# 2: CHEMICAL COMPOSITION OF THE BODY

## CHAPTER OVERVIEW

This chapter provides an overview of basic chemical principles that are important to understanding human physiological function and ultimately homeostasis. Key topics include a review of atomic structure, the interactions between atoms and molecular bond formation, properties of solutions, the role of hydrogen in determining pH, and lastly an overview of the structures and functions of the four classes of organic molecules that make up the human body.

## CONTEXT FOR CHAPTER 2

Most students enrolled in a human physiology course that utilizes this textbook have completed prior coursework in Biology, Chemistry, and Physics. This chapter serves very well as a review of the basic chemical principles that are important for understanding human function. As such, it is helpful to remind students that this chapter is an overview and provides the framework for future topics but that it is not all-inclusive. Although advanced students may find this chapter overly-basic, many undergraduate students express it is useful to review this content prior to more detailed study of human physiology.

The primary concepts presented in this chapter include:

1. **Atoms, Elements, Ions, and Molecules**: atom structure, chemical bond properties, the atomic composition of the human body, and how isotopes/radioisotopes are commonly used in diagnostic medicine
2. **Solutions and pH**: properties of water, molecular solubility, solute concentration, and that hydrogen concentration determines a solution's pH
3. **Classes of Organic Molecules**: an overview of the structures and basic functions associated with carbohydrates, lipids, proteins, and nucleic acids

## CONCEPTS COMMONLY FOUND TO BE CHALLENGING – TEACHING HINTS

1. Emphasize the differences between polar molecules, nonpolar molecules, amphipathic molecules, and ions. Many students find the difference between polar molecules and ions, in particular, difficult to conceptualize. A solid understanding of the distribution of electrical charges in molecules and ions is helpful for understanding upcoming topics such as enzyme actions, cell signaling (neurotransmitter, hormone, paracrine, autocrine agents as ligands that bind to protein receptors), and the mechanisms underlying the transport of molecules across

cell membranes. All of these processes will apply during discussion of how different organ systems operate.

2. An understanding of pH is vitally important to physiology, as pH is one physiological variable that is under tight physiological control. pH is an important signaling mechanism and strongly influences physiological function; for example, related to this chapter, the 3-dimensional shape of proteins and therefore protein function. It is important to understand the difference between acids and bases and their influences upon the pH of a solution.
3. It is beneficial to review the structures and functions of carbohydrates, lipids, and proteins. Each type of organic molecule contributes uniquely to human function. An understanding of carbohydrate structure and function, specifically glucose (and glycogen), is important for the discussion of the metabolic pathways and ATP production in Ch. 3 as well as regulation of energy balance in Ch. 16. Lipids are important for cell membrane structure (phospholipids, steroids such as cholesterol) and regulating which substances can move between the intracellular and interstitial fluid compartments; cell signaling via hormones (also steroid molecules); and ATP synthesis and energy balance (triglycerides). Proteins are widespread throughout the body and play numerous biological roles; it is their 3-dimensional shape that largely determines their activities.
4. Lastly, clearly identify the structural components of nucleotides. The similarities and differences in DNA and RNA structure will be particularly important to understand in Ch. 3 when protein transcription and translation are described.

**LECTURE OUTLINE**

I. Atoms
   A. Components of Atoms
   B. Atomic Number
   C. Atomic Mass
   D. Ions
   E. Atomic Composition of the Body
II. Molecules
   A. Covalent Chemical Bonds
   B. Ionic Bonds
   C. Hydrogen Bonds
   D. Molecular Shape
   E. Ionic Molecules
   F. Free Radicals
III. Solutions
   A. Water

B. Molecular Solubility
C. Concentration
E. Hydrogen Ions and Acidity

IV. Classes of Organic Molecules
A. Carbohydrates
B. Lipids
C. Proteins
D. Nucleic acids

## TEACHING/LEARNING OBJECTIVES BY SECTION

**Section 2.1 Atoms**

Students should be able to:

- Describe the relationship between atoms and elements.
- Describe the three subatomic particles that constitute the atom, and identify their atomic locations.
- Explain what an *orbital* is and discuss how electrons are arranged within orbitals.
- Explain the relationship between the number of electrons within the outermost orbital and atomic stability.
- Differentiate between the following atomic terms: atomic number, atomic mass, atomic weight, isotope, and gram atomic mass.
- Describe how ions are formed.
- Distinguish between anions, cations, and electrolytes.
- List the four major elements that comprise the human body.
- Identify the major cations and anions that are found in the human body.

**Section 2.2 Molecules**

Students should be able to:

- Identify three types of chemical bonds that can form molecules.
- Define *electronegativity*.
- Describe how polar covalent bonds are formed and how electrical charges are distributed in them.
- Describe how nonpolar covalent bonds are formed and how electrical charges are shared in them.
- Explain how ionic bonds are formed.
- Describe how polar covalent bonds lead to the formation of hydrogen bonds.
- Recognize the importance of hydrogen bonds to the structure of large molecules.
- Visualize molecules as three-dimensional and realize that their shape can change under many circumstances.

- Describe how ionization can occur in single atoms and also in atoms that are covalently linked in molecules.
- Identify the carboxyl group and the amino group.
- Define *free radical* and explain what it is at the molecular level, using atomic terminology.
- Explain why free radicals are highly reactive with other atoms and why this can be detrimental to cells.
- Identify three common, biologically-important, free radicals.

**Section 2.3 Solutions**

Students should be able to:

- Define *solute*, *solvent*, and *solution*.
- Describe the distribution of positive and negative charges in a water molecule and explain how this polarity influences the ability to react with other molecules in solution.
- Explain what is occurring at the molecular level during hydrolytic reactions (hydrolysis) and condensation reactions (dehydration).
- Distinguish between *hydrophilic, hydrophobic,* and *amphipathic* molecules.
- Describe the differences in water solubility between polar and nonpolar molecules.
- Describe the interactions that polar and ionic compounds have with water molecules which allow them to dissolve; explain the relationship to water solubility.
- Define *solute concentration* and the related terms *mole* and *molarity*.
- Determine the molarity of a solution, given the gram molecular weight of the solute.
- Differentiate between acids and bases, and between strong and weak acids and strong and weak bases.
- Define *pH* and describe the pH scale.
- Understand how pH relates to $H^+$ concentration in solution, and what it means for a solution to be acidic or basic.

**2.4 Classes of Organic Molecules**

Students should be able to:

- List the four classes of organic macromolecules in the body.
- Describe the structure and function of carbohydrates.
- Distinguish that monosaccharides are the subunits of carbohydrates, and that they can be combined to form disaccharides and polysaccharides.

- Identify glucose as an important monosaccharide and glycogen as an important polysaccharide in the human body.
- Describe the characteristics shared by all types of lipids.
- Describe the structure and function of the four subclasses of lipids: fatty acids, triglycerides, phospholipids, and steroids.
- Describe some of the major categories and functions of proteins.
- Describe the structural components of amino acids and how they bond together to form polypeptides.
- Distinguish between peptides, polypeptides, proteins, and glycoproteins.
- Describe the four levels of protein structure and the types of chemical bonds important for each level.
- Describe the structure and functions of the nucleic acids.
- Identify the structural components of nucleotides.
- Compare and contrast DNA and RNA, considering the sugar unit and the bases associated with each molecule, and their overall configurations.

## CHAPTER 2 REVIEW QUESTIONS & ANSWERS

1. Describe the electric charge, mass, and location of the three major subatomic particles in an atom.
   *The **electron** has one unit of negative charge and revolves around the atomic nucleus in orbitals. The **proton** has one unit of positive charge and is located within the nucleus. The **neutron** has no charge and is also found within the nucleus.*

2. Which four kinds of atoms are most abundant in the body?
   *Hydrogen (H), oxygen (O), carbon (C), and nitrogen (N)*

3. Describe the distinguishing characteristics of the three classes of essential chemical elements found in the body.
   *The four **major elements** listed above account for 99.3% of the total atoms in the body. There are seven essential **mineral elements—**calcium (Ca), chlorine (Cl), magnesium (Mg), phosphorus (P), potassium (K), sodium (Na), and sulfur (S). These are the most abundant substances dissolved in the body fluids. In addition, most of the body's calcium and phosphorus atoms make up the solid matrix of bone tissue. Thirteen other elements, called essential **trace elements**, are present in extremely small quantities but are nevertheless essential for normal body functions, such as growth and the blood's transport of oxygen.*

4. How many covalent bonds can be formed by atoms of carbon, nitrogen, oxygen, and hydrogen?

*Carbon can form four, nitrogen three, oxygen two and hydrogen one.*

5. What property of molecules allows them to change their three-dimensional shape?
*Molecules are not rigid structures. Atoms can rotate around their covalent bonds to form different shapes.*

6. Define *ion* and *ionic bond*.
***Ions** are formed when an atom either gains or loses one or more electrons. Atoms that gain electrons have a net negative charge and are called anions. Atoms that lose electrons have a net positive charge and are called cations. An **ionic bond** results from an electrical attraction between two oppositely charged ions.*

7. Draw the structures of an ionized carboxyl group and an ionized amino group.

*<u>Carboxyl</u>:*

```
    O
    ||
R — C — O⁻
```

*<u>Amino</u>:*

```
    H
    |
R — N⁺ — H
    |
    H
```

8. Define *free radical*.
*A free radical is an atom that contains a single (unpaired) electron in an orbital of its outer shell, as are molecules containing such atoms. Because of the lone electron in the outermost orbital, free radicals tend to be unstable and may form bonds with other atoms or molecules.*

9. Describe the polar characteristics of a water molecule.
*Water has the structure:*

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(+)  (-)  (+)
 H  — O —  H
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*The bonds between oxygen and each of the two hydrogen atoms are polar, meaning that oxygen, with eight times as many protons as hydrogen, draws the shared electrons closer to its nucleus. Water molecules interact with each other through hydrogen bonds formed between the positively charged poles associated with the hydrogen atoms and the more negatively charged region associated with the oxygen atom.*

10. What determines a molecule's solubility or lack of solubility in water?

*For a molecule to dissolve in water (i.e., be hydrophilic), it must be electrically attracted to water molecules. In other words, it must have a sufficient number of polar bonds and/or ionized groups. Nonpolar molecules do not dissolve in water because their electrically neutral covalent bonds are not attracted to water molecules. Nonpolar molecules are thus hydrophobic.*

11. Describe the organization of amphipathic molecules in water.
    *Amphipathic molecules have two parts or domains: a polar or ionized region at one end and a nonpolar region at the other end. In water, such molecules form clusters so that their hydrophilic "heads" are oriented on the outside of the cluster and their hydrophobic "tails" are oriented toward the inside, away from the water molecules.*

12. What is the molar concentration of 80 g of glucose dissolved in sufficient water to make 2 L of *solution*?
    *Glucose has a molecular weight of 180. Eighty g of glucose is 80/180 = 0.44 mol/2 L. This is equivalent to 0.22 mol/L.*

13. What distinguishes a weak acid from a strong acid?
    *Molecules that release hydrogen ions in solution are called acids. A strong acid releases 100% of its hydrogen ions, while a weak acid does not ionize completely (i.e., release its hydrogen ions) in solution.*

14. What effect does increasing the pH of a solution have upon the ionization of a carboxyl group? An amino group?
    *Increasing the pH of a solution decreases the concentration of free hydrogen ion in that solution, and thus will favor increasing the ionization of weak acids, such as a carboxyl group. It will decrease the ionization of weak bases, such as an amino group.*

15. Name the four classes of organic molecules in the body.
    *Carbohydrates, lipids, proteins, and nucleic acids*

16. Describe the three subclasses of carbohydrate molecules.
    *The basic unit of the carbohydrates is the* ***monosaccharide****, which has the chemical formula* $C_n(H_2O)_n$*, where "n" is any whole number. Two monosaccharides can join together to form a* ***disaccharide****.* ***Polysaccharides*** *are polymers of monosaccharides.*

17. What properties are characteristic of lipids?
    *Lipids are composed primarily of carbon and hydrogen atoms, which form nonpolar covalent bonds. Thus, lipids are nonpolar and hydrophobic.*

18. Describe the subclasses of lipids.
    *Fatty acids: Fatty acids consist of a chain of carbon and hydrogen atoms with an acidic carboxyl group at one end; therefore, they contain two oxygen atoms in addition to their complement of carbon and hydrogen atoms. Saturated fatty acids result when all the carbons are linked by single covalent bonds. Unsaturated fatty acids contain one or more double bonds between carbon atoms. If one double bond is present, the fatty acid is monounsaturated, and if there is more than one double bond, it is polyunsaturated.*
    *Triglycerides: Most of the body's lipids are triglycerides, or "fat." Each triglyceride is composed of three fatty acids linked to a three-carbon carbohydrate named glycerol.*
    *Phospholipids: A phospholipid is similar to a triglyceride except that in a phospholipid two fatty acid chains are linked to glycerol, with the sugar's third hydroxyl group attached to a phosphate group. Often a polar or ionized nitrogen-containing molecule is attached to the phosphate. Phospholipids, therefore, have a polar region as well as nonpolar ends and are thus amphipathic.*
    *Steroids: These are composed of four interconnected rings of carbon atoms bound to hydrogen atoms and each other, with a variety of chemical groups attached to different places in the rings.*

19. Describe the linkages between amino acids that form polypeptide chains.
    *Amino acids are linked together when the carboxyl group of one reacts with the amino group of another, forming a peptide bond and releasing a molecule of water (dehydration). The carboxyl group of the second amino acid can react with the amino group of a third, and so on, forming a polymer called a polypeptide.*

20. What distinguishes the terms *polypeptide* and *protein*?
    *A sequence of amino acids linked by peptide bonds is known as a polypeptide. Strictly speaking, the term polypeptide refers to a structural unit and does not necessarily suggest that the molecule is functional. By convention, if the number of amino acids in a polypeptide is 50 or fewer and has a known biological function, the molecule is referred to as a peptide. When one or more polypeptides are folded into a characteristic shape forming a functional molecule, that molecule is called a protein.*

21. What two factors determine the primary structure of a polypeptide chain?
    *The primary structure of a protein is determined by the number of amino acids in the chain and the specific type of amino acid at each position along the chain.*

22. Describe the types of interactions that determine the conformation of a polypeptide chain.

*The conformation of a polypeptide is its three-dimensional shape. It is determined by (1) hydrogen bonds between portions of the chain or with surrounding water molecules; (2) ionic bonds between polar and ionized regions along the chain; (3) attraction between nonpolar (hydrophobic) regions; (4) covalent bonds, called disulfide bonds, between the side chains of the amino acid cysteine (not all polypeptides have disulfide bonds); and (5) van der Waals forces, which are very weak and transient electrical interactions between the orbiting electrons in the outer shells of two atoms that are in close proximity to each other.*
*Hydrogen bonds between the hydrogen linked to the nitrogen in one peptide bond and the oxygen in another occur at regular intervals along the chain and coil it into a helical shape (alpha helix). Hydrogen bonds between peptide bonds running parallel to each other can force a straight structure called a beta pleated sheet.*
*Some proteins, called multimeric proteins, consist of more than one polypeptide chain.*

23. Describe the structure of DNA and RNA.
*DNA and RNA are nucleic acids, deoxyribonucleic acid, and ribonucleic acid, respectively. The subunits of both nucleic acids are called nucleotides, and consist of a phosphate group, a sugar (deoxyribose in DNA, ribose in RNA), and one of five possible carbon-nitrogen rings called purine or pyrimidine bases. Nucleotides are linked together by covalent bonds between the sugar and phosphate groups of adjacent subunits.*
*The three-dimensional structure of DNA is a double helix, with the two strands held together by hydrogen bonds between a purine base on one chain and a pyrimidine base on the other. RNA consists of a single chain of nucleotides.*

24. Describe the characteristics of base pairings between nucleotide bases.
*The bases in DNA are the purines, adenine and guanine, and the pyrimidines, thymine, and cytosine. Adenine binds only to thymine and guanine only to cytosine.*
*RNA can form base pairs with DNA, as above, except that RNA has the pyrimidine uracil instead of thymine. Uracil forms hydrogen bonds with adenine.*