comparisons are made and subjects are exercising at the same relative intensity (237, 392, 405, 407). The lack of an age difference in exercise-heat tolerance may be due in part to a greater convective heat loss capacity (higher skin blood flow) (157, 302, 439) and/or a greater sweating efficiency (ratio between evaporative heat loss and total sweating rate) (237) in children, which would compensate for their lower sweating rate. Thus, as long as the ambient temperature is no more than 5 to 7°C above skin temperature (i.e., ambient temperature <42°C), children regulate their body core temperature as effectively as adults during <1 h of exercise. However, in extremely hot environments (>45°C) children’s ability to dissipate heat is compromised and exercise tolerance is significantly lower than that of young adults (38).

Like adults, children and adolescent athletes often begin practice in a hypohydrated state (130, 471). For example, Stover et al. (471) reported high average USG (>1.020) in adolescent American football players during five consecutive days of two-a-day training. However, hypohydration during exercise tends to be lower in children than adults. In ad libitum fluid intake studies when water and a flavored drink were available hypohydration was typically <1% to 2% (40, 391, 512). In some cases hypohydration was avoided altogether, particularly when a flavored beverage was available (391, 512, 513). For example, heat-acclimatized boys maintained euhydration (+0.18%) with a flavored 6% carbohydrate solution with 18 mmol/L sodium, but incurred mild hypohydration (-0.94%) when only unflavored water was available during 3 h of interval cycling in the heat (≈30°C) (391). Most of the aforementioned studies involved testing of normally active healthy children in controlled laboratory conditions. Higher levels of hypohydration have been observed in some athletes during competition. Wilk et al. (511) measured body mass in ninety-two 8- to 17-year-old girls and boys before and immediately following the Costa Rica National Triathlon Championship (34-35°C). Approximately 15% of the junior (8-13 years of age) athletes and 20% to 30% of the senior (14-17 years of age) group lost 2% to 3% body mass and ~7% of the senior boys lost more than 3% of their body mass during the race.

There is limited data on the effects of hypohydration on physical performance in children. Compared to euhydration, Wilk et al. (514) found that 1% to 2% hypohydration impaired endurance performance in 10- to 12-year-old boys and Dougherty et al. (141) found that 2% hypohydration impaired basketball shooting accuracy and sprinting in 12 to 15 year old boys.

Prepubertal and pubertal boys and girls have been found to have a lower sweat sodium and chloride concentration than young adults, whereas there are no maturational differences in sweat potassium concentration (318). With the combination of lower sweating rates and lower sweat sodium concentration, total-body sodium losses during exercise are approximately half that of adults (when cycling at 50% VO2 max in the heat (42°C)) (318).

Children also differ physiologically from adults in their substrate utilization during exercise. They have smaller endogenous carbohydrate stores and lower glycolytic capacity, but exhibit higher fat oxidation rates and a higher oxidative capacity during exercise (250). It has also been suggested that children exhibit greater oxidation of exogenous carbohydrate compared to men. Timmons et al. (486) fed boys and adult men a 13-C-enriched 6% carbohydrate beverage during 60 min of cycling at 70% VO2 peak. They found that exogenous carbohydrate was oxidized at a significantly higher rate and provided a significantly greater relative proportion of total energy in boys than in men. However, the biological mechanism to explain this finding is unclear. As discussed previously, the rate limiting factor in carbohydrate oxidation is the rate of its absorption in the intestine (247, 251, 252); however, there is no evidence that intestinal carbohydrate absorption differs between children and adults (19, 523). Other potential mechanisms have been suggested (see Ref. 250 for review), but more research is needed to better understand carbohydrate oxidation in young athletes, especially highly trained young athletes.

Carbohydrate intake by children has been found to improve performance during various types of exercise, including a cycling time trial (389), basketball skills (141), and intermittent high-intensity shuttle running (372). A 6% carbohydrate solution was used in all three of these studies. An 8% carbohydrate solution has been associated with negative gastrointestinal symptoms during intermittent high-intensity exercise in adolescents (435), which is a similar response as that of adults (335). A dose-response study has not yet been conducted in children to determine the optimal carbohydrate concentration of a fluid replacement beverage during exercise.

According to the 2011 American Academy of Pediatrics policy statement on climatic heat stress and exercising children and adolescents (48) they recommend that fluid should be consumed at regular intervals to offset sweat loss and maintain adequate hydration while avoiding overdrinking. They suggest that water is generally sufficient when activity is less than 1 hour, but sodium-supplemented beverages may more effectively rehydrate individuals when activity is prolonged (≥ 1 h), involves repeated bouts of strenuous exercise/sport participation in one day, or when sweat loss is extensive (warm-to-hot weather conditions) (48). In a clinical report on sports drinks and energy drinks for children and adolescents, the American Academy of Pediatrics stated that pediatric athletes can benefit from sports drinks since they supply carbohydrate substrate to delay fatigue and maintain performance during prolonged, vigorous exercise (425). However, sports drinks are not generally necessary for less active youth and are contraindicated to replace water or low-fat milk during meals or snacks. In the same report, American Academy
of Pediatrics stated that energy drinks, containing stimulants such as caffeine and guarana, have no place in the diets of children and adolescents (106, 241), as they may be particularly vulnerable to the potentially adverse effects (including its effects on development and risk of physical dependence and addiction).

Older adults

Older individuals (> 60 years) have been characterized as being more susceptible to hypohydration than younger adults due to a deficient thirst response and an impaired ability of their kidneys to conserve water and sodium (321, 371). The attenuated renal function in older individuals has been attributed to the progressive decline in the number of functioning nephrons with age (402). Additional factors, such as impaired release of, or renal responsiveness to, plasma antidiuretic hormone and reduced renin-angiotensin-aldosterone system activity may also contribute to the age-related impairment of sodium and water conservation (402). The result is that the kidneys of healthy older individuals cannot concentrate urine as well as young adults. For example, in one study, the maximal urine osmolality of older (average 79 years) and young (average 24 years) men was 808 and 1089 mOsm/kg, respectively (140). This resulted in higher obligatory water losses by older adults compared to the young men (140).

Research (462, 464) suggests that the blunt thirst response with aging is due to attenuated low pressure baroreceptor sensitivity, while osmoreceptor sensitivity is intact. In one study, Stachenfeld et al. (464) infused older and younger adults with hypertonic saline to induce hyperosmotic hypervolemia and found that both groups voluntarily drank sufficient water during a 180 min recovery period to restore preinfusion plasma osmolality. In another study (462), older and younger adults dehydrated by overnight water restriction and subsequent exercise-heat stress. Subjects then recovered with or without head-out water immersion. By forcing blood volume centrally, head-out water immersion minimizes hypovolemia. In the younger adults, head-out water immersion caused an immediate fall in thirst and voluntary fluid intake. However, a similar central blood volume expansion had no effect on thirst in the older adults.

Inadequate fluid intake following hypohydration has implications for chronic adaptation to exercise-heat stress. Increased fluid intake during a heat acclimation regimen is critical for plasma volume expansion. Takamata et al. (477) and Zappe et al. (524) found that inadequate fluid intake in older men during recovery from 4 to 6 days of exercise-heat stress contributed to an inability to expand plasma volume. The younger men replaced significantly more of their fluid losses 2 h after exercise [80% vs. 34%; (477)] and increased their 24-h fluid intake to a greater extent [45 mL/kg/day vs. 32 mL/kg/day; (524)] than the older men. Subsequently, the younger men experienced a ~5% to 10% increase in plasma volume following repeated exercise-heat exposure, whereas the older men did not (477, 524).

Pathophysiologic factors

Some pathophysiological factors can increase water and/or electrolyte losses above normal ranges. For example, uncontrolled diabetes mellitus is associated with osmotic diuresis and thus increases the risk for hypohydration (239). The increased urine output is due to hyperglycemia-induced glycosuria and ketoadiduria. In addition, some medications, such as diuretics or lithium, stimulate urinary water loss. On the other hand, anticholinergic drugs can cause dry mouth and thus indirectly stimulate water intake (239).

A condition which increases sweat electrolyte losses is cystic fibrosis. Because of the genetic absence of a functioning cystic fibrosis transmembrane conductance regulator, sweat ducts of cystic fibrosis patients are limited in their ability to reabsorb sodium and chloride. In fact, the salt concentration of cystic fibrosis patients may be up to 3 to 5 times the normal concentration (150, 197, 403). The excessive loss of electrolytes can lead to a decrease or an attenuated rise in serum sodium concentration and serum osmolality during sweating-induced dehydration (64, 359). This presumably puts individuals with cystic fibrosis at a potentially greater risk for hyponatremia. It has also been speculated that cystic fibrosis patients are more susceptible to involuntary dehydration because of a decreased osmotic trigger for thirst. Cystic fibrosis patients have been found to drink less and incur significantly greater levels of hypohydration compared to age-matched controls during prolonged exercise in the heat (39). However, it appears that the lower ad libitum fluid intake exhibited by cystic fibrosis patients may not be due to a diminished thirst sensation but rather a physiological cue directed at preserving salt balance (64). In a recent study, Brown et al. (64) found no differences in thirst after prolonged cycling in the heat without drinking (to 3% hypohydration) between individuals with high and low sweat sodium. However, ad libitum fluid intake of a 20 mmol/L sports drink was 40% less in the cystic fibrosis group than that of the low sweat sodium group. The authors speculated that the lower volitional drinking response may have been influenced by the hypotonicity of the drink, as all of the cystic fibrosis subjects reported having strong salt cravings. Accordingly, another study, involving children with cystic fibrosis, found that a flavored drink with a very high sodium concentration (50 mmol/L) significantly enhanced drinking and attenuated voluntary hypohydration compared to a flavored drink with lower sodium (30 mmol/L) or water (274).

Conclusion

In this article, we have discussed various conditions in which perturbations of body fluid homeostasis occur and the physiological consequences of such fluid imbalances. We have also discussed considerations for the optimal composition of beverages to mitigate disturbances to physiological function and physical performance in various populations and applications.
Advances in our understanding of the optimal composition of fluid replacement beverages to replace fluid and electrolyte losses have stemmed largely from research regarding diarrheal diseases as well as individuals (e.g., laborers, military, or athletes) who incur large sweat losses from prolonged exercise and/or heat stress. This research has provided insight as to how the carbohydrate and electrolyte composition of a beverage impacts the intake, absorption, retention, and distribution of fluid and solutes for restoration of large fluid losses. Many other conditions or situations may arise in which challenges to fluid homeostasis occur through increased urinary or respiratory water losses, impaired thirst, or decreased voluntary fluid intake (e.g., exposure to microgravity or altitude, aging or disease states, use of certain medications, and psychological stress). A fluid-replacement beverage may also serve as a convenient vehicle to deliver nutrients (other than water) to augment physiological function. The optimal fluid replacement beverage is one that is customized according to the specific physiological needs, environmental conditions, desired performance, and individual characteristics and taste preferences.

Acknowledgements

Authors Lindsay B. Baker and Asker E. Jeukendrup are employees of the Gatorade Sports Science Institute, a division of PepsiCo, Inc. The views expressed in this article are those of the authors and do not necessarily reflect the position or policy of PepsiCo, Inc.

References


