CHAPTER 9

Water Balance

KEY CONCEPTS

- Water compartments inside and outside of the cells maintain a balanced distribution of total body water.
- The concentration of various solute particles in water determines the internal shifts and movement of water.
- A state of dynamic equilibrium among all parts of the body's water balance system sustains life.

Water is the most vital nutrient to human existence. Humans can survive far longer without food than without water. Only the continuous need for air is more demanding.

One of the most basic nutrition tasks is ensuring a balanced distribution of water to all body cells. Water is critical for the physiologic functions that are necessary to support life. This chapter briefly looks at the finely developed water balance system in the body, how this system works, and the various parts and processes that maintain it.

BODY WATER FUNCTIONS AND REQUIREMENTS

Water: The Fundamental Nutrient

Basic Principles

Three basic principles are essential to an understanding of the balance and uses of water in the human body.

A Unified Whole. The human body forms one continuous body of water that is contained by a protective envelope of skin. Water moves to all of the parts of the body, and it is controlled by solvents within the water and membranes that separate the compartments. Virtually every space inside and outside of the cells is filled with water-based body fluids. Within this environment, all processes that are necessary to life are sustained.

Body Water Compartments. The key word *compartment* is generally used in human physiology to refer to dynamic areas within the body. Body water can be discussed in terms of total body water as well as in separate individual locations throughout the body (i.e., intracellular or extracellular compartments). Membranes separate compartments of water. The body's dynamic mechanisms constantly shift water to places of greatest need and maintain equilibrium among all parts. Specific compartments are discussed later in this chapter.

Particles in the Water Solution. The concentration and distribution of particles in water (e.g., sodium, chloride, calcium, magnesium, phosphate, bicarbonate, protein) determine the internal shifts and balances among the compartments of body water.

Homeostasis

The body's state of dynamic balance is called **homeostasis**. W.B. Cannon, a physiologist, viewed these balance

homeostasis the state of relative dynamic equilibrium within the body's internal environment; a balance that is achieved through the operation of various interrelated physiologic mechanisms.

principles as "body wisdom."[1] Early in the twentieth century he applied the term *homeostasis* to the capacity that is built into the body to maintain its life systems, despite what enters the system from the outside. The body has a great capacity to use numerous finely balanced homeostatic mechanisms to protect its vital water supply.

Body Water Functions

The body water supply has the following characteristics: (1) it acts as a solvent; (2) it serves as a means of transport; (3) it regulates temperature control; and (4) it provides lubrication for the body.

Solvent. Water provides the basic liquid solvent for all chemical reactions within the body. The **polarity** of water effectively ionizes and dissolves many substances.

Transport. Water circulates throughout the body in the form of blood and various other secretions and tissue fluids. In this circulating fluid, the many nutrients, secretions, metabolites (i.e., products formed from metabolism), and other materials can be carried anywhere in the body to meet the needs of all body cells.

Thermoregulation. Water is necessary to help maintain a stable body temperature. As the body temperature rises, sweat is released and evaporates from the skin, thereby cooling the body.

Lubricant. Water also has a lubricating effect on moving parts of the body. For example, fluid within joints (i.e., synovial fluid) helps to provide smooth movement and prevents damage from friction.

Body Water Requirements

The Dietary Reference Intake for water, which was set for the first time by the National Academy of Sciences in 2004, is based on the median total water intake reported by participants in the Third National Health and Nutrition Examination Survey (NHANES), which took place from 1988 to 1994. The amount of total water includes water in both beverages and food. Set as Adequate Intakes, the Dietary Reference Intakes for water are the amounts that are required to meet the needs of healthy individuals who are relatively sedentary and living in temperate climates.[2] Recommendations are primarily established to prevent the harmful effects of dehydration, which include metabolic and functional abnormalities. To meet adult fluid needs and thus be hydrated, the average sedentary woman should consume 2.7 L (91 oz) of total water per day. Because approximately 19% of total water intake comes from food, a woman should aim for 74 fluid ounces (9 cups) of fluids in the form of beverages per day, with the rest being provided by food. A sedentary man should consume 3.7 L (125 oz) of total water per day.[2] Assuming that approximately 0.7 L of water is consumed within food, a man should aim for 101 fluid ounces (3 L) of fluid in the form of beverages per day. However, physical activity and alterations in climate require more fluid to offset losses. Table 9-1 lists the Adequate Intakes of fluid for all individuals.

The body's requirement for water varies in accordance with several factors: environment, activity level, functional losses, metabolic needs, age, and other dietary factors.

Surrounding Environment. As the temperature rises in the surrounding environment, body water is lost as sweat in an effort to maintain body temperature. Water intake must accommodate such losses in sweat. Increasing body temperatures may be caused by the natural climate or by the heat produced by physical work. On the opposite end of the spectrum, cold temperatures and altitude result in elevated respiratory water loss, hypoxia- or cold-induced diuresis, and increased energy expenditure, all of which increase water needs as well.[2]

Activity Level. Heavy work or extensive physical activity (e.g., participation in sports) increases the water requirement for two reasons: (1) more water is lost in sweat and respiration; and (2) more water is necessary for the increased metabolic demand that results from physical activity.

Athletes require a large increase in water intake, especially in hot weather. The American College of Sports Medicine, the Academy of Nutrition and Dietetics, and the Dietitians of Canada recommend drinking 5 to 7 mL per kilogram of body weight of water or sports drink at least 4 hours before exercise (see For Further Focus box entitled "Hydrating With Water or a Sports Drink" in Chapter 16 for more information about sports drinks). Fluid intake needs during activity will depend on body size, sweat rates, and type of activity. Athletes are encouraged to rehydrate by drinking at least 16 to 24 oz of fluid for every pound of body weight that is lost during exercise.[3]

Functional Losses. When any disease process interferes with the normal functioning of the body, water requirements are affected. For example, with gastrointestinal problems such as prolonged diarrhea, large amounts

polarity the interaction between the positively charged end of one molecule and the negative end of another (or the same) molecule.

TABLE 9-1 ADEQUATE INTAKE OF WATER (LITERS PER DAY)

	MALE			FEMALE		
Age	From Food	From Beverages	Total Water	From Food	From Beverages	Total Water
0 to 6 months	0.0	0.7	0.7	0.0	0.7	0.7
7 to 12 months	0.2	0.6	0.8	0.2	0.6	0.8
1 to 3 years	0.4	0.9	1.3	0.4	0.9	1.3
4 to 8 years	0.5	1.2	1.7	0.5	1.2	1.7
9 to 13 years	0.6	1.8	2.4	0.5	1.6	2.1
14 to 18 years	0.7	2.6	3.3	0.5	1.8	2.3
>19 years	0.7	3.0	3.7	0.5	2.2	2.7
Pregnancy, 14 to 50 years				0.7	2.3	3.0
Lactation, 14 to 50 years				0.7	3.1	3.8

1 L = 33.8 oz; 1 L = 1.06 qt; 1 cup = 8 oz.
Data from the Food and Nutrition Board, Institute of Medicine. *Dietary reference intakes for water, potassium, sodium, chloride, and sulfate.* Washington, DC: National Academies Press; 2004.

of water may be lost. Uncontrolled diabetes mellitus causes an excess loss of water through urine as a result of high blood glucose levels. In such cases, the replacement of lost water and electrolytes is vital to prevent dehydration.

Metabolic Needs. Body metabolism requires water. A general rule is that roughly 1000 mL of water is necessary for the metabolism of every 1000 kcal in the diet.

Age. Age plays an important role in determining water needs. High fluid intake (via breast milk or formula) is critical during infancy because an infant's body content of water is large (approximately 70% to 75% of the total body weight) and because a relatively large amount of this total body water is outside of the cells and thus is more easily lost.

Other Dietary Factors. Certain dietary additives and medications can affect water requirements because of their natural **diuretic** effects. Several medications contain diuretics specifically for the purpose of reducing overall body fluid, as in the case of antihypertensive medications (e.g., hydrochlorothiazide [Dyazide], furosemide [Lasix], bumetanide [Bumex], torsemide [Demadex]). Individuals who are taking medications that promote water loss should be monitored for dehydration and electrolyte imbalance. Other dietary factors that have long been viewed as diuretics are alcohol and caffeine. However, studies that have evaluated the hydration status of individuals consuming caffeinated and noncaffeinated beverages did not differ, which indicates that caffeine did not negatively affect the total water balance when it was consumed in moderation.[4] Although alcohol does acutely increase urine output after ingestion (i.e., within the first 3 hours), the long-term effect (i.e., up to 12 hours) is antidiuretic. Thus, alcohol intake does not appear to cause total body fluid loss over a 24-hour period (see the Drug-Nutrient Interaction box, "Drug Effects on Water and Electrolyte Balance").

Dehydration

Dehydration is the excessive loss of total body water. Relative severity can be measured in terms of the percentage of total body weight loss, with symptoms apparent after 2% of normal weight is lost. Initial symptoms include thirst, headache, decreased urine output, dry mouth, and dizziness. As the condition worsens, symptoms can progress to visual impairment, hypotension, loss of appetite, muscle weakness, kidney failure, and seizures. Chronic or severe dehydration is known to increase the resting heart rate; to contribute to kidney infections, gallstones, and constipation; and to adversely influence cognitive function, exercise performance (particularly in untrained individuals), and the maintenance of body temperature (i.e., thermoregulation).[2,5-8] Without correction, dehydration can advance to coma and death (see the Clinical Applications box, "Adverse Effects of Progressive Dehydration"). Fluid losses of more than 10% of body weight usually require medical assistance for a complete recovery.

Dehydration presents special concerns among elderly adults. The hypothalamus is the regulatory center for thirst, hunger, body temperature, water balance, and

diuretic any substance that induces urination and subsequent fluid loss.

DRUG-NUTRIENT INTERACTION

DRUG EFFECTS ON WATER AND ELECTROLYTE BALANCE

Some medications can affect fluid and electrolyte balance. Anticholinergics such as amitriptyline (Elavil) and chlorpromazine (Thorazine) may result in a thickening of the saliva and dry mouth. Individuals who are using these mediations should be advised to increase their fluid intake on a regular basis.

Antidepressants are divided into classes on the basis of their activity in the brain. Selective serotonin reuptake inhibitors (SSRIs such as Paxil, Zoloft, Prozac, Celexa), tricyclics, serotonin-norepinephrine reuptake inhibitors (SNRIs such as Effexor), and norepinephrine-dopamine reuptake inhibitors (NDRIs such as Wellbutrin) have oral and gastrointestinal side effects that include taste changes, nausea, vomiting, and dry mouth. Patients can avoid some of the negative side effects by drinking 2 to 3 L water per day and maintaining a consistent sodium intake.

Corticosteroids such as prednisone, methylprednisolone, and hydrocortisone increase the excretion of several nutrients, including potassium. Patients should be encouraged to increase their daily intake of fluids and of foods that are high in potassium to maintain an adequate body balance.

Loop diuretics (e.g., Lasix) and thiazide diuretics (e.g., hydrochlorothiazide) are both used to treat hypertension by increasing the urinary excretion of fluids. Minerals are lost in the urine along with fluid excretion. Patients who are taking these drugs should increase the amount of fresh fruits and vegetables in their diets and to eat other foods that are good sources of potassium. Although sodium and chloride also are lost in the urine, it is not necessary to increase the intake of these electrolytes, as long as the individual is consuming a normal varied diet.

Potassium-sparing diuretics (e.g., spironolactone) also work to rid the body of excess fluids, but they do so without wasting potassium in the urine. Therefore, patients should be careful to not use potassium-based salt substitutes so that they can avoid hyperkalemia (i.e., excessively high potassium levels in the blood).

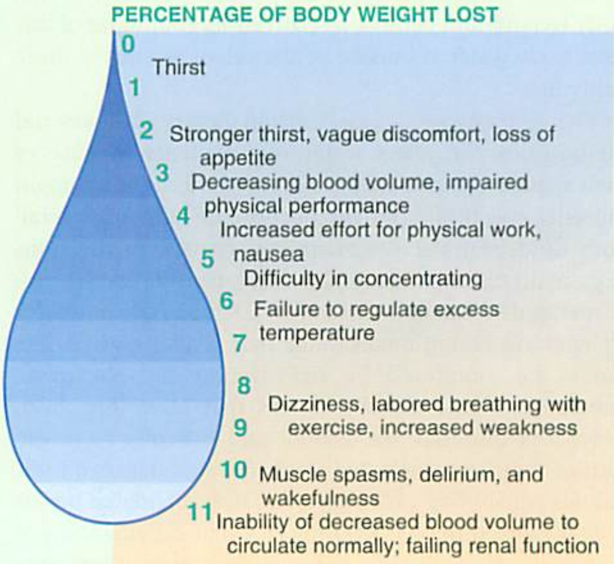
Antipsychotics (e.g., phenothiazines, chlorpromazine) can cause a condition known as *psychogenic polydipsia*. Patients who are taking these drugs often experience dry mouth, and they will consume large amounts of water. If the patient's fluid consumption exceeds his or her capacity for excretion, this can result in hyponatremia and water intoxication. Symptoms of water intoxication include vomiting, ataxia, agitation, seizures, and coma.

CLINICAL APPLICATIONS

ADVERSE EFFECTS OF PROGRESSIVE DEHYDRATION

A loss of as little as 3% of total body weight from dehydration can result in impaired physical performance.[1] Physical performance is relative to the individual in question. A runner who is progressively losing body water in the form of sweat, without appropriate fluid replacements, will likely suffer from decreased speed or endurance. However, an elderly person who has also lost 3% of his or her body weight may suffer dramatically more complicated physical impairments (e.g., a fall that results in an injury).

Individuals with fever, diarrhea, and vomiting can lose body weight in the form of fluids quite rapidly. Likewise, the risk of dehydration increases in hot, humid environments and at altitudes of more than 8200 feet.[2] The figure shown in this box demonstrates the progressive complications that are associated with total body water loss. Note that the thirst response is not present until a loss of approximately 0.5% of the total body weight. This is why solely relying on thirst for an indication of fluid needs is not a sensitive indicator. By the time you are thirsty, you have already lost precious body water.



1. Kraft JA, Green JM, Bishop PA, et al. *Impact of dehydration on a full body resistance exercise protocol. Eur J Appl Physiol.* 2010;109(2): 259-267.
2. Rodriguez NR, DiMarco NM, Langley S. Position of the Academy of Nutrition and Dietetics, Dietitians of Canada, and the American College of Sports Medicine: Nutrition and athletic performance. *J Am Diet Assoc.* 2009;109(3):509-527.

blood pressure. However, physiologic changes in the hypothalamus naturally occur with age and, as a result, elderly individuals exhibit an overall decreased thirst sensation and reduced fluid intake when they are dehydrated compared with younger adults.[9,10] Other physiologic changes (e.g., diminishing kidney function) accompany the aging process and may exacerbate body fluid losses.

Water Intoxication

Although it is not nearly as common, water intoxication from overconsumption can occur. The excessive intake of plain water may result in the dangerous condition of hyponatremia (i.e., low serum sodium levels of less than 136 mEq/L). Under normal situations, excess water that is consumed is lost by increased urine output, and this is not likely to pose a problem for a normal healthy person who is eating an otherwise typical diet. However, individuals with renal insufficiency or neurologic disorders that affect the thirst mechanism and those who participate in heavy endurance exercise may not be able to dilute or excrete urine appropriately.

As blood volume is diluted with excess water, the water moves to the intracellular fluid (ICF) spaces to reestablish equilibrium with sodium concentrations there, thereby diluting ICF as well. This movement causes edema (Figure 9-1), lung congestion, and muscle weakness. Individuals who are at risk for hyponatremia from water intoxication are infants (if they are forced to drink by an adult), psychiatric patients with **polydipsia**, patients who are taking psychotropic drugs, and individuals who are participating in prolonged endurance events without fluid and electrolyte replacement.[2]

Figure 9-1 Edema. Note the finger-shaped depressions that do not rapidly refill after an examiner has exerted pressure. (From Thibodeau GA, Patton KT. *Anatomy & physiology*. 6th ed. St. Louis: Mosby; 2007.)

WATER BALANCE

Body Water: The Solvent

Amount and Distribution

Normal body water content ranges from 45% to 75% of the total body weight in adults. Men usually have 10% more body water than women for an average of 60% and 50% of total body weight, respectively. Differences are generally attributable to a higher ratio of muscle to fat mass in males. Muscle contains significantly more water compared with adipose tissue.

Total body water is categorized into two major compartments (Figure 9-2).

Extracellular Fluid. The total body water outside of the cell is called the *extracellular fluid* (ECF). This water collectively makes up approximately 20% of the total body weight and 34% of the total body water. One fourth of the ECF (i.e., 4% to 5% of the total body weight) is contained in the blood plasma or the intravascular compartment. The remaining three fourths (i.e., 15% of the total body weight) is composed of the following: (1) water that surrounds the cells and bathes the tissues (i.e., interstitial fluid); (2) water within the lymphatic circulation; and (3) water that is moving through the body in various tissue secretions (i.e., transcellular fluid). Interstitial fluid circulation helps with the movement of materials in and out of body cells. Transcellular fluid is the smallest component of ECF (i.e., approximately 2.5% of total body water). Transcellular fluid consists of water within the gastrointestinal tract, cerebrospinal fluid, ocular and joint fluid, and urine within the bladder.

Intracellular Fluid. Total body water inside cells is called the *intracellular fluid*. This water collectively amounts to roughly twice the amount of water that is outside of the cells, thus making up approximately 40% to 45% of total body weight and 66% of total body water.

The relative amounts of water in the different body water compartments are compared in Table 9-2.

Overall Water Balance. Water enters and leaves the body by various routes that are controlled by basic mechanisms such as thirst and hormones. The average adult

polydipsia excessive thirst and drinking.

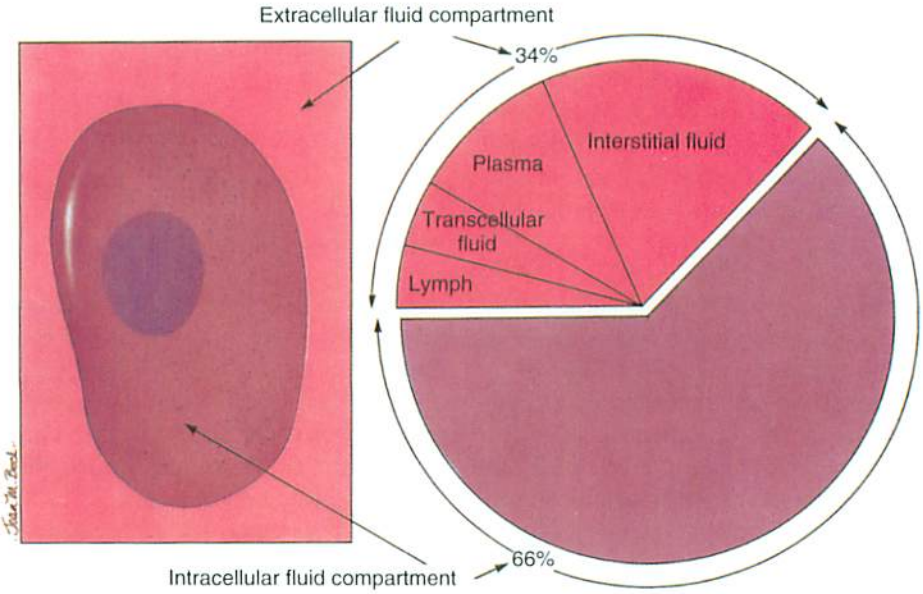
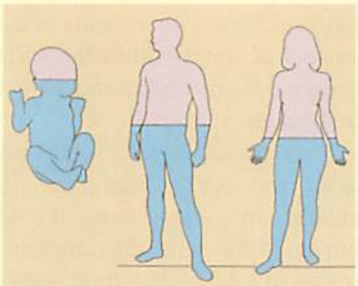


Figure 9-2 The distribution of total body water. (From Thibodeau GA, Patton KT. *Anatomy & physiology*. 6th ed. St. Louis: Mosby; 2007.)

TABLE 9-2 VOLUMES OF BODY FLUID COMPARTMENTS AS A PERCENTAGE OF BODY WEIGHT

Body Fluid	Infant	Adult Male	Adult Female
Extracellular Fluid			
Plasma	4	4	4
Interstitial fluid	26	16	11
Intracellular Fluid	45	40	35
Total	75	60	50



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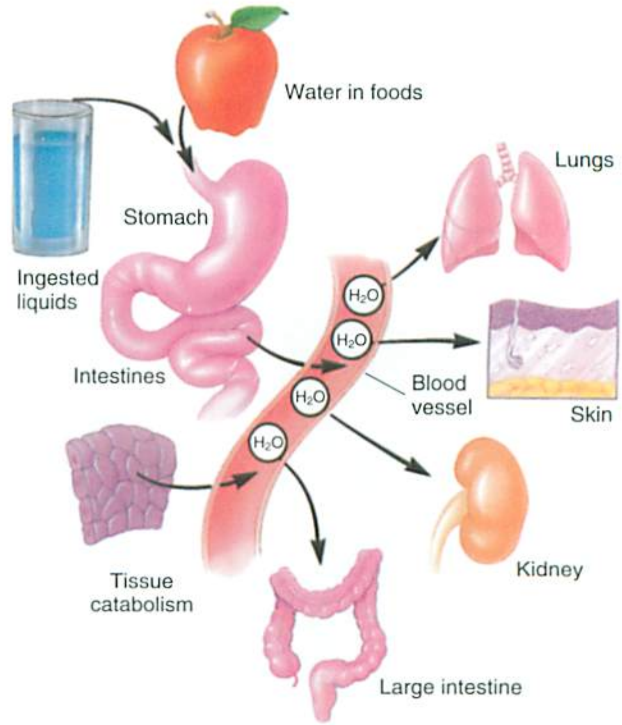

Figure 9-3 Sources of fluid intake and output. (From Thibodeau GA, Patton KT. *Anatomy & physiology*. 6th ed. St. Louis: Mosby; 2007.)

TABLE 9-3 WATER CONTENT OF SELECTED FOOD

Food	Water Content (%)
Apple, raw	86
Apricot, raw	86
Banana, raw	75
Bread, white	36
Bread, whole wheat	38
Broccoli, cooked	89
Cantaloupe, raw	90
Carrots, raw	88
Cheese, cheddar	37
Cheese, cottage	79
Chicken, roasted	64
Corn, cooked	70
Grapes, raw	81
Lettuce, iceberg	96
Macaroni/spaghetti, cooked	66
Mango, raw	82
Orange, raw	87
Peach, raw	89
Pear, raw	84
Pickle	92
Pineapple, raw	86
Potato, baked	75
Squash, cooked	94
Steak, tenderloin, cooked	50
Sweet potato, boiled	80
Turkey, roasted	62

Modified from the Food and Nutrition Board, Institute of Medicine. *Dietary reference intakes for water, potassium, sodium, chloride, and sulfate.* Washington, DC: National Academies Press; 2004.

metabolizes 2.5 to 3 L of water per day in a balance between intake and output.

Water Intake. Water enters the body in three main forms: (1) as preformed water in liquids that are consumed; (2) as preformed water in foods that are eaten; and (3) as a product of cell oxidation when nutrients are burned in the body for energy (i.e., metabolic water or "water of oxidation") (Figure 9-3). A variety of foods and their relative water content are listed in Table 9-3.

Older adults are at higher risk for dehydration as a result of inadequate intake and the physiologic changes that are associated with aging. Many older people suffer from **xerostomia**, which is caused by a severe reduction in the flow of saliva; this in turn negatively affects food intake. The condition may be associated with the use of certain medications, with certain diseases or conditions, or with radiation therapy of the head and neck. Conscious attention to adequate fluid intake (i.e., not less than the recommended minimum of 1500 to 2000 mL/day) is an important part of health maintenance and care in this population. Fluid intake should not depend on thirst, because the thirst sensation is an indicator of present dehydration rather than an advance warning.

TABLE 9-4 AVERAGE DAILY ADULT INTAKE AND OUTPUT OF WATER

Form of Water	Intake (mL/day)	Body Part	Output (mL/day)
Preformed		Lungs	350
In liquids	1500	Skin	
In foods	700	Diffusion	350
Metabolism (i.e.,	200	Sweat	100
the oxidation		Kidneys	1400
of food)		Anus	200
Total	2400	Total	2400

Modified from Thibodeau GA, Patton KT. *Anatomy & physiology.* 6th ed. St. Louis: Mosby; 2007.

Water Output. Water leaves the body through the kidneys, skin, lungs, and feces (see Figure 9-3). Of these output routes, the largest amount of water exits through the kidneys. A certain amount of water must be excreted as urine to rid the body of metabolic waste. This is called *obligatory water loss,* because it is compulsory for survival. The kidneys may also put out an additional amount of water each day, depending on body activities, needs, and intake. This additional water loss varies in accordance with the climate, the physical activity level, and the individual's intake. On average, the daily water output from the body totals approximately 2400 mL, which balances the average intake of water.

Table 9-4 summarizes the comparative intake and output that affect body water balance.

Solute Particles in Solution

The solutes in body water are a variety of particles in varying concentrations. Two main types of particles control water balance in the body: electrolytes and plasma proteins.

Electrolytes

Electrolytes are small inorganic substances (i.e., either single-mineral elements or small compounds) that can dissociate or break apart in solution and that carry an

xerostomia the condition of dry mouth that results from a lack of saliva; saliva production can be hindered by certain diseases (e.g., diabetes, Parkinson's disease) and by some prescription and over-the-counter medications.

electrical charge. These charged particles are called *ions*. In any chemical solution, separate particles are constantly in balance between cations and anions to maintain electrical neutrality.

Cations. Cations are ions that carry a positive charge (e.g., sodium [Na^+], potassium [K^+], calcium [Ca^{2+}], magnesium [Mg^{2+}]).

Anions. Anions are ions that carry a negative charge (e.g., chloride [Cl^-], bicarbonate [HCO_3^-], phosphate [PO_4^{3-}], sulfate [SO_4^{2-}]).

The constant balance between electrolytes—specifically sodium and potassium—maintains the electrochemical and cell membrane potentials. Because of their small size, electrolytes can freely diffuse across most membranes of the body, thereby maintaining a constant balance between the intracellular and extracellular electrical charge. The fluid and electrolyte balances are intimately related, so an imbalance in one produces an imbalance in the other.

Electrolyte concentrations in body fluids are measured in terms of milliequivalents (mEq). Milliequivalents represent the number of ionic charges or electrovalent bonds in a solution. The number of milliequivalents of an ion in a liter of solution is expressed as mEq/L. Table 9-5 outlines the balance between cations and anions in the ICF and ECF compartments, which are exactly balanced.

Plasma Proteins

Plasma proteins—mainly in the form of albumin and globulin—are organic compounds of large molecular size.

TABLE 9-5 BALANCE OF CATION AND ANION CONCENTRATIONS IN EXTRACELLULAR FLUID AND INTRACELLULAR FLUID*

Electrolyte	Extracellular Fluid (mEq/L)	Intracellular Fluid (mEq/L)
Cation		
Na^+	142	35
K^+	5	123
Ca^{2+}	5	15
Mg^{2+}	3	2
Total	155	175
Anion		
Cl^-	104	5
PO_4^{3-}	2	80
SO_4^{2-}	1	10
Protein	16	70
CO_3^{2-}	27	10
Organic acids	5	
Total	155	175

*This balance maintains electroneutrality within each compartment.

They do not move as freely across membranes as electrolytes do, because the electrolytes are much smaller. Thus, plasma protein molecules are retained in the blood vessels, and they control water movement in the body and maintain blood volume by influencing the shift of water in and out of capillaries in balance with the surrounding water. In this function, plasma proteins are called *colloids*, which exert **colloidal osmotic pressure (COP)** to maintain the integrity of the blood volume. Cellular proteins help to guard cell water in a similar manner.

Small Organic Compounds

In addition to electrolytes and plasma protein, other small organic compounds are dissolved in body water. Their concentration is ordinarily too small to influence shifts of water; however, in some instances, they are found in abnormally large concentrations that do influence water movement. For example, glucose is a small particle that circulates in body fluids, but it can increase water loss from the body and result in a condition known as **polyuria** when it is in abnormally high concentrations (e.g., uncontrolled diabetes).

Separating Membranes

Two types of membranes separate and contain water throughout the body: capillary membranes and cell membranes.

Capillary Membranes

The walls of capillaries are thin and porous. Therefore, water molecules and small particles can move freely across them. Such small particles, having free passage across capillary walls, include electrolytes and various nutrient materials. However, larger particles such as plasma protein molecules cannot pass through the small pores of the capillary membrane. These larger molecules remain in the capillary vessel and exert COP to bring water and small molecules back into the capillary.

colloidal osmotic pressure (COP) the fluid pressure that is produced by protein molecules in the plasma and the cell; because proteins are large molecules, they do not pass through the separating membranes of the capillary walls; thus, they remain in their respective compartments and exert a constant osmotic pull that protects vital plasma and cell fluid volumes in these areas.

polyuria an excess water loss through urination.

Cell Membranes

Cell membranes are specially constructed to protect and nourish the cell's contents. Although water is freely permeable, other molecules or ions use channels within the phospholipid bilayer (see Figure 3-6) for passage across the membrane. The membrane channels are highly specific to the molecules that are allowed to pass. For example, sodium channels only allow sodium to pass, and chloride channels only allow chloride to pass.

Forces Moving Water and Solutes Across Membranes

A variety of forces are at work in the cell membrane to allow for the maintenance of dynamic equilibrium.

Osmosis

Osmosis is the movement of water molecules from an area with a low solute concentration to an area with a high solute concentration. When solutions of different concentrations exist on either side of selectively permeable membranes, the **osmotic pressure** moves water across the membrane to help equalize the solutions on both sides. Therefore, osmosis can be defined as the force that moves water molecules from an area of greater concentration of water molecules (i.e., with fewer particles in solution) to an area of lesser concentration of water molecules (i.e., with more particles in solution). Figure 9-4 illustrates how water will move from the 10% glucose solution across the semipermeable membrane to the 20% glucose solution to equalize the solute concentrations. Because the membrane is permeable to glucose, the amount of glucose will also change on either side of the membrane to establish equilibrium.

Diffusion

As osmosis applies to water molecules, diffusion applies to the particles in solution. Simple diffusion is the force by which these particles move outward in all directions from an area of greater concentration of particles to an area of lesser concentration of particles (see Chapter 5). The relative movement of water molecules and solute particles by osmosis and diffusion effectively balances solution concentrations—and hence pressures—on both sides of the membrane. Again, refer to Figure 9-4, in which the two balancing forces of osmosis and diffusion are shown.

Facilitated Diffusion

Facilitated diffusion follows the same principles of simple diffusion in that particles passively move down a concentration gradient. The only difference is that, with facilitated diffusion, membrane transporters assist particles

osmosis the passage of a solvent (e.g., water) through a membrane that separates solutions of different concentrations and that tends to equalize the concentration pressures of the solutions on either side of the membrane.

osmotic pressure the pressure that is produced as a result of osmosis across a semipermeable membrane.

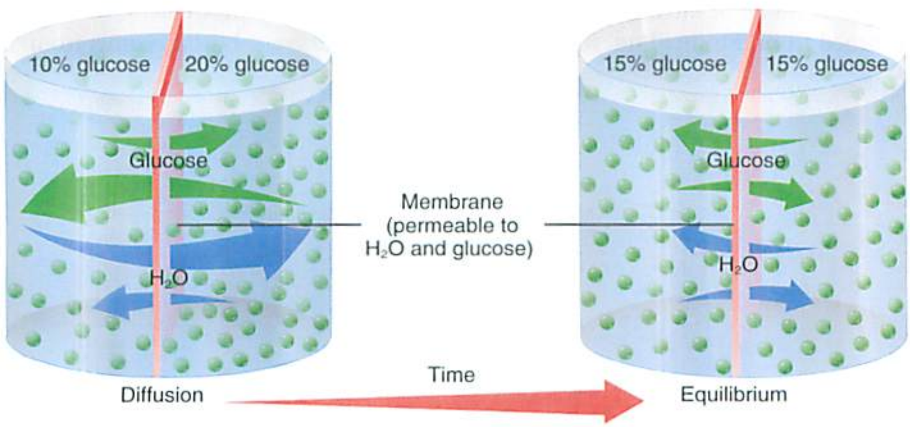

Figure 9-4 Osmosis and diffusion through a membrane. Note that the membrane that separates a 10% glucose solution from a 20% glucose solution allows both glucose and water to pass. The container on the left shows the two solutions separated by the membrane at the start of osmosis and diffusion. The container on the right shows the results of osmosis and diffusion after some time. (From Thibodeau GA, Patton KT. *Anatomy & physiology.* 6th ed. St. Louis: Mosby; 2007.)

with the crossing of the membrane. Some molecules (e.g., glucose) can diffuse across the cell membrane by either simple diffusion or facilitated diffusion, but they move much faster with the help of a transporter.

Filtration

Water is forced or filtered through the pores of membranes when the pressure outside of the membrane is different. This difference in pressure results from the differences in the particle concentrations of the two solutions, which cause water and small particles to move back and forth between capillaries and cells according to shifting pressures to establish homeostasis.

Active Transport

Particles in solution that are vital to body processes must move across membranes throughout the body at all times, even when the pressures are against their flow. Thus, energy-driven active transport is necessary to carry these particles "upstream" across separating membranes. Such active transport mechanisms usually require a carrier to help ferry the particles across the membrane (see Chapter 5).

Pinocytosis

Sometimes larger particles (e.g., proteins, fats) enter absorbing cells by the process of pinocytosis (Figure 9-5). In this process, larger molecules attach themselves to the thicker cell membrane, and they are then engulfed by the cell. In this way, they are encased in a vacuole, which is a small space or cavity that is formed in the protoplasm of the cell. In this small cavity, nutrient particles are carried across the cell membrane and into the cell. Once inside the cell, the vacuole opens, and cell enzymes metabolize the particles. Pinocytosis is one of the basic mechanisms by which fat is absorbed from the small intestine.

Tissue Water Circulation: The Capillary Fluid Shift Mechanism

One of the body's most important controls in maintaining overall water balance is the capillary fluid shift mechanism. This mechanism performs a balancing act between opposing fluid pressures to nourish the life of the cell.

Purpose

Water and other nutrients constantly circulate through the body tissues by way of blood vessels. However, to nourish cells, the water and nutrients must get out of the blood vessels (i.e., the capillaries) and into the cells. Water and cell metabolites, which are the products of metabolism that are leaving the cell, must then get back into the capillaries to circulate throughout the body. In other words, essential water, nutrients, and oxygen must be pushed out of the blood circulation and into the tissue circulation to distribute their goods throughout the body; at this point, water, cell metabolites, and carbon dioxide must be pulled back into the blood circulation to dispose of metabolic wastes through the kidneys or the lungs. The body maintains this constant flow of water through the tissues and carries materials to and from the cells by means of opposing fluid pressures: (1) hydrostatic pressure, which is an intracapillary blood pressure from the contracting heart muscle pushing blood into circulation; and (2) COP, which is pressure from the plasma proteins drawing tissue fluids back into the ongoing circulation. A filtration process operates according to the differences in osmotic pressure on either side of the capillary membrane.

Process

When blood first enters the capillary system from the larger vessels that come from the heart (i.e., the

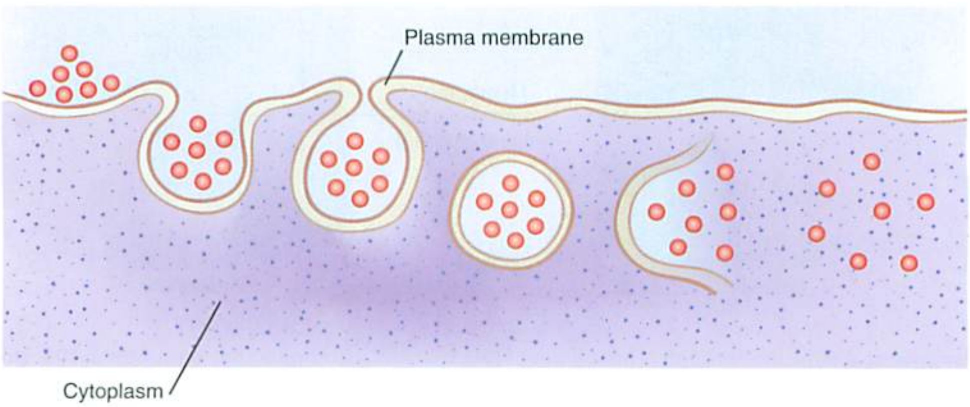

Figure 9-5 Pinocytosis; the engulfing of a large molecule by the cell.

arterioles), the greater blood pressure from the heart forces water and small particles (e.g., glucose) into the tissues to bathe and nourish the cells. This force of blood pressure is an example of hydrostatic pressure. However, plasma protein particles are too large to go through the pores of capillary membranes. When the circulating tissue fluids are ready to reenter the blood capillaries, the initial blood pressure has diminished. The COP of the concentrated protein particles that remain in the capillary vessel is now the greater influence. COP draws water and its metabolites back into the capillary circulation after having served the cells and carries them to larger vessels for blood circulation back to the heart. A small amount of normal turgor pressure from the resisting tissue of the capillary membrane remains the same and operates throughout the system. This fundamental fluid shift mechanism constantly controls water balance through its capillary and tissue circulation to nourish cells all over the body. This vital fluid flow through tissue is maintained by the balance between the blood pressure and the osmotic pressure of the plasma protein particles.

TABLE 9-6 APPROXIMATE TOTAL VOLUME OF DIGESTIVE SECRETIONS*

Secretion	Volume (mL)
Saliva	1500
Gastric secretions	2500
Bile	500
Pancreatic secretions	700
Intestinal secretions	3000
Total	8200

*As produced over the course of 24 hours by an adult of average size.

TABLE 9-7 APPROXIMATE CONCENTRATION OF CERTAIN ELECTROLYTES IN DIGESTIVE FLUIDS (MEQ/L)

Secretion	Na^+	K^+	Cl^-	HCO_3^-
Saliva	10	25	10	15
Gastric secretions	40	10	145	0
Pancreatic secretions	140	5	40	110
Jejunal secretions	135	5	110	30
Bile	140	10	110	40

Organ Systems Involved

In addition to blood circulation, two other major organ systems help to protect the homeostasis of the body water: gastrointestinal circulation and renal circulation.

Gastrointestinal Circulation

Secretions that help with the process of digestion and absorption include saliva, gastric juice, bile, pancreatic juice, and intestinal juice. Of these secretions, all but bile are predominantly water. In the latter portion of the intestine, most of the water and electrolytes are then reabsorbed into the blood to circulate over and over again. This constant movement of a large volume of water and its electrolytes among the blood, the cells, and the gastrointestinal tract is called the *gastrointestinal circulation.* The sheer magnitude of this vital gastrointestinal circulation, as shown in Table 9-6, indicates the seriousness of fluid loss from the upper or lower portion of the gastrointestinal tract. This circulation is maintained in isotonicity with the surrounding extracellular water, and it carries a risk for clinical imbalances.

Law of Isotonicity. The gastrointestinal fluids are part of the ECF compartments, which also includes the blood. These fluids are isotonic, which means that they are in a state of equal osmotic pressure that results from equal concentrations of electrolytes and other solute particles. For example, when a person drinks plain water without any solutes or accompanying food, electrolytes and salts enter the intestine from the surrounding blood supply to equalize pressures. If a concentrated solution of food is ingested, additional water is then drawn into the intestine from the surrounding blood to dilute the intestinal contents. In each instance, water and electrolytes move among the parts of the ECF compartment to maintain solutions that are isotonic in the gastrointestinal tract with the surrounding fluid (see the Clinical Applications box, "Principles of Oral Rehydration Therapy").

Clinical Applications. Because of the large amounts of water and electrolytes involved, upper and lower gastrointestinal losses are the most common cause of clinical fluid and electrolyte problems. Such problems exist, for example, in cases of persistent vomiting or prolonged diarrhea, in which large amounts of water and electrolytes are lost. The large concentration of electrolytes involved in the gastrointestinal circulation is shown in Table 9-7.

Renal Circulation

The kidneys maintain appropriate levels of all constituents of the blood by filtering the blood and then selectively reabsorbing water and needed materials to be carried throughout the body. Through this continual "laundering" of the blood by the millions of nephrons in the kidneys, water balance and the proper solution of blood are maintained. When disease occurs in the kidneys and this filtration process does not operate normally, water imbalances occur (see Chapter 21).

CLINICAL APPLICATIONS

PRINCIPLES OF ORAL REHYDRATION THERAPY

Diarrhea is usually considered a trivial problem in developed countries, however; it is the second leading cause of death among children who are younger than 5 years old worldwide (pneumonia is the leading cause).[1] Although 90% of the deaths from diarrhea are associated with fluid loss, the mere provision of water alone can be dangerous. The principles of electrolyte absorption dictate appropriate rehydration methods for children with diarrhea.

Intravenous therapy, which was developed by Darrow in the 1940s, provided sodium chloride (a base) and potassium in water and proved to be very successful. Unfortunately, intravenous therapy is not readily available to those who need it most. A large number of isolated, poor, rural families in both developed and developing countries do not have access to health care facilities. Fortunately, the World Health Organization has developed a means of oral rehydration therapy that is much less expensive and that is being used in the United States as well as in developing countries. If safe drinking water is available, the oral rehydration salt solution packet can be mixed at home and administered by a care provider. The ingredients of the oral rehydration salt packets are 2.6 g of sodium chloride (table salt), 2.9 g of trisodium citrate dihydrate, 1.5 g of potassium chloride (or a salt substitute such as Diamond Crystal or Morton Salt Substitute), and 13.5 g of glucose.[2] These salts are mixed with 1 L of safe water. (A premade formula such as Pedialyte [Abbott Laboratories, Abbott Park, Ill] is also appropriate.)

This combination is based on the principles of sodium absorption that have been observed in the small intestine.

Transport of Metabolic Compounds

A number of metabolic compounds—principally glucose but also certain amino acids, dipeptides, and disaccharides—depend on sodium to allow them to cross the intestinal wall.

Additive Effects

The rate at which sodium is absorbed depends on the presence of substances such as glucose or other protein metabolic products. The more substances that are present, the better the absorption of sodium will be.

Water Absorption

The rate of water absorption is enhanced as sodium absorption improves. Thus, a solution of sodium and potassium salts plus glucose can be given orally.

In addition to oral rehydration therapy, infants and older children with acute diarrhea should continue to eat well-tolerated foods. Fasting practices were based on the former belief that recovery is more effective if the bowel is allowed to rest and heal. To the contrary, children should be fed their regular age-appropriate diets (i.e., breast milk, formula, or solid foods), allowed to determine the amount of food that they need, and given extra food as the diarrhea subsides to recover nutritional deficits. Food choices should be guided by individual tolerances. The use of the BRAT diet (**b**ananas, **r**ice, **a**pplesauce, and **t**ea or **t**oast) is not recommended, because it does not include typical foods that are consumed by infants and small children and only worsens the energy and nutrient decline.

1. World Health Organization. *Diarrhoea: why children are still dying and what can be done*. World Health Organization: Geneva; 2009.
2. World Health Organization. *Oral Rehydration Salts: Production of the new ORS*. World Health Organization: Geneva; 2006.

Hormonal Controls

Two hormonal systems help to maintain constant body water balance.

Antidiuretic Hormone Mechanism. Antidiuretic hormone, which is also called *vasopressin,* is synthesized by the hypothalamus and stored in the pituitary gland for release. Antidiuretic hormone conserves water, and it works on the kidneys' nephrons to induce the reabsorption of water. In any stressful situation with a threatened or real loss of body water, this hormone is released to conserve body water and to reestablish the normal blood volume and osmotic pressure (Figure 9-6).

Renin-Angiotensin-Aldosterone System. As blood flow through the kidneys drops below normal, the enzyme renin is released into the blood. Renin acts to convert angiotensinogen, which is produced by the liver and circulates within the blood, to angiotensin I. Angiotensin I travels to the lungs, where angiotensin-converting enzyme (ACE) converts it into angiotensin II. Angiotensin II results in vasoconstriction and triggers the release of aldosterone from the adrenal glands, which are located on top of each kidney. Aldosterone stimulates the kidneys' nephrons to reabsorb sodium (Figure 9-7). Therefore, the renin-angiotensin-aldosterone system is primarily a sodium-conserving mechanism, but it also exerts a secondary control over water reabsorption, because water follows sodium. Both antidiuretic hormone and aldosterone may be activated by stressful situations (e.g., body injury, surgery).

ACID-BASE BALANCE

The optimal degree of acidity or alkalinity must be maintained in body fluids to support human life. This vital balance is achieved with the use of chemical and physiologic buffer systems.

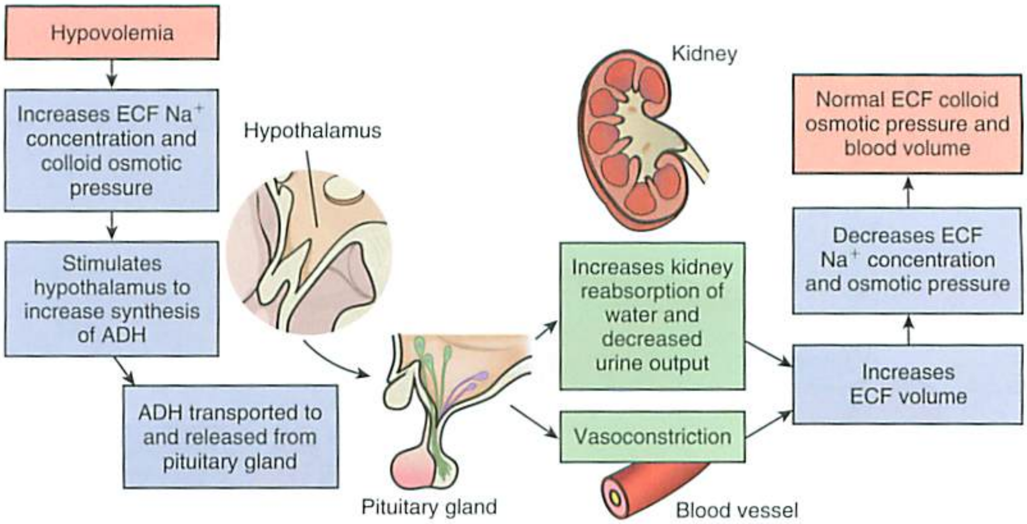

Figure 9-6 The antidiuretic hormone (ADH) mechanism. The ADH mechanism helps to maintain the homeostasis of extracellular fluid (ECF) colloid osmotic pressure by regulating its volume and electrolyte concentration.

Acids and Bases

The concept of acids and bases relates to hydrogen ion concentration. Acidity is expressed in terms of pH. The abbreviation *pH* is derived from a mathematical term that refers to the power of the hydrogen ion concentration. A pH of 7 is the neutral point between an acid and a base. Because pH is a negative mathematic factor, the higher the hydrogen ion concentration (i.e., the more acid), the lower the pH number. Conversely, the lower the hydrogen ion concentration (i.e., the less acid), the higher the pH number. Substances with a pH of less than 7 are acidic, and substances with a pH of more than 7 are alkaline.

Acids

An acid is a compound that has more hydrogen ions and that also has enough to release extra hydrogen ions when it is in solution.

Bases

A base is a compound that has fewer hydrogen ions. Thus, in solution, it accepts hydrogen ions, thereby effectively reducing the solution's acidity.

Acids and bases are the normal by-products of nutrient absorption and metabolism. As such, mechanisms to reestablish equilibrium within the body are constantly at work. Box 9-1 lists various sources of acids and bases.

Acid-Base Buffer System

The body deals with degrees of acidity by maintaining buffer systems to handle an excess of either acid or base. The human body contains many buffer systems, because only a relatively narrow range of pH (i.e., 7.35 to 7.45) is compatible with life.

BOX 9-1 **SOURCES OF ACIDS AND BASES**

Acids

Carbonic acid and lactic acid: the aerobic and anaerobic metabolism of glucose
Sulfuric acid: the oxidation of sulfur-containing amino acids
Phosphoric acid: the oxidation of phosphoproteins for energy
Ketone bodies: the incomplete oxidation of fat for energy
Minerals: chlorine, sulfur, and phosphorus

Bases

Minerals: potassium, calcium, sodium, and magnesium
Sodium bicarbonate
Calcium carbonate

Chemical Buffer System

A chemical buffer system is a mixture of acidic and alkaline components. It involves an acid and a base partner that together protect a solution from wide variations in its pH, even when strong bases or acids are added to it. For example, if a strong acid is added to a buffered solution, the base partner reacts with the acid to form a weaker acid. If a strong base is added to the solution, the acid partner combines with it to form a weaker base. The carbonic acid (H_2CO_3)/bicarbonate ($NaHCO_3$) buffer system is the body's main buffer system for the following reasons.

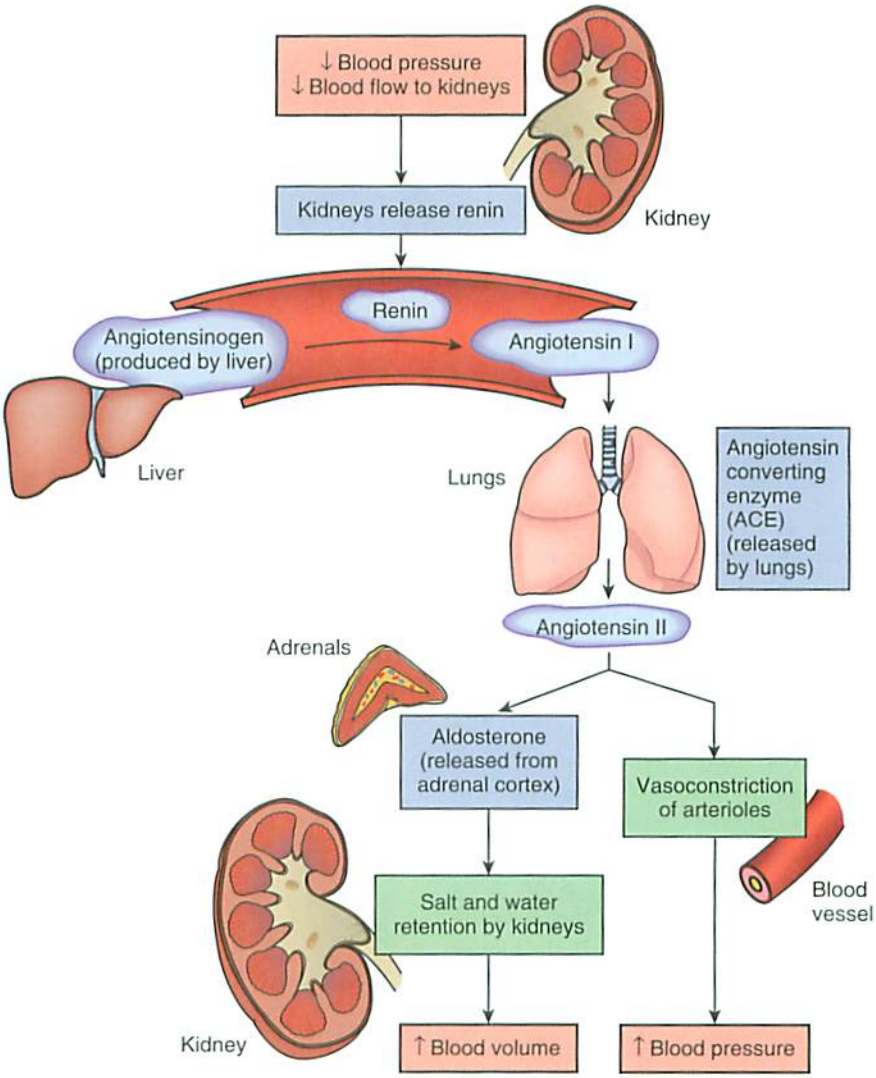

Figure 9-7 The renin-angiotensin-aldosterone mechanism. The renin-angiotensin-aldosterone mechanism restores normal extracellular fluid (ECF) volume when that volume decreases to less than normal by retaining sodium and water in the kidneys and vasoconstriction.

Available Materials. The raw materials for producing carbonic acid (H_2CO_3) are readily available: these are water (H_2O) and carbon dioxide (CO_2).

Base-to-Acid Ratio. The bicarbonate buffer system is able to maintain this essential degree of acidity in the body fluids because the bicarbonate (base) is approximately 20 times more abundant than the carbonic acid. This 20:1 ratio is maintained even though the absolute amounts of the two partners may fluctuate during adjustment periods. Whether or not additional base or acid enters the system, as long as the 20:1 ratio is maintained, over time, the ECF pH is held constant.

Physiologic Buffer Systems

When chemical buffers cannot reestablish equilibrium, the respiratory and renal systems will respond.

Respiratory Control of pH. With every breath, CO_2 (an acid) leaves the body. Therefore, changes in respiration rates can either increase or decrease the loss of acids. Hyperventilation (i.e., increasing the depth and rate of breathing) increases the release of CO_2, thereby combating **acidosis**. Conversely, hypoventilation (i.e., slowing down the depth and pace of breathing) retains CO_2, which ultimately increases the acidity of blood to alleviate **alkalosis**.

Urinary Control of pH. In the event that chemical buffer systems and the respiratory buffer system do not reestablish blood pH, the kidneys can adapt by excreting more or less hydrogen ions. If blood pH is too acidic, the kidneys will accept more hydrogen ions from the blood in exchange for a sodium ion. Because sodium ions are basic, blood is losing an acid (i.e., H^+) while gaining a base, thereby increasing blood pH back to normal.

Chemical and physiologic buffer systems are critical for maintaining the blood pH within an acceptable range for life.

acidosis a blood pH of less than 7.35; respiratory acidosis is caused by an accumulation of carbon dioxide (an acid); metabolic acidosis may be caused by a variety of conditions that result in the excess accumulation of acids in the body or by a significant loss of bicarbonate (a base).

alkalosis a blood pH of more than 7.45; respiratory alkalosis is caused by hyperventilation and an excess loss of carbon dioxide; metabolic alkalosis is seen with extensive vomiting in which a significant amount of hydrochloric acid is lost and bicarbonate (a base) is secreted.

SUMMARY

- The human body is approximately 45% to 75% water. The primary functions of body water are to provide the water environment that is necessary for cell work, to act as a transporter, to control body temperature, and to lubricate moving parts.
- Body water is distributed in two collective body water compartments: ICF and ECF. The water inside of the cells is the larger portion, which accounts for approximately 40% to 45% of the total body weight. The water outside of the cells consists of the fluid that is in spaces between cells (e.g., interstitial and lymph fluid), blood plasma, secretions in transit (e.g., the gastrointestinal circulation), and a smaller amount of fluid in cartilage and bone.
- The overall water balance of the body is maintained by fluid intake and output.
- Two types of solute particles control the distribution of body water: (1) electrolytes, which are mainly charged mineral elements; and (2) plasma proteins, which are chiefly albumin. These solute particles influence the movement of water across cell or capillary membranes, thereby allowing for the tissue circulation that is necessary to nourish cells.
- The acid-base buffer system, which is mainly controlled by the lungs and kidneys, makes use of electrolytes and hydrogen ions to maintain a normal ECF pH of approximately 7.4. This pH level is necessary to sustain life.

CRITICAL THINKING QUESTIONS

1. If a large amount of dietary sodium were consumed in one day, what effect would that likely have on the total body water level, and which compartment would be the most affected?
2. Define the term *homeostasis.* Give examples of how this state is maintained in the body.
3. Describe five factors that influence water requirements. List and describe four functions of body water.
4. Apply your knowledge of the capillary fluid shift mechanism to account for the gross body edema that is seen in malnourished individuals.

CHAPTER CHALLENGE QUESTIONS

Matching

Match the terms provided with the corresponding items listed below.

DEFINITIONS

1. The chief electrolyte that guards the water outside of cells
2. An ion that carries a negative electrical charge
3. A sodium-conserving mechanism or control agent
4. The simple passage of water molecules through a membrane that separates solutions of different concentrations from the side of a lower concentration of solute particles to the side of a higher concentration of particles, thereby tending to equalize the solutions
5. A substance (i.e., an element or compound) that, in solution, conducts an electrical current and that is dissociated into cations and anions

CHAPTER CHALLENGE QUESTIONS—cont'd

6. Particles in solution (e.g., electrolytes, protein)
7. The state of dynamic equilibrium that is maintained by an organism among all of its parts and that is controlled by many finely balanced mechanisms
8. The chief electrolyte that guards the water inside of cells
9. The major plasma protein that guards and maintains blood volume
10. The fluid that is located inside the cell wall
11. An ion that carries a positive electrical charge
12. The body's method of maintaining tissue water circulation by opposing fluid pressures
13. The force that is exerted by a contained fluid (e.g., blood pressure)
14. The movement of particles throughout a solution and across membranes outward from an area of a denser concentration of particles to all surrounding spaces
15. A type of fluid that exists outside of cells
16. The movement of particles in solution across cell membranes and against normal osmotic pressures that involves both a carrier and energy for the work

TERMS

a. Osmosis
b. Solutes
c. Diffusion
d. Cation
e. Interstitial fluid
f. Homeostasis
g. Anion
h. Potassium
i. Albumin
j. Hydrostatic pressure
k. Sodium
l. Electrolyte
m. Active transport
n. Aldosterone
o. Capillary fluid shift mechanism
p. Intracellular fluid

evolve Please refer to the Students' Resource section of this text's Evolve Web site for additional study resources.

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FURTHER READING AND RESOURCES

The following organizations provide up-to-date recommendations regarding water and electrolyte balance in addition to a plethora of other health information.

American College of Sports Medicine. www.acsm.org (search for fluid requirements)

Mayo Clinic, Food and Nutrition. www.mayoclinic.com/health/water/NU00283

Jequier E, Constant F. Water as an essential nutrient: the physiological basis of hydration. *Eur J Clin Nutr.* 2010;64(2):115-123.

Popkin BM, D'Anci KE, Rosenberg IH. Water, hydration, and health. *Nutr Rev.* 2010;68(8):439-458.

These two recent reviews address the importance of maintaining adequate hydration.

Robinson JR. Water, the indispensable nutrient. *Nutr Today.* 1970;5(1):16-23, 28-29.

This classic article by a New Zealand physician who is a world authority in this field clearly describes the processes that are involved in body water balance. This article is filled with excellent charts and diagrams to illustrate key principles.