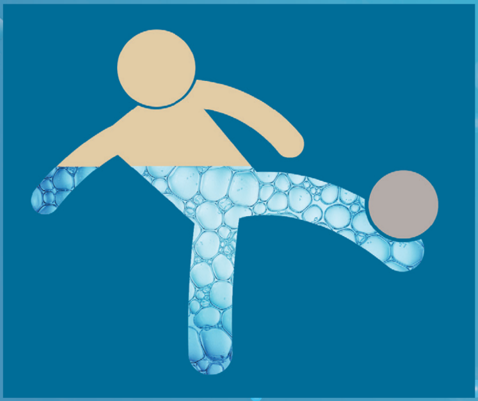
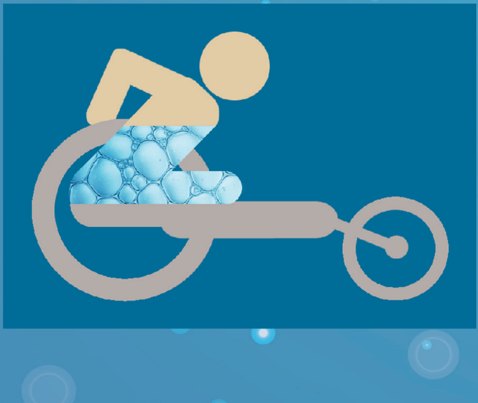
Fluid Balance, Hydration, and Athletic Performance





Edited by
Flavia Meyer
Zbigniew Szygula
Boguslaw Wilk

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Dedication

In memory of Professor Oded Bar-Or, MD (1937–2005), with thanks for his mentorship and valuable scientific guidance that has been leading us throughout our professional lives

Flavia Meyer
Zbigniew Szygula
Boguslaw Wilk

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SECTION IV Recommendations

Preface

This book presents a comprehensive review of aspects relating to body fluid balance, rehydration, sport, and physical exercise. The content is scientifically supported, practical, and suitably written for a range of audiences, including academics (professors and students) and sports and health professionals (coaches, physical educators, nutritionists, and physicians), as well as athletes and individuals involved in physical activities.

Compared to other books previously published in this area, *Fluid Balance, Hydration, and Athletic Performance* does not limit body hydration issues to the average or elite adult athlete; it also addresses aspects relevant to a range of individuals of different ages (adolescents and master athletes) competing in various sports. In recognition of the growing number of individuals with specific medical conditions who have been exercising more and even participating in competitive sports, separate chapters on prevalent diseases or medical conditions associated with risks of body fluid homeostasis are also presented. To achieve such a complete and qualified publication, the book is written by top experts and professionals experienced in their respective research areas.

The book presents the basics of fluid balance and provides updates on controversial fluid intake–related issues such as hyponatremia, optimal recovery, intermittent sports, and perceptual responses.

We hope that readers will find this book useful and easy to apply to their respective theoretical and/or practical needs.

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Editors

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Dr. Meyer's doctoral thesis involved a series of original studies on fluid balance, thermoregulation, and hydration in exercising youth. Dr. Meyer has researched and published in the field of pediatric exercise and nutrition science, and more specifically in hydration, thermoregulation, obesity, and chronic diseases.

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Dr. Wilk's main research interest areas are, fluid and electrolyte replenishment in the exercising child and adult, and thermal regulation and tolerance of exercise in high and low environmental temperatures in health and disease. Throughout Dr. Wilk's research and clinical roles, he has continued publishing in a variety of scientific journals as well as serving as a referee and a member of international scientific editorial boards.

Dr. Wilk was previously a member of several scientific organizations in Poland and North America, and he is currently a fellow of the American College of Sports Medicine.

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Section I

The Fundamentals

1 Body Water

Balance, Turnover, Regulation, and Evaluation

Craig Horswill and Jeremy Fransen

CONTENTS

1.1 INTRODUCTION

Undeniably, water, the nutrient comprising the greatest percentage of mass in the human body, has the most dramatic impact on function and structure when its balance is upset. The human body is resilient to some change. However, during physical activities, such as athletics, the effects of water deficit can be magnified to that point where physical and mental functions are diminished. Additionally, depending on the extent of water imbalance, the safety and well-being can be at risk.

Specific functions that water serves in the body include providing the medium for metabolic reactions, serving as a *substrate* or a reactant for specific reactions, transporting nutrients and waste products to specific locations, contributing in several ways to thermoregulation, and contributing to lubrication. For the athlete, transport of nutrients and waste and thermoregulation are especially critical roles in the body. The athlete's ability to sustain performance and avoid fatigue is in many ways attributed to the maintenance of homeostasis with substrate availability, transport of metabolites, and transfer of heat from the muscle, all of which require adequate blood flow at some point during the performance. Blood flow is highly dependent on having adequate blood volume, which hydration status will impact.

The objective of this chapter is to provide an overview of hydration of the athlete's body. Our review will include defining total body water (TBW) and its components; defining water balance and turnover; identifying the factors that influence water balance particularly during exercise; describing mechanisms of body water regulation to ensure balance is maintained; and identifying and describing methods of assessing hydration status and the state of fluid balance. In the spirit of this textbook, care will be taken to provide examples and data that are most relevant to the athlete.

1.2 TBW AND ITS COMPONENTS

The cumulative water volume in the body is called *total body water*. TBW comprises about 50%–65% of body weight (Mack and Nadel 2011; Schoeller 2005). In the reference adult male of 70 kg and 15% body fat, his body water volume is approximately 42 L. TBW is dependent on age, gender, and body composition. TBW is highest in infants (~70%) and decreases over the lifespan. Much of the age-associated decline in TBW is due to the increase in body fat, which decreases the percentage of TBW. Likewise, women usually have a higher body fat percentage than men, and therefore, TBW average about 50% of total body weight. Because body mass is highly variable based on the fat mass, and fat mass is essentially anhydrous, the TBW as a percentage of body mass is a poor indicator of the hydration status. In Section 1.5 of this chapter, we will return to the topic of hydration assessment.

TBW is compartmentalized into extracellular fluid (ECF) space and intracellular fluid (ICF) space. The ECF is further divided into the blood plasma found in the vascular space, and the interstitial fluid, which baths the cells but is outside of the vascular space. One other general ECF compartment that can be identified but will not be discussed further in this chapter is the transcellular space. This includes fluids in the cerebrospinal space, intraocular space, synovial space, and peritoneal and pericardial spaces. The total combined transcellular fluid amounts to approximately 1–2 L.

1.2.1 Extracellular Fluid

The fluid outside the cell is called the *extracellular fluid*. The ECF is divided between the interstitial fluid, which is approximately 11 L, and the blood plasma, which equals about 3 L (Mack and Nadel 2011; Schoeller 2005). Therefore, for the average 70 kg man, the ECF totals approximately 14 L. The plasma is the fluid of the blood that does not contain cells. The plasma is in continuous exchange with the interstitial fluids through pores in the capillary membrane. Therefore, with the exception of higher concentrations of proteins in the plasma, the plasma and interstitial fluids have about the same composition. The ECF contains a high concentration of chloride and sodium ions with low concentrations of potassium, calcium, phosphate, and magnesium.

1.2.2 Intracellular Fluid

The fluid inside the cells is called the *intracellular fluid*. The ICF is about 28 L or approximately 40% of total body weight of the average person (Mack and Nadel 2011; Schoeller 2005). In contrast to the ECF, the ICF contains high concentrations of proteins, potassium, and phosphate and low concentrations of sodium and chloride.

1.2.3 Plasma Volume

The plasma volume is the extracellular component of the blood volume. Blood plasma is nearly 95% water that contains dissolved proteins, clotting factors, electrolytes, glucose, hormones, and small amounts of oxygen and carbon dioxide. Besides plasma volume, the blood volume is also composed of ICF most of which is contained in the red blood cells. In the resting, normally hydrate state, roughly 60% of the blood is plasma with the remaining 40% red blood cells in humans. For the average adult, the blood volume equals about 7% of body weight or approximately 5 L (Astrand and Rodahl 1977).

1.3 WATER BALANCE AND TURNOVER

1.3.1 Balance and Euhydration

TBW is constantly changing with gains and losses of fluid even in the sedentary, weight-stable adult. The volume is regulated through a complex system of exchange of fluids, solutes, and ions within the compartments in the body and also influenced

TABLE 1.1
Routes and Rates of Daily Fluid Loss in Sedentary Human

Route of Loss	Volume (L/24 h)
Insensible from skin and breath (water vapor)	700 ml
Feces	100 ml
Urine	0.5–20
Sweat	0.1–7.0

Source: Horswill, C. A., *Int. J. Sport Nutr.*, 8, 175–95, 1998.

by the environment. A human is described as euhydrated or in a state of euhydration when the volume of water is that which supports good health and normal function. The assessment of hydration status will be addressed later in this chapter, but suffice to say, a single accurate and precise indicator of euhydration is yet to be identified (Armstrong 2007). To maintain the proverbial *well-hydrated* state, variable daily fluid intake or gain must match the daily losses. Water gain originates from ingested beverages and foods (~90%) and from metabolism during the oxidation of carbohydrate and lipids within the cell (~10%). Losses occur through a number of routes including insensible loss from skin, water vapor in the breath, urine production, fecal loss, and perspiration or sweating (see Table 1.1 for summary).

1.3.2 Water Turnover

Closely related to water balance is daily water turnover or the volume of body water that is exchanged in 24 h. In the sedentary adult male, daily water turnover is approximately 3.6 L, and in the sedentary adult female, it is about 3 L (Raman et al. 2004). The amount is lower in female mainly due to the smaller body mass and pool of body water. Using these data, the Institute of Medicine (IOM) has identified daily water needs to be 3.7 L/24 h for the sedentary adult male and 2.7 L/24 h for the sedentary female (Institute of Medicine 2004). Body water balance is the mathematical difference between the sum of all intakes and sum of all losses in 24 h. A positive balance indicates a water surplus and a negative balance indicates a water deficit.

1.3.3 Process of Change and Resultant States of Hydration

When fluid intake does not match fluid loss, a water deficit occurs. The process leading to a deficit is defined as *dehydration*. A human who undergoes dehydration and remains in that state is said to be in a steady-state of *hypohydration*. This can occur voluntarily such as in athletes that must make a weight class for competition or involuntarily in athletes who are at altitude or in a desert climate and may not realize the greater body water loss that has occurred. The process of fluid replacement to correct the deficit defines *rehydration*. Complete rehydration would restore euhydration. In the case of excess fluid intake that creates a water surplus, the new state produced is one of *hyperhydration*. Hyperhydration might be accomplished transiently by forced ingestion of excess fluids; however, to maintain a state of hyperhydration would require the addition of osmolytes that generate an osmotic pressure for fluid retention. Strategies to help achieve complete rehydration post exercise or hyperhydration before exercise in the heat are provided in Chapter 18 of this book.

Dehydration can occur in several ways, and the specific processes discussed here are the ones having relevance to the athlete. The most common type is referred to as *hypovolemic hypertonic dehydration,* which has also been described as *hypernatremia dehydration*. High sweat rates during training or competition typically promote hypovolemic hypertonic dehydration. Because the sweat gland draws on the plasma water to produce sweat, plasma volume decreases (hypovolemic). The sweat gland reabsorbs electrolytes, and thus, water is lost disproportionately to the ions in the vascular space. Consequently, the remaining sodium, chloride, and other ions are concentrated resulting in greater tonicity of the blood (hypertonic). Because sodium is the most prominent ion in the blood, sodium concentrations will rise above normal producing hypernatremia, which is an increase in plasma sodium concentration. Although ECF is the frontline source of water being lost, the higher tonicity or osmolality of the blood will draw fluid from the ICF. Consequently, both compartments may experience a decrease in water volume. Hypertonicity, or hyperosmolality, plays a critical role in water regulation, which is discussed in Section 1.4 of this chapter.

Less probable but still possible, dehydration can result from a loss of sodium chloride and partial rehydration that dilutes blood sodium; this state is termed *isotonic hypovolemic dehydration*. This type of dehydration may occur with diuretic use such as in athletes who make weight or use diuretics to mask the use of banned substances. Certain diuretics work by increased ion excretion by the kidney; expulsion of sodium, potassium, or other minerals draws water too. Consequently, water and the electrolytes are lost proportionately to give the appearance of the blood not being dehydrated. Besides the ill effects of dehydration, the large potassium losses might put individuals at risk of cardiac arrhythmia.

Finally, *hyponatremia dehydration* has been reported, though infrequently, at medical tents for endurance events conducted in the heat. Tremendous losses of sodium in the sweat as a consequence of high sweat sodium concentrations and high sweat rates for an extended period are risk factors for hyponatremia. In addition, consumption of fluids that partially rehydrate but fail to replace any sodium contributes to dilution of the already compromised blood sodium content. This phenomenon has been reported during training in the heat by the American football players (Horswill et al. 2009) and in distance events (Laird and Johnson 2012).

1.3.4 Factors Contributing to Water Imbalance in Athletes

Hydration status can be compromised by factors that include behavior of drinking, access to fluids, physical activity including mode, intensity, and duration of the effort; the macro- and micro-environment. Macro-environment consists of the external surroundings, and micro-environment is determined by clothing such as athletic uniform or protective gear. For example, as an extreme case, an American football player wearing full gear lost ~7.7 kg while training for 2 h in a hot humid environment (author's observations while conducting—the study by Horswill et al. 2009).

Likewise, despite minimal uniform, a triathlete in the World Championship in Hawaii competes in the heat for ~8.5–15 h depending on his or her level of ability and risks severe dehydration and electrolyte depletion with high sweat rates and inadequate intake along the race course.

1.3.4.1 Environment

The external environment influences body water balance through air temperature, humidity, atmospheric pressure (i.e., altitude), microgravity, and hyperbaric conditions (i.e., deep water diving). Several of the factors may be present for additive effects. For example, mountaineering at a moderate to high terrestrial elevations (>2300 m) along with cold temperatures and dry air can increase water loss through the respiratory passages. Most often, the environmental factor that can impair TBW balance is high ambient temperature. When combined with a high relative humidity, heat storage in the body can increase resulting in an increase in sweat rate to cool the body and thus a decrease in TBW unless fluid loss is replaced with fluid consumption. In microgravity, body fluids shift to the head and torso resulting in a diuresis effect, increasing urine output thus decreasing TBW. At the same time, weightlessness can cause nausea and vomiting, which would compound fluid losses. Effects in specific environments will be briefly discussed in the next paragraphs.

1.3.4.1.1 Altitude

Acute and chronic exposure to altitude can impact water turnover through several physiologic responses and adaptations. Upon ascent to altitude, the immediate compensatory response to the low partial pressure of oxygen (PO_2) is an increase in pulmonary ventilation (V_E). Increases in V_E facilitate respiratory water loss due to the respiratory passages heating and humidifying the air breathed into the trachea. Exposure to moderate-to-high altitude further facilitates respiratory water loss because air at high terrestrial altitude is often cold and dry, which accentuates the gradient between lung moisture and the environment. With the elevated V_E, bicarbonate production is increased, which is excreted by kidneys. However, the expulsion of the bicarbonate anion and renal clearance rate increases water excretion, which is a diuresis that promotes dehydration with a reduction in blood plasma and TBW. With sustained exposure to elevation, the body undergoes adaptations, and through the stimulation of thirst, fluids are regained and help to eventually restore plasma volume and TBW.

1.3.4.1.2 Microgravity

Spaceflight promotes a negative body water balance as a result of several different physiological stressors during the take-off: hyper-gravity g-forces, the microgravity environment itself, and the hydration status of the individual along with psychological stress. TBW, ECF volume, and plasma volume have been measured on several NASA flight missions. After the Skylab missions of the 1970s, TBW decreased by an average of 1.7% at landing (Leach and Rambaut 1977). ECF volume was 2% lower than pre-flight levels following the Skylab mission and decreased by 10% after 24 h of spaceflight on the shuttle missions. ECF volume returned to normal values upon landing (Huntoon et al. 1998). Plasma volume has been shown to decrease by up to 17% within 24 h of spaceflight and then seems to stabilize at 10%–15% of pre-flight values after 60 days (Huntoon et al. 1998). In addition, the length of stay in microgravity can have an impact on the physiologic adaptations that take place. Without gravity, fluids from an interstitial space return to the vascular space and shift to the upper body. This increases venous return, atrial stretching, and consequently the release of atrial natriuretic peptide, which increases urine output. The decreased plasma volume and blood volume has consequences on systemic cardiovascular function. Over time, a decreased blood volume can decrease cardiac size. Orthostatic intolerance or the ability to maintain normal blood pressure and reduced blood flow to the brain while standing results from the decrease in blood volume and cardiac size. Upon returning to a gravitational field when landing, individuals are more susceptible to dizziness and fainting.

To combat these negative consequences, different fluid intake strategies have been suggested by NASA. Astronauts usually consume a fluid beverage containing moderate amounts of sodium to expand plasma volume prior to reentry to mitigate orthostatic intolerance (Buckley 2006).

1.3.4.1.3 Underwater

Impact of the underwater environment has been examined using head-out immersion in thermoneutral water. This causes a translocation of fluid from the limbs and increases intrathoracic blood volume (Epstein 1992). The transient fluid shifts increase venous return, atrial stretch, and compensatory diuresis. The shift in transcapillary fluid from the extravascular compartment into the blood results in an initial expansion of plasma volume, which returns to normal following diuresis and increased urine output. The fluid shift is from the intracellular compartment, and the kidney maintains this balance by increasing water loss to prevent a large increase in plasma volume and cardiac output (Krasney 1996; Miki et al. 1986). Plasma volume can initially increase by approximately 7% during immersion, and as immersion depth increases, there is a concomitant increase in tissue pressure, capillary pressure, and central venous pressure. While there are no changes in plasma osmolality, the hemodilution results in a decline in plasma oncotic pressure. Interstitial fluid remains constant suggesting the shift in fluids come from the ICF compartment (Pendergast and Lundgren 2009). Similar to the astronauts returning to a gravitational field, the diver returning from underwater will experience the challenges of orthostatic hypotension due to hypohydration and compromised cardiac output.

1.3.4.2 Heat and Humidity

When the human body is exposed to higher than normal ambient temperatures (i.e., above 28°C), skin vessels vasodilate to increase blood flow and facilitate heat loss via conduction and convection. If high ambient temperatures and/or humidity exist, the sweat glands are activated because heat dissipation may not be adequate merely by conduction, convection, and/or radiation. Heat is then lost via evaporation of the sweat from the surface of the skin. Evaporation of water via sweat production on the surface of the skin provides approximately 600 kcal, or 2400 kJ of heat transfer per liter of sweat. The relative humidity also plays a large role in the ability to transfer heat from evaporative sweat. In high humidity, the evaporation of sweat is decreased in part to higher water vapor pressure independent of the air temperature. For example, lower ambient temperatures with high humidity (30°C; 70% RH; ~3 kPa) will have a higher water vapor pressure and decrease evaporative heat loss compared to a higher ambient temperature and lower relative humidity (40°C; 20% RH; ~1.5 kPa). In addition to skin, respiratory heat exchange is responsible for conductive, convective, and evaporative heat loss. The mechanisms are described later in this chapter, but briefly, water conservation engaged during thermal stress is dependent on individual sweat rate and the ability of the kidneys to conserve water and electrolytes. With acute exposure to high ambient temperatures, urine output may be reduced to half of normal, from approximately 22 to 10 ml/h (Lee 1964). With progressive dehydration, urine output continues to decrease with minimal excretion for removal of waste as the kidney attempts to conserve body water. Regardless, though, if fluid loss continues with sweating, heat production continues due to exercise, and fluids are not ingested to replace, the safety and function of the individual will eventually be compromised.

1.3.4.3 Exercise and Heat Acclimation

Independent of environmental effects, exercise increases metabolic heat production, which raises core temperature and signals the sweating response. Exercise-induced sweating is then dependent on heat production, which is affected by the mode, duration, and intensity of the physical activity (Sawka and Wenger 1988). In addition, sweat capacity can vary considerably between individuals due to the number of sweat glands, activation of the sweat glands and their efficiency (Burke and Hawley 1997; Maughan 1991). The ability of an individual to sweat decreases with age due to the declining function of the sweat glands (Inoue 1996). Sweat production can exceed several liters per hour and may reach as high as 6–7 L in a day when workers are exposed to a hot environment. There have been reports of sweat loss totaling 12 L within a 24-h time period (Leithead and Lind 1964). As a result of exercise with chronic heat exposure, that is, 90–100 min of exercise a day for 10–14 days, heat acclimatization will elevate human sweat production at a given ambient temperature by about 50%. The composition of the sweat becomes more dilute during acclimatization, as the sweat gland increases electrolyte reabsorption and conserves the ions (Armstrong and Maresh 1991; Kirby and Convertino 1986). Prolonged sweating at a higher sweat rate promotes greater water loss and increases the chances of an athlete developing chronic dehydration with training for several days and particularly if multiple training sessions are held each day in a hot environment.

1.3.4.4 Illness and Travel

Illness can affect hydration of athletes as a result of overtraining, exposure to viral or other pathogens, and during traveling for competition. Illness accompanying diarrhea, vomiting, and fever that results in sweating will promote water loss. Inability to hold down fluids or stop diarrhea also compromises nutritional status beyond hydration and includes deficits of electrolytes such as sodium, potassium, and chloride. The consequences of illness can be hyponatremia and hypokalemia with decreases in ECF volume and plasma volume. As described above, hyponatremia can cause severe swelling of the brain. If the hyponatremia occurs slowly over time, the brain responds by transporting electrolytes and solutes from the cells to the ECF compartment thus attenuating the osmotic flow of water into the cells mitigating swelling. If hyponatremia is severe with a rapid onset, osmotic injury of the neurons and demyelination occur.

Independent of illness, travel, particularly air travel, can disrupt fluid balance. Confined to a cabinet of relatively dry air that circulates rapidly, insensible fluid loss from the skin is accelerated. Some estimates put fluid loss during a 3-to-4 h flight to that similar to losses during 8 h of sleep. While the risk may be low during flight, trans-Atlantic or transpacific air travel that induces dehydration may increase the risk of deep vein thrombosis particularly with limited movement (Chee and Watson 2005).

1.3.4.5 Other Factors

Cultural events, religion expression, and sports-specific behaviors that are based on misconceptions can influence water turnover, balance, and potentially alter hydration state. Fasting for religious reasons such as Ramadan will potentially reduce fluid intake and be quantified as reduced fluid turnover during the month of observation. It is clear that fasting promoted dehydration (Leiper et al. 2003) and that in athletes observing Ramadan, the potential for acute dehydration during training or competition is great but the variability does not seem to adversely affect sweating for thermoregulation (Shirreffs and Maughan 2008). Food and fluid restriction to make weight for competition in combative sports reduces fluid turnover and promotes hypohydration over a period of days according to one case control (Horswill 2009). Finally, misconceptions such as avoiding water consumption for a period of time in hopes of *oxidizing more body fat* also reduce fluid ingestion and promote hypohydration that could adversely affect subsequent training and athletic competition.

1.4 REGULATION OF FLUID BALANCE

1.4.1 Mechanisms

Given the importance of water and its functions in the body, regulation to ensure preservation and restoration of an adequate amount and distribution within the body would seem to be essential. The body has two general mechanisms by which to do so: that which is driven by osmoreceptors and that driven by baroreceptors. Thorough reviews have been provided by Mack and Nadel (2011), Wade and Freund (1990), and Zambraski (1990). In brief and simplified terms, chemical and physical changes are detected by the vascular compartment of the body and lead to hormonal signals that result in physiological or behavioral responses to conserve or replenish the vascular water space, thereby restoring TBW and in particular the ECF compartment, which includes the plasma volume. Additional details of each mechanism are presented in the following Sections 1.4.1.1 through 1.4.1.3.

1.4.1.1 Osmoreceptor Mechanisms and Responses

As water is lost from the body in the form of sweat during exercise, the remaining ECF becomes more concentrated with osmolytes such as sodium. Sweat is hypotonic relative to the blood thereby increasing the particle content in the body fluid.

The increased osmolality of the blood, which is a component of the ECF compartment, is detected by osmo- or chemoreceptors located in the anterior hypothalamus. This stimulates the release of arginine vasopressin (AVP), also known as antidiuretic hormone, from the posterior hypothalamus. The release of AVP stimulates the kidney to decrease free water clearance as a means to conserve body water. Urine production decreases and osmolyte clearance, namely sodium retention, increases. AVP also stimulates thirst, which will induce the drinking behavior to help restore body water via exogenous sources in contrast to the other responses merely conserving existing body water.

1.4.1.2 Baroreceptor Mechanisms and Responses

Besides increasing osmolality, the reduction in water volume of the vascular space decreases the blood pressure. This is sensed by baro- or pressure-receptors located in the cardiopulmonary system. In response, aldosterone is secreted by the adrenal cortex and renin from nephrons. Renin release also stimulates angiotensin secretion, which indirectly can stimulate aldosterone release. This hormone system stimulates a sodium appetite leading to increased sodium intake that could promote water retention. The hormones also stimulate the nephrons of the kidney to reabsorb more sodium which will simultaneously draw more water for reabsorption and conservation. Renin–angiotensin also causes vasoconstriction to help conserve the central blood volume to maintain cardiac output when the body is functioning during a fluid deficit. The end result of these actions is an increase in extracellular sodium; an increase in arterial pressure, which would help restore blood pressure to normal; and an increase in glomerular filtration rate.

1.4.1.3 Other Mechanisms of Conserving Fluid Balance

Other responses that occur during dehydration and exercise include an elevation of plasma catecholamines, epinephrine, and norepinephrine and an increase in the autonomic nervous system activity. These responses are mechanisms that help to maintain central blood volume at a time when it may be decreasing due to sweat loss and vasodilation in the active skeletal muscle. However, they do not seem to be directly involved in body water conservation or replacement from exogenous sources.

1.4.2 Limitations

During physical exertion such as training or competition, the mechanisms previously described are intact. However, because AVP doesn't initiate a thirst response until plasma osmolality reaches a critical level, 1%–2% reduction in body weight can occur before an athlete or exerciser has the desire to drink. This phenomenon has been described as *involuntary dehydration*, as in an unintended outcome (Greenleaf 1966; Greenleaf and Sargent 1965). The outcome is fairly consistent among children and young and older adults but may differ between men and women (Baker et al. 2005; O'Neal et al. 2012; Passe et al. 2007; Wilk and Bar-Or 1996). Males seem to develop dehydration, whereas females are more likely to consume adequate or excess volumes (Baker et al. 2005; Wilk and Bar-Or 1996; Wilk et al. 2007). The reason is unknown with speculation being that males, the hunters in ancient civilizations, have the capability to override the drive to drink in pursuit of food or avoidance of predators, while females that could possibly be carrying offspring are more assured of staying well hydrated for the safety of the fetus.

Quite surprisingly, limitations of these mechanisms appear to exist in the opposite direction; in some cases, the biological system appears to allow overhydration during exercise and has received increasing scrutiny in research and clinical settings. Acute overhydration is a relatively infrequent event during prolonged athletic competition such as marathons or triathlons; however, the result can be and has been deadly. Excess water results in the dilution of plasma sodium. If the concentration drops below 136 mmol/L, hyponatremia is indicated (Montain et al. 2001). The relative decrease in sodium reduces the osmotic effect for maintaining fluid in the extracellular space. Consequently, fluids shift into cells (ICF), to an extent that tissues such as the brainstem become impaired if not damaged, and ventilation and brain function are disrupted. The exact mechanism for hyponatremia is unclear. In most individuals, the excess fluid load would promote free water clearance with the excretion of dilute urine, but for whatever reason, this does not happen in victims of hyponatremia. Syndrome of inappropriate antidiuretic secretion, that is, excess secretion of AVP at a time when it is not needed to conserve fluid, has been implicated. Epidemiological-type studies at endurance events indicate the prevalence of symptomatic hyponatremia may be 0.1%–4% of participants with percentages being higher, between 3% and 27% of those athletes who report to the medical tent (Almond et al. 2005; Montain et al. 2001). The risk of hyponatremia is further discussed in Chapter 2.

1.5 EVALUATION OF BODY HYDRATION STATUS/BALANCE

1.5.1 Research Methods

1.5.1.1 Total Body Water

To assess TBW, the criterion method is to use a tracer that equilibrates in the body water space. The extent of dilution, once the tracer has been given enough time to equilibrate, establishes the volume of water—the TBW—required to achieve that dilution. The tracer used is a heavy form of water, either a stable isotope such as deuterium oxide (D_2O) or a very small amount of a radioactive isotope, tritium oxide. Alternatively, a tracer with labeled oxygen, that is, ^{18}O-water, can be used. A sample of body fluid (D_2O or ^{18}O-water) or breath sample that is in equilibration with the body water (^{18}O-water) is collected before dosing, to establish background levels and then 3 or 4 h post ingestion when the tracer has had adequate time to equilibrate in the body water pool (Schoeller et al. 1980).

TBW, though, does not establish the hydration status of an individual; it is merely a measure of the absolute water volume, which is related to the size of the individual. Because of a fairly fixed ratio with the fat-free tissue of the body, fat-free mass (FFM) can be established once TBW has been measured. Table 1.2 lists the generally accepted ratio across the life span. The general pattern is a decrease in the hydration status of the fat-free body due to the rate of increase in solids (protein and mineral) surpassing the rate of increase in water with maturation. In contrast to what

TABLE 1.2
Ratio of Total Body Water to Fat-Free Mass (TBW/FFM) in Healthy Females (F) and Males (M)

Phase of Life	TBW/FFM Ratio
Infant	0.806
Child, 10 years	F: 0.765; M: 0.746
Young adult, 21–30 years	0.73 with range of 0.69–0.77
Elderly adults, ~70 years	0.725–0.733

Source: Schoeller, D. A., Hydrometry. In S. B. Heymsfield, T. G. Lohman, Z. Wang, and S. B. Going (Eds.), *Human Body Composition,* 2nd ed., Human Kinetics, Champaign, IL, 2005, pp. 35–50; Bossingham, M. J. et al., *Am. J. Clin. Nutr*., 81, 1342–50, 2005; Wells, J. C. K. et al., *Am. J. Clin. Nutr.*, 69, 904–12, 1999.

is thought for elderly, hydration of the fat-free body may not differ that much from the commonly cited value of 0.738 (Brozek et al. 1963).

Therefore, to determine the hydration status, an independent assessment of the FFM is needed along with the TBW water assessment. Densitometry, whole body potassium, or DEXA can be used to provide FFM. The ratio of TBW from the tracer method to FFM from the independent method will reveal the hydration status of the individual and can be contrasted to the expected norms for the appropriate reference group.

Quite surprising, the ratio has been found to fluctuate in college-age athletes who are presumed to be biologically mature, and the discrepancy has generated a debate about what is normal for athletes. Researchers at the University of Georgia have reported that the TBW to FFM ratio may be higher or lower depending on gender and the type of athlete being assessed (Prior et al. 2001). Table 1.3 summarizes mean values for the athletes studied.

The fluctuation could be due to a variety of factors including genetics, diet, acute and chronic state of the subjects, and specific training. Athletes that *survive* youth and adolescent sport leagues to go on to participate at the collegiate level likely

TABLE 1.3
Hydration Status of Athletes Based on Total Body Water (TBW) and Fat-Free Mass (FFM)

Athlete	TBW/FFM Ratio
Male football players	0.744
Male swimmer	0.752
Female swimmer	0.750
Female gymnast	0.690

Source: Prior, B. M. et al., *J. Appl. Physiol.,* 90, 1520–31, 2001.

have a genetic predisposition that gives them the phenotype required to succeed in their sport. The natural selection process (minimal success, injury, etc.) may weed out those athletes that lack the ideal phenotype and composition. Diet, particularly a high-carbohydrate diet, could promote hyperhydration in the skeletal muscle. Several decades ago, Olsson and Saltin (1970) reported an increase in TBW due to carbohydrate loading. Dietary supplements such as creatine may act as an osmolyte to promote water retention within skeletal muscle fibers. Creatine in fact has been shown to elevate TBW (Powers et al. 2003). If athletes are acutely but unknowingly dehydrated at the time of their assessment, the water to FFM ratio is expected to be lower due to less dilution of the tracer or an inflated estimate of body density if FFM was determined by hydrostatic weighing (Girandola et al. 1977). The subjects from which the data in Table 1.3 were derived were reportedly euhydrated based on an average urine specific gravity of 1.020 ± 0.009. As an example of the effect of chronic state, heat acclimation results in expanded body water possibly due to sodium retention and an increase in plasma albumin both of which would contribute to greater retention of water in extracellular compartment. Finally, the type of training the subjects had done over the course of their sports career, more impact training for example in football or gymnastics, might alert the bone mass, which would change the denominator, that is, FFM and thereby alter the ratio.

Besides using a tracer to measure TBW in a static state, the same tracer can be used to assess fluid turnover, the dynamic state of water flux as defined early in this chapter. While this has relevance in research settings, it would not be practical or cost effective in field settings. The observed rates of water turnover in athletes are summarized in Section 1.3.

1.5.1.2 Extracellular Fluid and Intracellular Fluid

As an approximate index, ICF comprises 67% of the TBW and ECF fluid accounts for the remaining third (Schoeller 2005). ECF is composed of interstitial fluid and the plasma volume. Similar to the methodology used for TBW, administering a tracer that equilibrates only in the ECF fluid provides a means to quantifying the ECF volume via the dilution of the tracer. The difference between TBW and ECF provides the ICF volume. Among the tracers used to measure ECF, sodium bromide is effective. Bromide being a halogen behaves similarly to chloride by equilibrating primarily in the extracellular space. Its dilution, 2–3 h after a specific dose is ingested, indicates the ECF volume with appropriate corrections for tracer loss. Currently, a tracer to directly assess ICF volume is not available. If one were, it would require invasive sampling such as a biopsy or biopsies of tissue to examine and quantify the dilution in the intracellular space.

1.5.1.3 Blood Volume and Plasma Volume

Blood volume is quantified with a tracer such as Evan's blue dye, radioactively labeled albumin, or carbon monoxide. The principles of the method rely on (1) a marker that is introduced into the vascular space; (2) the marker does not to leave that space, or if losses occur, they can be estimated or quantified; and (3) the dilution of the marker after a relatively short equilibration period is established by the volume of blood required to achieve the dilution.

The use of a tracer for the direct measure of blood volume is infrequent due to required technology, invasiveness and risks to the subjects, and time required to make analytical quantifications. More common is the measurement of relative plasma volume, or the change in plasma volume, known as the Dill and Costill method (1974). Unlike the tracer methods that provide an absolute volume, the Dill–Costill approach assumes starting with 100% of the blood volume in a rested, euhydrated state; acute changes can be quantified by using changes in hemoglobin and hematocrit as a result of exercise, dehydration, rehydration, or posture changes.

1.5.2 Clinical Methods

The choice of method to categorize hydration status depends on the situation and environment. The choice made also depends on efficiency for the number of assessments, invasiveness, costs and resources, and the consequences of false negatives and false positives if categorization is in error. The criteria used to estimate the category for various methods are summarized in Table 1.4. A brief description of the methods is provided in the subsequent section.

1.5.2.1 Blood and Urine Parameters

In research and clinical settings, plasma osmolality is often considered the gold standard for verifying or determining the hydration status. Measurements are done using osmometers relying on freezing point depression or vapor pressure (change in the dew point temperature for pure water as a result of a change in vapor pressure of the sample). Osmolality of human plasma can range from 275 to 300 mOsm/kg (Scott et al. 1999) with normal values between 260 and 280 mOsm/kg for a euhydrated state.

As a proxy for blood osmolality, urine samples can be obtained noninvasively and assessed for osmolality. Again, freezing point depression or the change in vapor

TABLE 1.4
Summary of Criteria of Body Fluid Samples Used to Estimate Hydration Status

Criteria	Euhydrated	Dehydrated (>−2% Mass)
Plasma osmolality (mOsm/kg)	260–280	>290
Hemoglobin (g/dL)		
Males, 15–44 years	11.7–17.3	Increase versus baseline
Females, 15–44 years	11.7–15.5	Increase versus baseline
Hematocrit (%)		
Males, 15–44 years	35–48	Increase versus baseline
Females, 15–44 years	34–44	Increase versus baseline
Urine osmolality (mOsm/kg)	200–400	>900
Urine-specific gravity	1.001–1.020	>1.020

Source: Burtis, C. A. and E. R. Ashwood, *Tietz Textbook of Clinical Chemistry*, 3rd ed. Philadelphia, PA: Saunders, pp. 1817–26, 1999; Horswill, C. A. and L. M. Janas. *Am. J. Lifestyle Med.* 5, 304–15, 2011; Kavouras, S. A. *Curr. Opin. Clin. Nutr. Metab. Care*. 5,519–24, 2002; Kenefick, R. W. and S. N. Cheuvront. *Nutr. Rev.* 70(Suppl. 2), S137–42, 2012; Oppliger, R. A. and C. Bartok. *Sports Med.* 32, 959–71, 2002.

pressure method could be used to make the assessment. Urine osmolality values less than 600 mOsm/kg are generally regarded as indicating euhydration, whereas values at or above 900 mOsm/kg are considered to indicate hypohydration (Shirreffs and Maughan 1998).

1.5.3 Field and Noninvasive Assessment

For the purpose of athletics and tracking hydration status during training and competition, field methods are most practical as long as they are reliable and accurate. Field methods and those not requiring relatively long and invasive procedures are also of great value when coaches or sports medicine personnel are evaluating a large group, for example, team of athletes, and need to be efficient and effective with time and limited exposure to the athletes. It should be noted in the case of predictions, there is always a prediction error, technically the standard error of estimate from the regression analyses. This means applying a prediction equation developed from a sample of people will have an error when applying the prediction to an individual.

1.5.3.1 Bioelectrical Impedance

Conduction of an electrical current through the body has been used to track changes in the hydration status of individuals. The principle of the method is that the ability of the body to conduct an electrical current is dependent on conductivity and resistance of individual tissues in the body, and the water and electrolyte content of the tissues determined, in large part, the tissues ability to conduct electricity. Having established a baseline measure of a person in a euhydrated state, a subsequent measure after an abrupt change in hydration status should be detectable and quantifiable. However, the original impedance technology on the market was not consistent in detecting acute changes in TBW as a result of exercise-induced acute weight loss.

1.5.3.2 Urine Characteristics

Collecting urine to assess it as a proxy of internal body fluids has also been used to predict the hydration status. The primary application of urine markers has been for discrete categorization: a person as either euhydrated or hypohydrated, and possibly *predicted to be inadequately hydrated* would be a more accurate description than hypohydrated. Urine osmolality was described earlier as a clinical measure of hydration status. Given that osmometers are expensive and rarely found outside of clinical or research laboratories, osmolality has little use in the field for a rapid and real-time assessment. Instead, urine-specific gravity and/or urine color is commonly used. The correlation between urine osmolality and urine specific gravity is highly significant (Stover et al. 2006).

Urine density or more commonly urine-specific gravity, the measure of the mass-to-volume ratio standardized to water, increases when a person is not drinking adequately or the body is in a state of energy conservation such as during exercising. (Exercise induces hemo-concentration and volume reduction independent of sweat loss, and the kidneys respond by decreasing urine product to conserve the blood and body water volume.) The urine subsequently passed is more concentrated—has a high particle content and mass relative to the volume; this is detected as an increase in specific gravity. Specific gravity is quantified by using a refractometer or a reagent strip that uses color change to evaluate the urine as a proxy for hydration status. Sports medicine experts and professional societies have agreed that 1.020 is the cut-off for decision making: urine having a specific gravity of less than or equal to 1.020 indicates euhydration, while urine-specific gravity in excess indicates inadequate hydration (Casa et al. 2000). The potential error with urine specific gravity is that the change in urine characteristics can lag behind the internal state of the body (Popowski et al. 2001; Ryan et al. 1998).

Urine electrical conductivity can also be used to predict osmolality. Shirreffs and Maughan (1998) demonstrated consistency between the two methods: testing athletes in a euhydrated state and again in a dehydration state (~2% body weight reduction).

The appearance of the urine will increase in intensity, darken in shade of color, and the urine becomes more translucent than transparent. Color charts have been developed as a simplified method for athletes (Casa et al. 2000). While practical and simple, color may be oversimplified, influenced by diet independent of hydration status, and varies depending upon environmental conditions (e.g., color appearance depends on the type of overhead lighting, dilution in toilet water, etc.).

Despite the limitations, urine-specific gravity continues to be used commonly as a practical assessment and has been demonstrated as being highly sensitive and specific when changes in TBW are assessed using the isotope methods previously described (Bartok et al. 2004). The debate over its validity continues. A recent review argues against using a single void at any given time of the day (spot urine concentration) to establish the hydration status (Cheuvront et al. 2015). However, given the required application for weight-class athletes who frequently practice dehydration to achieve a lighter weight for competition, the barrier of passing the urine test reduces the severity of the dehydration that otherwise puts the participants in peril.

1.5.3.3 Change in Body Mass

Acute change in body weight consequent to fluid lost as sweat during exercise, diuresis, fasting, or diarrhea and/or vomiting due to illness is a very practical and often applied means to tracking relative hydration status. The assumption during exercise is that the majority of the change in body mass is due to fluid lost as sweat. In the case of athletes who exercise for prolonged periods, the accuracy of this method has been debated (Baker et al. 2009; Tam et al. 2011; Maughan et al. 2007). In the case of exercise-induced weight change in warm or hot environments, the majority of mass lost is that of water and minor amounts due to substrate oxidation. In cooler environments, in which sweating is curtailed due to more efficient heat exchange with a greater heat gradient between the active body and environment, substrate oxidation may play a more prominent component of the reduction in mass, possibly approaching 25% of the weight change if respiratory water loss is also included (Ly et al. 2013).

1.6 SUMMARY AND CONCLUSION

TBW makes up at least 50% of the body mass and closer to 65% in the lean athlete. It is distributed within various compartments within the body and serves critical functions. The plasma volume is of particular importance because of its role in cardiovascular function and signaling the responses that lead to water conservation or water replacement. Numerous factors impact the turnover of the body water and the potential to alter the hydration state of the individual. Various methods of assessment can help guide research and application in the field to better understand water flux and develop strategies to restore euhydration in athletes, respectively.

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2 Sodium Balance during Exercise and Hyponatremia

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CONTENTS

2.1 INTRODUCTION

Dietary sodium intake is vital for cellular homeostasis and physiological function. Sodium is the most abundant cation of the extracellular space and one of the primary regulators of the extracellular fluid volume (Ball 2013). Sodium balance influences plasma volume and atrial pressure, playing a key role in the regulation of cardiac output and stroke volume both at rest and during exercise. Sodium is also involved in the acid–base regulation, neural signal transmission, muscular contraction, and metabolism (Farquhar et al. 2015; Montain, Sawka, and Wenger 2001). Dietary sodium is readily absorbed from the digestive track and travels freely in the blood (Fordtran, Rector, and Carter 1968). The renal system is the main regulator of sodium. Excessive intake of sodium can lead to natriuresis (urinary sodium excretion) in healthy individuals (Mack and Nadel 1996). Dietary sodium intake has drawn a lot of media attentions since excessive sodium intake has been linked to hypertension. Even though the minimum daily amount of sodium required to maintain homeostasis is very low (<500 mg), most Americans consume more than 3,000 mg. The U.S National Academy of Sciences Food and Nutrition Board has established adequate intake (AI: recommended average daily intake) and tolerable upper level (UL: the individuals' maximum level of daily nutrient intake that is likely to pose no adverse effects) of 1.5 and 2.3 g/day, respectively (Institute of Medicine US Panel on Dietary Reference 2005). Salt is ~40% sodium by weight. So, 1 g of salt consists of 400 mg of sodium. AI and UL for sodium refer mainly to inactive individuals, while physically active individuals and athletes who lose large volume of sweat regularly would require much greater dietary sodium intake. For instance, during a 90-min soccer training session, sodium losses could range from 600 mg to 3.12 g (Maughan et al. 2010). During exercise, an average athlete's sweat contains around 40 mmol or 920 mg of sodium per liter of sweat. During intense exercise in the heat, sweat volume could exceed 2 L/h (American College of Sports et al. 2007). So it is not unreasonable for an athlete to have well over 2–3,000 mg of sodium lost from sweat alone, which is almost twice that of recommended intake (Rehrer 2001; Sallis 2008).

2.2 DEFINITION OF HYPONATREMIA

Hyponatremia is clinically defined by plasma or serum sodium concentration lower than 135 mmol/L (Montain, Sawka, and Wenger 2001). Due to the fact that hyponatremia between 134 and 130 mmol/L is usually asymptomatic, it has been also described as *mild hyponatremia* (Sallis 2008). Even though hyponatremia develops more often in clinical conditions, not related to exercise, for the purpose of this chapter we will focus on the exercise-associated hyponatremia (EAH) (Hew-Butler et al. 2008). The first line of symptoms is non-specific and they can develop in the absence of EAH (bloating, nausea, vomiting, headache bloating, and puffiness). During more severe EAH, the symptoms are associated with cerebral edema encephalopathy causing changes in mental status like confusion or disorientation and even seizures or delirium. When EAH cell swelling is developed in the lungs (pulmonary edema), breathing becomes short and difficult (Ayus, Varon, and Arieff 2000). As symptoms progress, coma or even death can happen. The intensity of the symptoms is related to how rapid hyponatremia has developed, as well as the level of serum sodium. There are two types of EAH: (1) dilutional hyponatremia and (2) hyponatremia due to mixed sodium and water loss (Armstrong 1999). The most common type of EAH is the first one when hyponatremia develops as a response to increased total body water relative to total sodium content in the circulation. In the dilutional hyponatremia, there is a concomitant increase in the body weight.

2.3 INCIDENCE OF HYPONATREMIA

Several studies have reported that endurance athletes that participate in events lasting more than 3 h can develop asymptomatic hyponatremia. The incidence of clinically significant hyponatremia is 0.1%–0.3%, but the actual mortality rate is very low, although exact numbers are unknown (Carter 2008). The first case of EAH was reported in South Africa during the Comrades Marathon by Dancaster and Whereat (1971). Later on, Noakes et al. (1985) reported four cases of water intoxication (hyponatremia) in athletes participating in endurance exercise. One of the largest cross-sectional studies was published in the *New England Journal of Medicine* based on the 2002 Boston Marathon (Almond et al. 2005). The data indicated that most of the hyponatremic runners were either asymptomatic or mildly symptomatic, even though 13% of the subjects has serum sodium <135 mmol/L while 0.6% has <120 mmol/L. In a study from the New Zealand Ironman triathlon, the incidence of hyponatremia defined as plasma sodium <135 mmol/L was 18% (Speedy, Noakes, and Schneider 2001). In a different study, based on the Houston marathon, the prevalence of hyponatremia (<135 mmol/L) was 0.4%, while the incidence of severe hyponatremia (<120 mmol/L) was 0.04% (Hew et al. 2003). Noakes and colleagues (2005) compiled data from 8 different endurance races and reported hyponatremia (<130 mmol/L) in 1.4% of the runners. They also concluded that EAS occurred in athletes that drank in excess while running and that retained fluid due to an inadequate suppression of the antidiuretic hormone (ADH).

2.4 PREDISPOSING RISK FACTORS

2.4.1 Excessive Drinking

Over-consumption of hypotonic drinks (mainly water) during exercise above fluid losses (urine and sweat) leading to weight gain is the main cause of hyponatremia. This type of hyponatremia has been described as *dilutional hyponatremia*. ADH or vasopressin is the main hormone that regulates water balance. Based on the regulation of vasopressin, someone would expect that over-drinking would stimulate diuresis in order to maintain homeostasis (Robertson 2011; Robertson, Shelton, and Athar 1976). Over-drinking decreases plasma osmolality, which in turn will rapidly decrease ADH leading to large urinary excretion. Interestingly, case studies have indicated that during hyponatremia, even though plasma osmolality and sodium are low, ADH remains high. Based on this observation, the term *inappropriate antidiuretic hormone secretion* has been used, and it has been linked in the development of EAH (Siegel et al. 2007; Speedy et al. 2001). A potential explanation is that some of the non-osmotic stimuli of ADH include nausea and exercise. Figure 2.1 demonstrates that gaining weight during exercise is a strong predictor of hyponatremia (Noakes et al. 2005). Also the study from the 2002 Boston marathon with 488 runners indicated that those who gained 3–4.9 kg during the race had 30% and 70% greater risk of developing severe (<130 mmol/L) or mild hyponatremia (<135 mmol/L) (Almond et al. 2005). However, runners who gain 3–4.9 kg in a marathon (42 km), for example, will have to drink about 715–1,167 mL above their overall body fluid losses (sweat + urine) every 10 km.

2.4.2 Drink Composition

The composition of the drinks can also play an important role on the development of EAH. Several studies have shown that sodium-free fluid ingestion during prolonged