

# The Science of Nutrition

Heather L. Lehman, Ph.D.



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## About the Author

Heather Lehman, PhD is an Associate Professor at Millersville University. She is passionate about reducing the cost of her courses for students and making materials more accessible. Dr. Lehman wrote this book to meet the needs of Biology and Allied Health students in her Nutritional Science course and non-Biology major students in her Nutrition course.



Heather L. Lehman, PhD

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# Chapter 1: the Science of Nutrition

## Introduction

Nutrition is a science, not an opinion. In a world often focused too much on surface appearances, and access to millions of opinions throughout the online space, it is important to remember that nutrition is rooted in science. The foods we choose to eat impact our quality of life, both in terms of immediate health and risk of disease. To understand a complete picture of how nutrition and human health fit together, it is essential to understand the biological and chemical bases of what nutritional science has discovered for us. Nutritional science spans almost all disciplines, including medicine, immunology, genetics, physiology, biochemistry, and psychology. Some nutritionists study food production and availability, and others study why people choose to eat certain foods, or the relationship between diet and diseases, athletic performance, weight management, and so forth. Comprehending the nutrients we need, how to obtain them and in what amounts, what our body does with them, and how these nutrients impact our overall health today and in the future are the keys to connecting the science of nutrition to our personal lives.

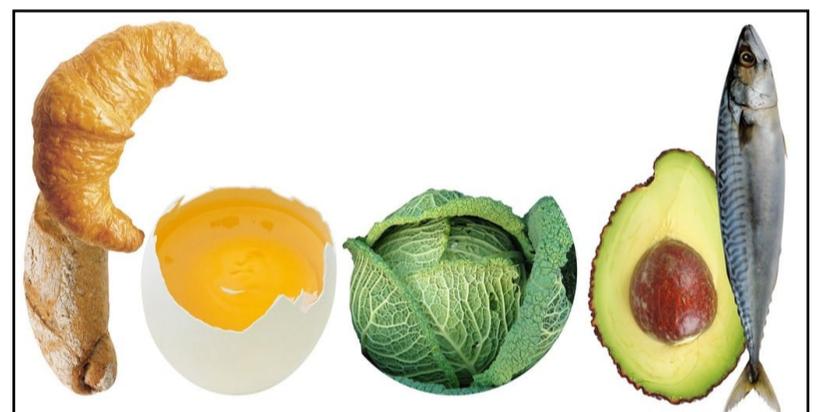


Figure 1.1 Image by [Stefan Schwehofer](#) from [Pixabay](#).

## Major Nutrients

Nutrition is the science of how living organisms obtain and use food to support required processes to function and exist.

**Nutrients** are the substances in those foods that are required or used by the body for energy, maintenance of structures, or regulation of chemical processes. Nutrients are distinguished into six categories based on chemical structure and composition: carbohydrates, proteins, lipids (fats), water, vitamins, and minerals. Table 1.1 shows the major nutrients, some of their major functions in the body, and examples of foods that contain these nutrients.

**Table 1.1 Major Functions of Nutrients in the Body**

Nutrient	Major Functions	Food Sources
<b>Carbohydrates</b>	Primary source of energy for cells Support brain and nervous system function	Fruits, vegetables, whole grains, legumes, dairy
<b>Proteins</b>	Source of energy Build and repair tissues Produce enzymes, hormones, body chemicals	Meat, poultry, fish, nuts, seeds, dairy, legumes, tofu
<b>Lipids (Fats)</b>	Provide long-term energy storage Support cell membrane structure Aid absorption of fat-soluble vitamins	Fatty fish, oils, butter, avocado, nuts, seeds
<b>Water</b>	Facilitates chemical reactions Maintains body temperature Transports nutrients, gases, wastes	Water, fruits, vegetables, soups
<b>Vitamins</b>	Regulate metabolism Support immune function Promote growth & development Antioxidant roles	Fruits, vegetables, dairy, whole grains, eggs, fortified foods
<b>Minerals</b>	Regulate fluid balance Assist in nerve transmission and muscle function Build strong bones and teeth	Meat, dairy, whole grains, legumes, nuts, seeds

Carbohydrates, proteins, lipids, and water are considered **macronutrients**, while vitamins and minerals are **micronutrients**. Macronutrients are required in larger amounts each day — greater than one gram/day — and micronutrients are required in small amounts — less than one gram per day (Table 1.2).

**Table 1.2 Macronutrients vs. Micronutrients**

Macronutrients (Need > 1 gram/day)	Micronutrients (Need < 1 gram/day)
Carbohydrates	Vitamins
Proteins	Minerals
Lipids	
Water	

Nutrients are also categorized by their requisite of consumption, as essential, nonessential, or conditionally essential nutrients.

- **Essential nutrients** are those that must be consumed through the diet because the body needs them but either can't make them or can't make enough of them to meet the body's needs. About 50 nutrients are considered essential and must be supplied through food.
- **Nonessential nutrients** are those that the body can make in adequate amounts and therefore don't need to be consumed through the diet to meet physiological requirements.
- **Conditionally essential nutrients** are normally nonessential nutrients that become essential at a point in life. For example, babies need at least four lipids from their diet, but adults only need two, making those extra two lipids conditionally essential during the infant years.



Figure 1.2 Berries are rich sources of a variety of antioxidants. [Image](#) by [Stephan](#) on [Pixabay](#).

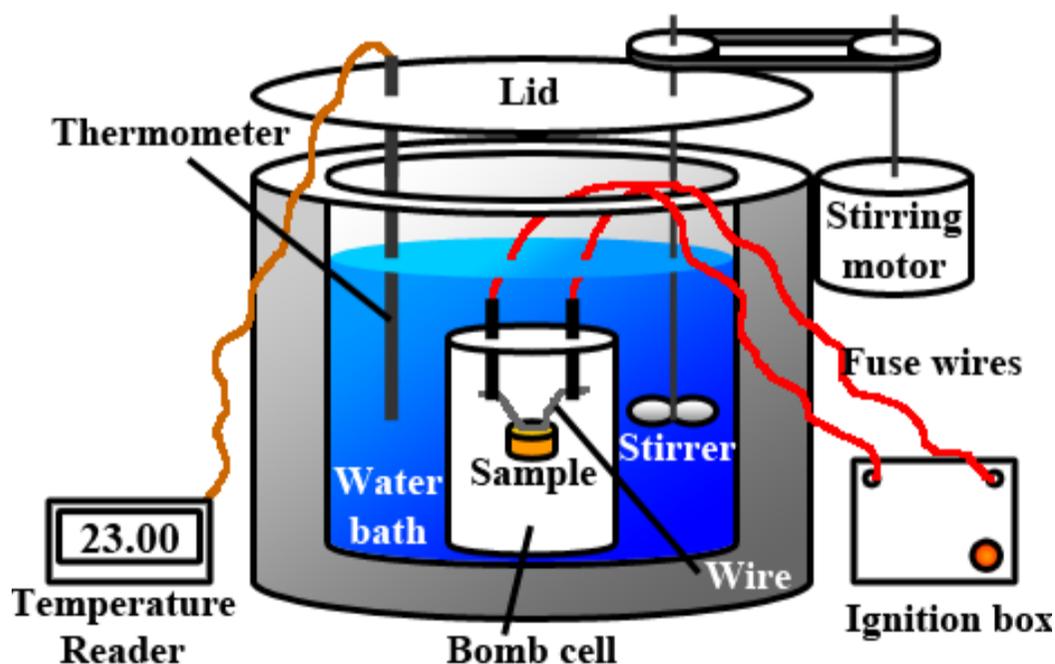
Some foods also contain beneficial **nonnutrients** — substances that are not nutrients, yet have healthful benefits. Plants make hundreds of phytochemicals, or health-promoting substances. For example, resveratrol is a compound found in grapes and berries that has antioxidant activity and may reduce the risk of heart disease (Figure 1.2). Antioxidants protect cells and their membranes from being damaged and destroyed by oxidation by chemically unstable factors called free radicals. Similarly, zoonutrients are health-promoting substances found in animal foods. For example, fish contains beneficial fatty acids that may reduce the risk of heart disease. Both phytochemicals and zoonutrients are often found in functional foods (a term often used interchangeably with 'super foods') — foods that have enhanced amounts of traditional nutrients and may promote optimal health above and beyond helping the body meet its nutritional needs.

## Food Is Energy

Food is more than just what we eat. It is the source of the energy our body needs to function. Energy is defined as the capacity of a physical system to do work. Nutrients from our food supply us with that energy, though not all nutrients! Our energy-yielding nutrients include carbohydrates, proteins, and lipids. Our cells transfer chemical energy from these energy-yielding nutrients into adenosine triphosphate (ATP) and our body uses it to support its biological and chemical processes.

In nutrition, energy is measured as calories; the more calories a food has, the more ATP can be made. The measurement of kilocalories (kcal), equivalent to 1,000 calories and 1 Calorie, expresses the energy content of a food. One kcal is the energy required to raise 1 kilogram of water by 1° Celsius. The scientific measurement of "calorie" is too small to work with when discussing nutrition, so kcal or Calorie is used. For example, instead of saying that a bowl of soup has 425,000 calories, we say that it has 425 Calories. Therefore, on nutrition labels, when it says "Calories," it is referring to the scientific notation of kilocalories.

Classically, the energy content of food was determined with an apparatus called a bomb calorimeter (Figure 1.3). Food was placed in a container that was then filled with oxygen, and the food sample was ignited. The sealed food container was surrounded by water, and the rise in water temperature reflected the amount of energy found in the food. Specifically, a 1° Celsius change in the temperature



of 1 gram of water represented 1 calorie of energy. Present-day, it is more common that mathematical means are used to determine the energy content of food. It has been determined that carbohydrates and proteins provide 4 kcal/gram and lipids provide 9 kcal/gram. With that in mind, it is recommended that 45-65% of our daily energy should come from carbohydrates, 10-35% from proteins, and 20-35% from lipids.

Figure 1.3 Bomb calorimeter used to measure the amount of energy in a food sample. "Bomb Calorimeter Diagram" by Lisdavid89 is licensed under CC BY-SA 3.0.

## Nutritional Research

The recommendations for nutritional intake are founded in years of nutrition research. But how is nutrition research conducted? Like other scientific research, the field of nutrition uses the **scientific method**, a series of steps that scientists follow to test a theory (Figure 1.4). The first step of the scientific method involves making an appropriate and accurate observation, followed by the second and third steps of asking a question and proposing a hypothesis. There are two main types of hypotheses — **causative** and **correlative**. A causative hypothesis predicts a cause-and-effect relationship, whereby a change in one factor causes a change in another, while a correlative hypothesis predicts correlations, or associations, whereby a change in one factor is related to a change in another. Correlations can be positive, where variables change in the same direction, or negative, where variables change in opposite directions.

Correlative relationships can be simple or complex. In a simple relationship, the effect of 'Factor A' on 'Factor B' is not influenced by anything. For example, a diet low in iron (Factor A) leads to an iron deficiency (Factor B). A complex relationship, however, suggests that the effect of 'Factor A' on 'Factor B' is influenced by 'Factor C'. For example, fat consumption (Factor A) is related to heart disease (Factor B), but lifestyle, genetics, and environment (Factors C) also play a role in the relationship.

The fourth step of the scientific method is to test the hypothesis through experimentation. The hypothesis of a nutritional study is typically tested through an epidemiological study or an intervention study.

### Epidemiological Studies

Epidemiological studies evaluate only correlative relationships, by making observations and recording information. People being observed are not asked to change their behaviors or receive treatments. The National Institutes of Health's Framingham Heart Study initiated in the 1940s is one of the longest-running epidemiological studies to date. For multiple generations, the study has been making observations with the goal of identifying common factors or characteristics that contribute to

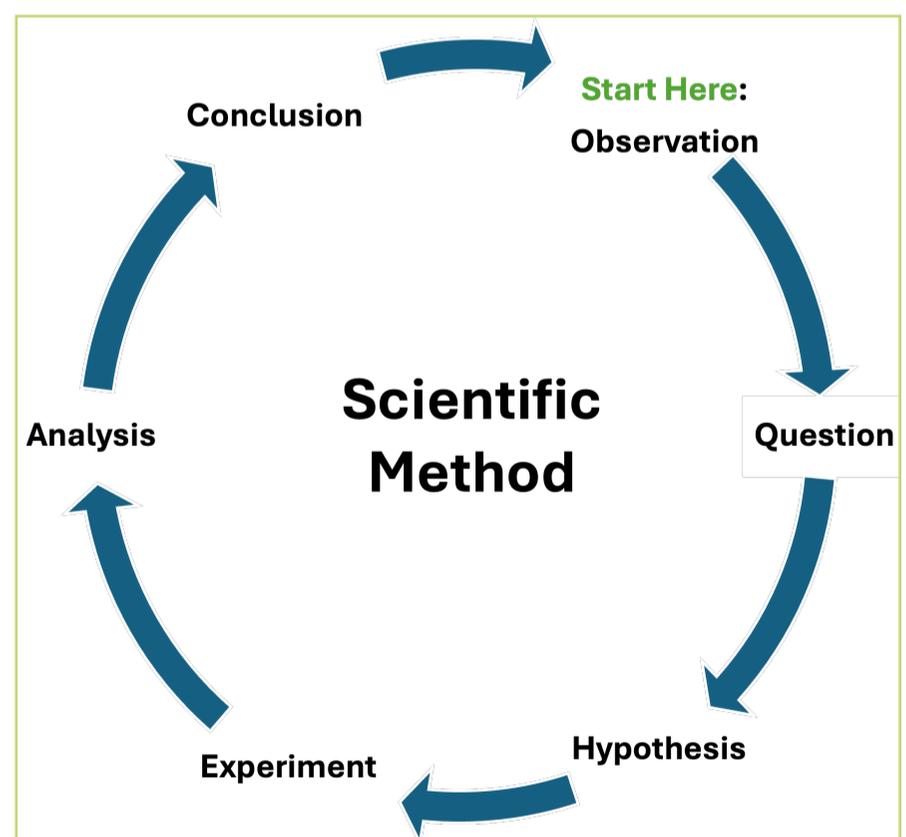


Figure 1.4 The scientific method is a continuous cycle, beginning with making an observation. Image by Author.

cardiovascular disease. Because of this, we know that cardiovascular disease is caused by modifiable risk factors like smoking, high blood pressure, obesity, high cholesterol levels, and physical inactivity.

There are various advantages and limitations to any type of study. Epidemiological studies offer several key advantages in understanding health and disease in populations. Many of these studies can be conducted relatively quickly and with limited funding. They provide insights into the overall health and disease status of populations, helping pinpoint the factors that increase or decrease the likelihood of developing a particular disease or condition. Furthermore, epidemiological studies provide a great jumping-off point for developing interventions. By understanding causes and risk factors, epidemiology guides the development of targeted public health interventions to prevent and control diseases. Though, a major limitation of epidemiological studies is that they can only show associations between factors, but they can't prove a cause-and-effect relationship, therefore making it difficult to control for confounding variables. Furthermore, study subjects may not be representative of a diverse population. Though epidemiological findings can often be generalized to other populations with similar characteristics, the results of a study on a particular population of people may not be directly applicable to another group. Another significant limitation is the potential for biased results. The Hawthorne effect is a phenomenon where individuals alter their behavior when they are aware of being observed or studied, highlighting the importance of social and psychological factors in influencing human behavior. The awareness of observation can lead to biased results, as the participants' actions may change.

## **Intervention Studies**

Intervention studies test for causality and require subjects to undergo some type of intervention. In the nutrition realm, interventions may include things such as dietary changes, lifestyle modifications, introduction of supplements or medication, or education and counseling, for example. Typically an intervention study also involves a control group that does not receive the intervention or receives a placebo, an inactive substance (often a pill or injection) that appears to be a medication but contains no active ingredients.

Intervention studies also offer a host of advantages and limitations. There is great benefit to an intervention study being able to answer a question of cause-and-effect. These studies investigate the impact of specific dietary interventions on health outcomes, providing evidence for targeted recommendations. They help to improve health outcomes and enhance our knowledge about behaviors that can promote disease prevention and management. Intervention studies are often carried out in cell cultures and animals before proceeding to human studies, confirming efficacy at multiple steps, and potentially leading to more effective and personalized treatment strategies. There are, however, some key

items that should be considered in an intervention study. Intervention studies can be financially costly, requiring more time and money, which impacts the feasibility of the work. Furthermore, humans are sometimes difficult subjects to study! Ensuring participants are following an intervention protocol as planned is challenging, as is relying on participants to self-report any of their personal data. Sustainability is often a question as well — whether the changes made during an intervention can actually be maintained over the long-term beyond the timeframe of the study.

Bias is always a variable to consider in any type of study. Social factors influencing human behavior are a consideration here, as participants may alter reports of compliance with the intervention to portray themselves as a desirable participant. Even if not consciously altering reported data, participants may have difficulty accurately recalling their self-reported data. Researcher bias can be an issue if researchers unconsciously influence a study's design, participant selection, data collection, or data analysis.

Given these considerations, the ideal nutrition intervention study would be a randomized, double-blind, placebo-controlled study. Random assignment of subjects to experimental groups (control versus treatment) helps get rid of confounding variables — factors other than ones of interest that might influence the outcome of the study. Double-blind implies the “blinding” of the researchers and participants as to who gets treatment and who does not. And a placebo-controlled study is one with the use of a placebo in the control group. As studies are continued, there is always a need for emphasis on improving the scientific rigor of these studies, ensuring they provide reliable and actionable insights for public health.

## **Nutrition Research Impacts Public Health**

Nutrition epidemiology and intervention studies are crucial for impacting public health by identifying the effects of diet on disease risk and informing evidence-based dietary recommendations and policies. The findings of these nutrition studies guide the development of dietary guidelines, food fortification programs, and policies related to food composition and labeling. By identifying dietary risk factors and understanding the links between diet and diseases, nutritional science studies help us understand how diet impacts health outcomes, contributing to preventative measures and improving overall well-being. For example, studies have shown the benefits of diets rich in fruits and vegetables or certain nutrients on reducing cardiovascular disease risk or cancer risk.

The types of diseases that ranked highest in causing mortality decades ago are not the same in the present day. While infectious diseases such as tuberculosis, influenza, and diphtheria were among the leaders in mortality rate in the early 1900s (Figure 1.5) (Jones et al., 2012), there has been a shift to noninfectious

diseases, including chronic degenerative diseases, causing increased mortality (Figure 1.6) (Kochanek et al., 2024). Ischemic heart disease and cancer are now among the top causes of mortality in the world. The Nutrition Transition Theory highlights significant shifts in dietary patterns and activity levels that occur alongside broader epidemiological trends. It could be surmised that given the rise in noninfectious diseases such as heart disease, diabetes, and cancer over the last several decades, there could be a potential link between our societal shift in diet to more processed, high-fat, high-sugar foods and the shift in prevalent diseases. This possibility highlights the need for us to be informed, aware, and encourage ongoing nutritional research.

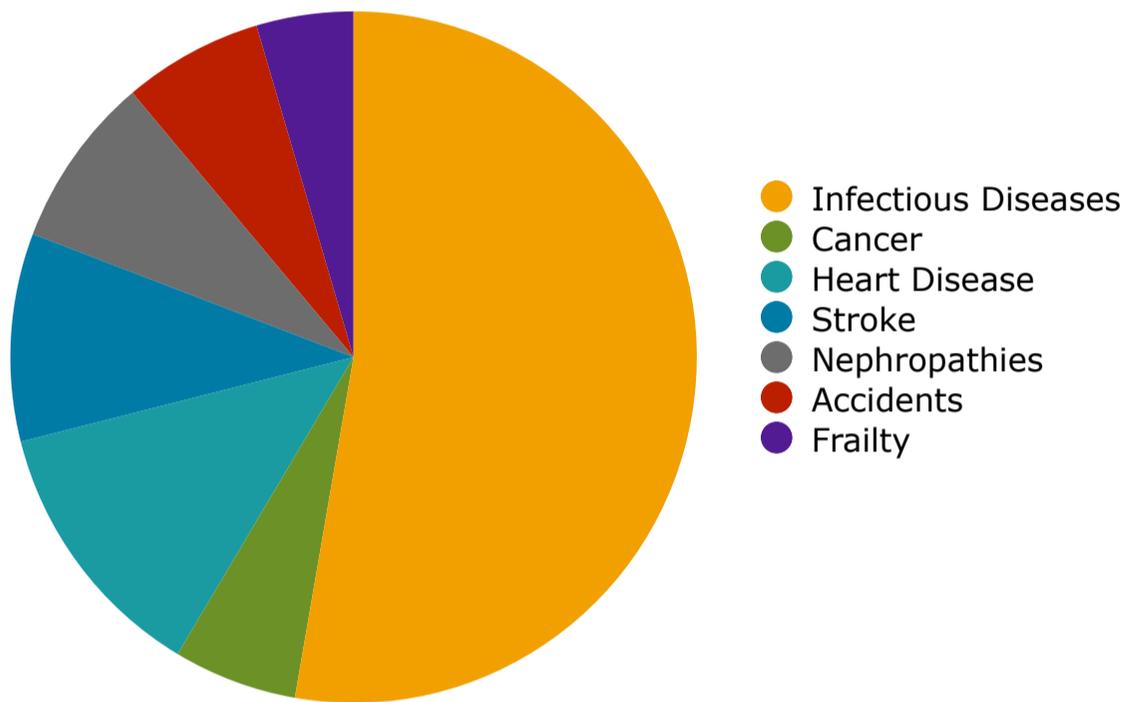


Figure 1.5 Deaths per 100,000 standard U.S. population in 1900. Infectious diseases accounted for 580 deaths per 10,000 people. Data from [Jones et al., The Burden of Disease and Changing Task of Medicine, NEJM, 2012.](#)

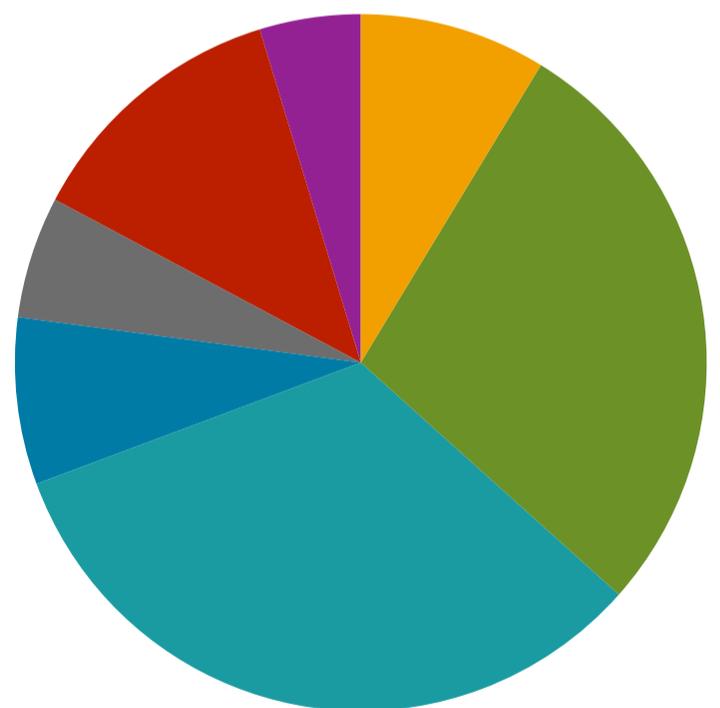
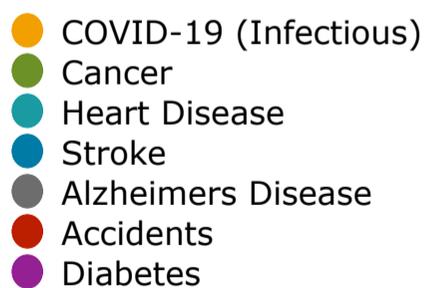


Figure 1.6 Deaths per 100,000 standard U.S. population in 2022. Heart disease and cancer are the leading causes of mortality. Data from [Kochanek et al., National Center for Health Statistics Data Brief No. 492, 2024.](#)

# Chapter 2: Nutritional Assessment

Scientists have been able to estimate the required amounts of many essential nutrients. A nutrient requirement can be defined as the smallest amount of a nutrient that maintains a defined level of nutritional health. For an individual to have optimal nutrition, there needs to be adequate consumption of essential nutrients each day in order to maintain sufficient levels of them in the body.

## Nutritional Status

**Nutritional adequacy** implies daily optimal nutrient intake for optimal physiological function. This may vary from person to person, as everyone has their own slightly different nutritional needs. Though in any individual, optimal nutrient intake (nutritional adequacy) correlates with optimal health impacts (Figure 2.1).

With too little intake of a nutrient, we can end up in a deficiency, or **undernutrition**, status. On the other end of the bell curve is **nutritional toxicity**, resulting from overconsumption of a nutrient. Either of these situations would be considered malnutrition — a state of poor nutrition with an imbalance between the nutrients required and nutrients consumed. A **primary malnutrition** is typically due to

inadequate or excess food intake, whereby the malnutrition can be addressed by a change in diet. A **secondary malnutrition** is typically due to other factors such as an underlying condition. For example, a person may be deficient in vitamin B1 because their diet is lacking vitamin-rich fruits and vegetables, or because an illness interferes with the absorption of vitamin B1. Someone with celiac disease, a digestive disorder triggered by an immune reaction to gluten (protein in wheat, barley, and rye) that damages the intestinal lining, may have multiple nutritional deficiencies, not because they aren't eating well (this would

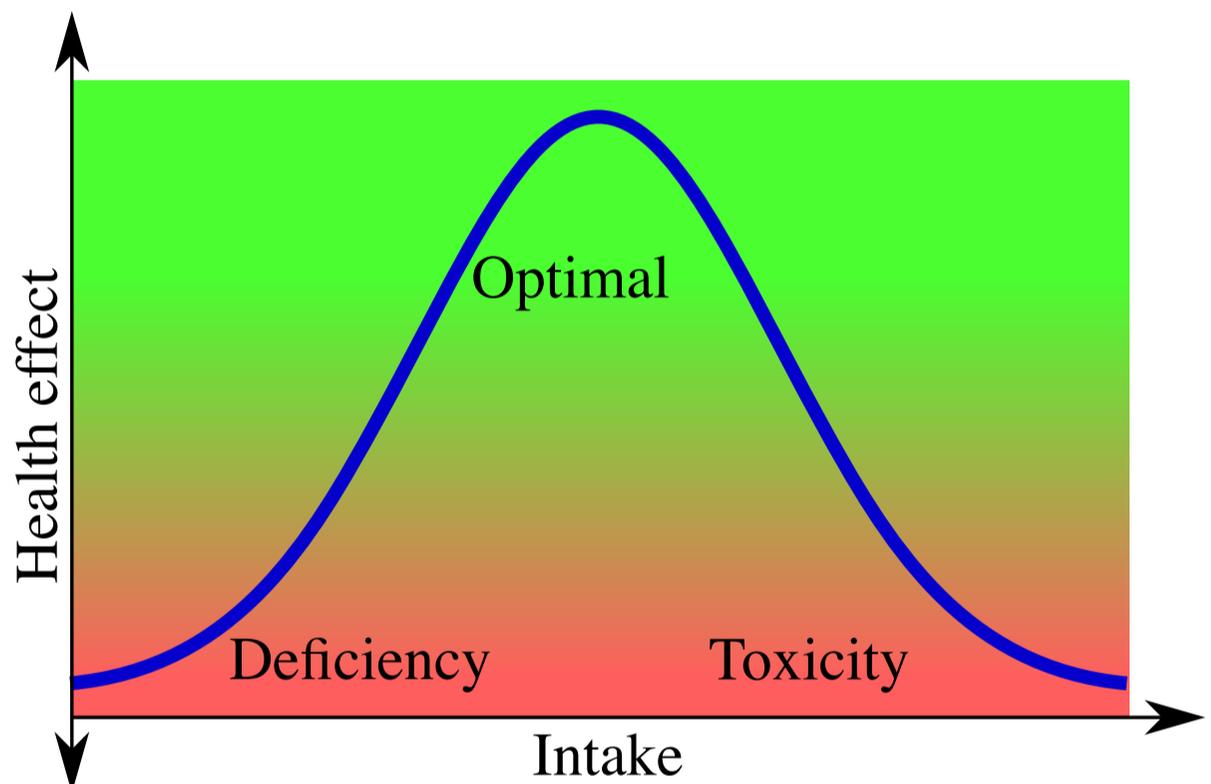


Figure 2.1 Optimal nutrient intake correlates with optimal health effects. "Bell curve of intake vs health effect" is from the [Medical gallery of Mikael Häggström 2014](#), WikiJournal of Medicine. Licensed by [Creative Commons CC0 1.0](#).

be a primary malnutrition) but because their damaged intestines can't absorb and use the nutrients they're consuming (hence, a secondary malnutrition).

## **Diet Assessment for Nutritional Adequacy**

Clinical methodology can be used to assess nutritional status. A clinical exam can assess a patient's medical history and appearance of skin, hair, eyes, and so forth. Anthropometric measurements can be taken to establish height, weight, and body circumference. Blood and/or urine tests can be obtained to look at things such as protein status or vitamin and mineral status. Biomarkers, or indicators that reflect a nutrient's function, can be evaluated. For example, hemoglobin content of the blood is often measured as a biomarker for iron status. This is because hemoglobin levels decrease during iron deficiency; so, biomarkers can help diagnose a specific nutrient issue. Even further, clinicians can assess body composition, distribution of fat, water, muscle, and mineral mass in tissues, or perform functional neurological or developmental tests that imply nutrient status.

Whether seeking the help of a clinician for assessment of nutritional status and adequate intake or using one's own resources, retrospective and/or prospective dietary assessments are tools used to aid in the understanding of an individual's intake.

## **Retrospective Dietary Assessments**

Retrospective dietary assessments are methods used to evaluate an individual's past food and nutrient intake, typically relying on memory and self-reporting. Common tools include **food frequency questionnaires** (FFQs) (Table 2.1), 24-hour dietary recalls, and diet histories. These assessments are valuable in epidemiological research and clinical settings to identify dietary patterns, estimate nutrient intake, and explore associations between diet and health outcomes. However, their accuracy can be limited by recall bias, misreporting, and the difficulty individuals may have in estimating portion sizes or remembering food consumed over extended periods. Additionally, humans tend to lack honesty with these tools, often overestimating the amount and frequency at which they're consuming "healthy" items and underestimating "unhealthy" items. Despite these limitations, retrospective assessments remain widely used due to their practicality and cost-effectiveness compared to prospective methods.

**Table 2.1 Food frequency questionnaire example**

Food Item	Never	1-3x/ month	1x/ week	2-4x/ week	5-6x/ week	1x/ day	2-3x/ day	4-5x/ day	6+x/ day
Fruits (apples, bananas, etc.)	<input type="checkbox"/>								
Vegetables (carrots, potatoes, etc.)	<input type="checkbox"/>								
Dairy (cheese, milk, yogurt, etc.)	<input type="checkbox"/>								
Red meat (beef, pork, lamb)	<input type="checkbox"/>								
Sweetened beverages	<input type="checkbox"/>								
Leafy greens (spinach, kale, etc.)	<input type="checkbox"/>								
Grains (breads, pasta, rice, etc.)	<input type="checkbox"/>								
Sweets (candy, cookies, pie, etc.)	<input type="checkbox"/>								
Nuts (almonds, cashews, etc.)	<input type="checkbox"/>								

### Prospective Dietary Assessments

Prospective dietary assessments involve the real-time or forward-looking collection of dietary intake data, typically recorded by individuals as they consume foods and beverages. Common methods include **food diaries** or food records, where individuals document everything they eat and drink over a specified period, often ranging from three to seven days (Table 2.2). The ideal prospective assessment is kept for at least three days, including part of a weekend to account for potential variations in diet from weekdays to weekends. These are typically considered to be one of the most accurate dietary assessment methods. This approach reduces reliance on memory and can provide more accurate and detailed information about portion sizes, meal timing, and preparation methods. Many computerized nutrient databases now exist to allow ease of recording intake as well as caloric and nutrient consumption. And while prospective methods can yield high-quality data, they may still be burdensome for people and prone to underreporting or changes in eating behavior due to increased self-awareness. Despite these challenges, prospective assessments are

valuable tools in both research and clinical practice for closely monitoring dietary intake and identifying relationships between diet and health outcomes.

**Table 2.2 Example day of dietary journal**

Time	Food & Beverage	Amount	Notes (Hunger, Mood, etc.)
7:30 AM	Oatmeal with banana and almonds	1 cup oatmeal, 1/2 banana, 1 tbsp almonds	Slightly hungry, feeling good
10:00 AM	Greek yogurt with honey	1 small container, 1 tsp honey	Light snack, felt energized
12:45 PM	Grilled chicken sandwich, side salad	1 sandwich, 1 cup salad	Moderately hungry, satisfied after
3:30 PM	Apple and peanut butter	1 medium apple, 1 tbsp PB	Craving something sweet
6:30 PM	Spaghetti with marinara sauce, steamed broccoli	1.5 cups pasta, 1 cup broccoli	Very hungry, comfort meal
8:00 PM	Herbal tea and chocolate chip cookies	1 cup tea, 4 cookies	Relaxed, nice treat

## Nutritional Adequacy Standards

Dietary assessment methods allow us to understand our dietary intake. But how do we know whether our intake aligns with our nutrient requirements? As mentioned previously, a nutrient requirement can be defined as the smallest amount of a nutrient that maintains a defined level of nutritional health. The daily consumption of a nutrient requirement typically prevents an individual from experiencing any physiological or disease symptoms caused by a nutrient deficiency. Yet, nutrient requirements differ amongst people due to a number of factors. The amount of a nutrient a person must consume for optimal health depends on sex, life stage (age group and/or physiologic state, such as pregnancy), genetics, lifestyle choices, activity levels, environment, medications, and the like.

### Dietary Reference Intakes

Dietary Reference Intakes (DRIs) are a set of scientifically developed nutrient reference values established by the Food and Nutrition Board (FNB) as part of the National Academies of Sciences, Engineering, and Medicine (Figure 2.2). The DRIs are used to guide dietary planning and assess nutrient intakes for healthy individuals and populations. DRIs are used by healthcare professionals, researchers, and policymakers to guide nutritional recommendations, assess diet quality, and set standards for food labeling and fortification (addition of nutrients to common foods). DRIs encompass several different values, each serving a

specific purpose in evaluating or planning diets. These include the Estimated Average Requirement (EAR), Recommended Dietary Allowance (RDA), Adequate Intake (AI), and Tolerable Upper Intake Level (UL). Together, these values support nutritional policy, research, and clinical practice by helping identify nutrient deficiencies and prevent overconsumption. And while their initial development was spurred by malnutrition due to undernutrition and nutritional deficiencies, over time it has been recognized that these standards are important, beyond the scope of deficiencies, in decreasing risk for chronic degenerative diseases.

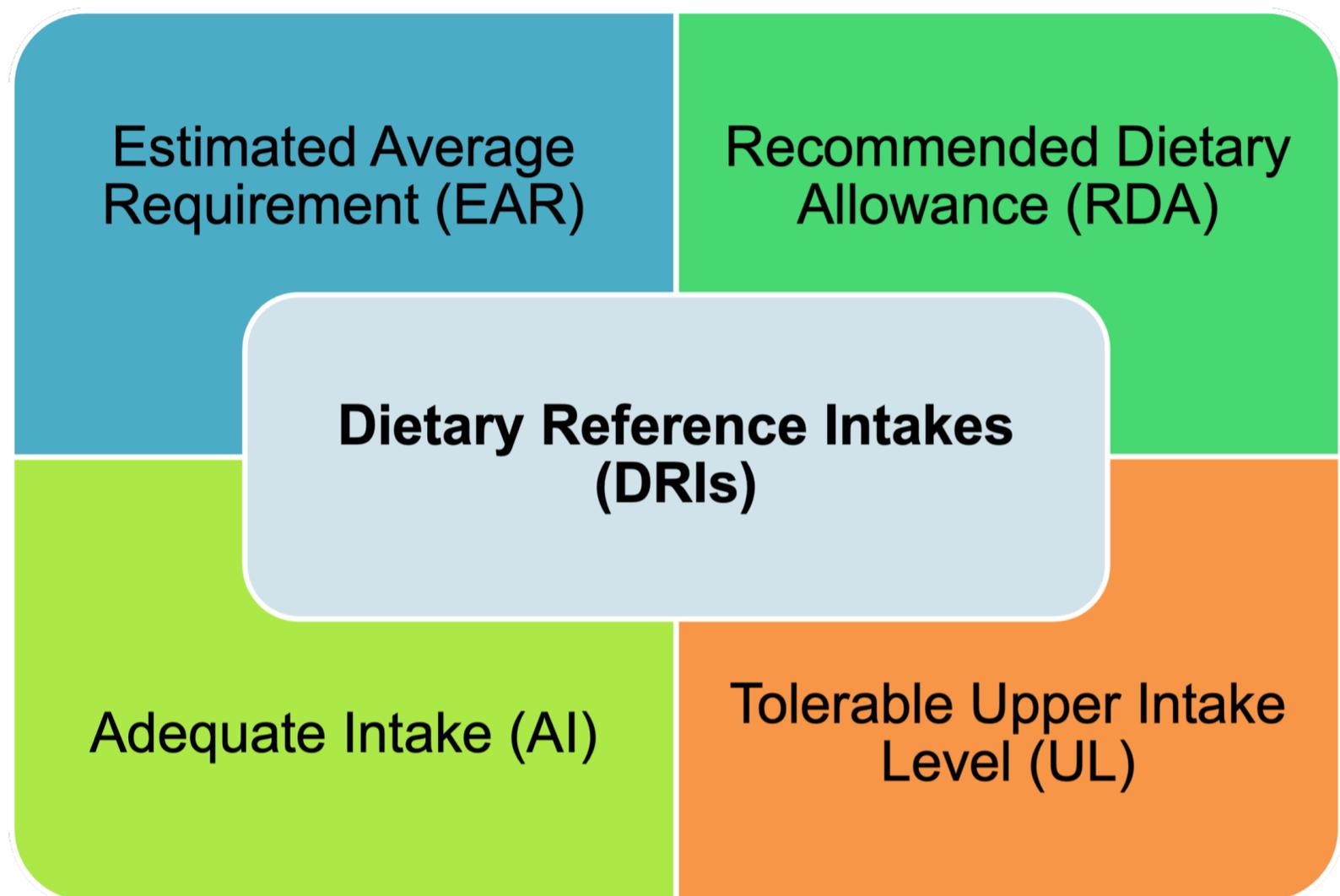


Figure 2.2 The established Dietary Reference Intakes (DRIs) include four standards for nutrient intake: the Estimated Average Requirement, Recommended Dietary Allowance, Adequate Intake level, and Tolerable Upper Intake Level. Image by Author.

### **Estimated Average Requirement (EAR)**

The Estimated Average Requirement (EAR) is the daily nutrient intake level estimated to meet the needs of 50% of healthy individuals in a specific age and life stage group. EARs are primarily used in research and policy development to assess the adequacy of nutrient intakes in populations rather than individuals. They also serve as the basis for calculating the recommended dietary allowance (RDA). If an individual's intake is below the EAR, it suggests a higher likelihood of inadequacy, whereas intake above the EAR has a higher probability of being sufficient.

## Recommended Dietary Allowance (RDA)

The Recommended Dietary Allowance (RDA) is the average daily intake level sufficient to meet the nutrient requirements of nearly all (97–98%) healthy individuals in a particular life stage and sex group. RDAs are based on the EAR, with an added margin to account for individual variability in nutrient needs. They are the most widely recognized and used DRI values in both clinical and public health contexts, serving as a daily goal for individual intake to ensure nutritional adequacy.

## Adequate Intake (AI)

Adequate Intake (AI) levels are established when there is insufficient evidence to determine an EAR and, by extension, an RDA. AI values are based on observed or experimentally determined approximations of nutrient intake by healthy populations that are assumed to be adequate. While AIs are not as precise as RDAs, they still offer practical guidance for nutrient intake when more definitive data are lacking, especially for infants or emerging nutrients.

## Tolerable Upper Intake Level (UL)

The Tolerable Upper Intake Level (UL) represents the maximum average daily nutrient intake that is unlikely to pose risks of adverse health effects for almost all individuals in the general population. ULs are not recommended targets but instead act as safety limits to prevent toxicity or negative health outcomes from excessive intake, particularly for nutrients that are commonly consumed as supplements or found in fortified foods. ULs are important in monitoring high-dose nutrient consumption and ensuring public safety.

## Using DRI Standards To Assess Intake

Combining the tools of dietary recording and assessment with established recommended intake standards allows us to compare personal dietary intake with the suggested intake values for a particular sex and life stage.

Let's look at an example of this using calcium intake for a 19-year-old female:

- The **EAR** for calcium for females aged 19–30 is 800 mg/day. This is the intake estimated to meet the needs of 50% of individuals in this group. If her intake is below 800 mg/day, there's a higher likelihood that she's not meeting her calcium needs.
- The **RDA** for this age group is 1,000 mg/day. This level is expected to meet the needs of ~97% of individuals. If she consumes 1,000 mg or more per day, it is likely her intake is sufficient.
- The **AI** is not used in this scenario. Calcium has an RDA based on sufficient evidence, so there is no need for an AI. However, if it were a nutrient with

no established RDA, such as potassium, the AI would be the target for intake.

- The **UL** for calcium for this age group is 2,500 mg/day. Consistently consuming calcium above this amount could increase the risk of adverse effects, such as kidney stones or impaired absorption of other minerals.

The daily goal for an individual is to meet or exceed the RDA for a nutrient and stay below the UL (Figure 2.3). So, for example, if this 19-year-old female is consuming around 1,500 mg of calcium per day, her intake is above the RDA and well below the UL, meaning it is likely adequate and not considered excessive. However, if her intake were closer to 700 mg, it would be below the EAR, indicating a likely risk of inadequate calcium intake. If her intake were to fall between the EAR and RDA, it may be likely that it is sufficient, though the specific recommendation would likely be to increase intake to meet or exceed the RDA.

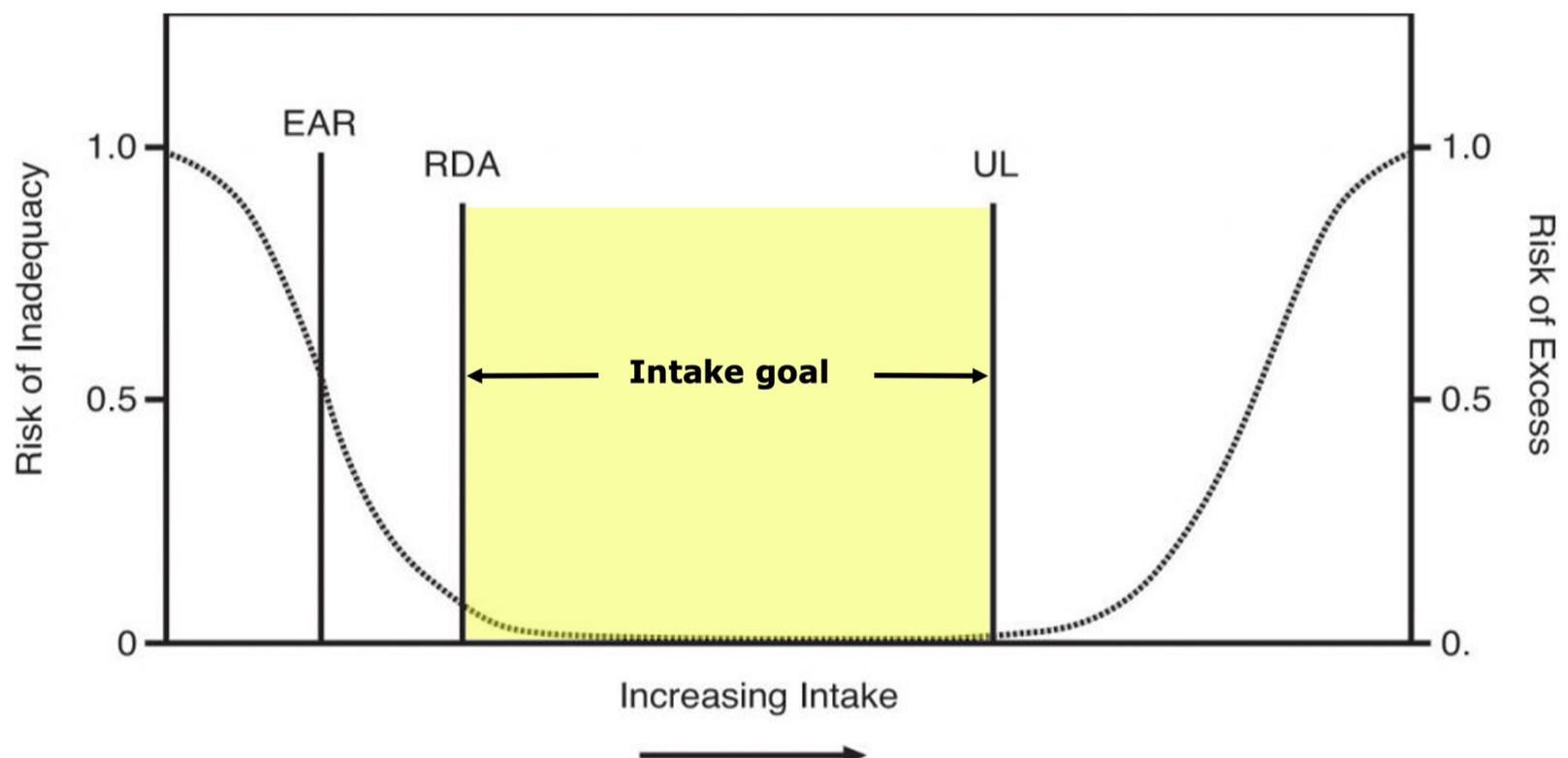


Figure 2.3 Dietary reference intake standards. The daily intake goal for a nutrient lies between the recommended dietary allowance (RDA) and the tolerable upper intake level (UL), avoiding the risk for inadequate or excessive nutrient intake. Modified by author from “DRI Graph” from [Human Nutrition by Langara College, Nutrition and Food Service Management Program](#) is licensed under a [Creative Commons Attribution 4.0 International License](#).

## Acceptable Macronutrient Distribution Range (AMDR)

Acceptable Macronutrient Distribution Ranges (AMDRs) describe the recommended proportions of energy (calories) that should come from each of the three **energy-yielding macronutrients**—carbohydrates, proteins, and fats—to promote health and reduce the risk of chronic disease.

These ranges are expressed as percentages of total daily caloric intake and are based on evidence linking nutrient intake with health outcomes. For adults, the AMDRs suggest that 45–65% of daily total calories come from carbohydrates,

10–35% from protein, and 20–35% from fat. Staying within these ranges supports adequate nutrient intake while helping to prevent conditions such as cardiovascular disease, type 2 diabetes, and nutrient deficiencies. For example, Table 2.3 shows that a person consuming 2,000 calories per day should aim for about 900–1,300 calories from carbohydrates (225–325 grams), 200–700 calories from protein (50–175 grams), and 400–700 calories from fat (44–78 grams). AMDRs provide flexibility for individual preferences and dietary patterns while guiding balanced macronutrient consumption.

**Table 2.3 Acceptable Macronutrient Distribution Ranges for adults consuming 2,000 kcal/day**

Macronutrient	AMDR (% of total energy intake)	Calories
Carbohydrate	45-65	900-1300
Protein	10-35	200-700
Fat	20-35	400-700

## Energy Requirements

### Estimated Energy Requirements

The Estimated Energy Requirement (EER) is the average dietary energy intake required for growth or maintenance in a healthy individual of a defined age, gender, weight, height, and level of physical activity. Unlike nutrient-specific recommendations, the EER focuses on caloric intake necessary to support basic physiological functions and sustain a healthy body weight.

EER values vary widely based on life stage and activity level. For example, an active 11-year-old male may require approximately 2,300 calories per day, while a sedentary 11-year-old male might need closer to 1,700 calories per day.

**Table 2.4 Age and activity level affect EERs. EERs for a 25-year-old female, weighing 65 kg (143 lbs) and 165 cm (5'5") tall, across different activity levels.**

Activity level	EER (~kcal/day)
Sedentary (little to no exercise)	1,675
Low Activity (light exercise/sports 1-3 days/week)	1,920
Moderately Active (moderate exercise/sports 3-5 days/week)	2,165
Very Active (hard exercise/sports 6-7 days/week)	2,650

Similarly, a 25-year-old female may require approximately 2,500 calories per day, while a sedentary 25-year-old female might need closer to 1,600 calories. Activity level greatly impacts the EER for any individual at any life stage, with even great differences at various tiers of activity levels (Table 2.4). The EER is a useful tool for diet planning, weight management, and public health guidelines. It also plays a foundational role in calculating the AMDRs, as the percentage recommendations for macronutrients are based on total energy needs.

## Use of Energy From Food

Our bodies rely on the energy from food to power essential processes that keep us alive and functioning. This energy fuels chemical reactions that maintain and repair body tissues, ensuring our cells and organs stay healthy and operate properly. It also supports the electrical conduction of nerve impulses, allowing communication between the brain and body for movement, sensation, and reflexes. In addition, the mechanical work of muscles—whether it's walking, breathing, or even pumping blood—depends on this energy. The body uses energy to produce heat, helping to regulate internal temperature and keep it within a narrow, healthy range despite changes in the external environment.

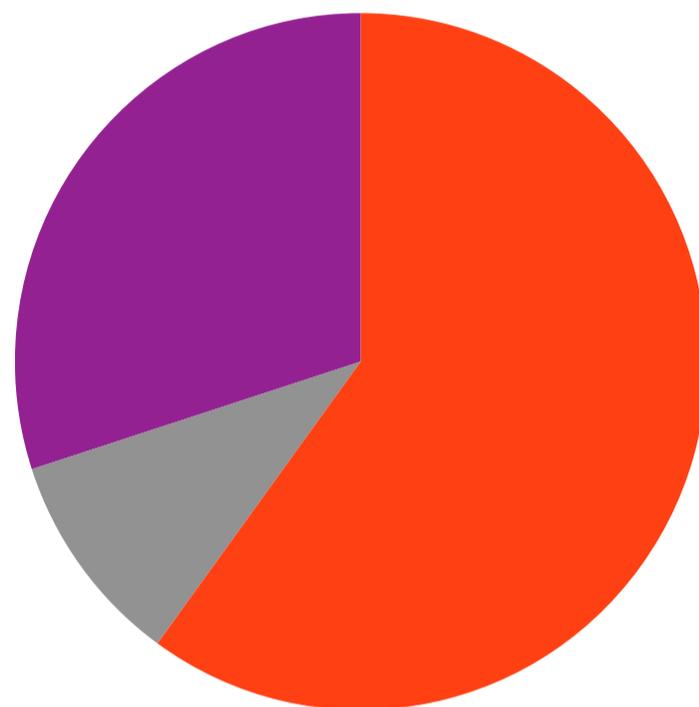


Figure 2.4 Main components of total energy expenditure (TEE) include basal metabolic rate (BMR), activity thermogenesis (AT), and thermic effect of food (TEF). BMR typically accounts for approximately 60% of TEE, while TEF accounts for close to 10%, and AT accounts for 30% (National Academies Press, 2023).

## Total Energy Expenditure

Total energy expenditure (TEE) is the total amount of energy the body uses in a day, and it is made up of three main components (Figure 2.4). The largest portion is the **Basal Metabolic Rate (BMR)**, which accounts for the energy used to maintain basic bodily functions at rest, such as breathing, circulation, and cell production. The second component is the **Thermic Effect of Food (TEF)**, which is the energy required to digest, absorb, and process the nutrients from the food we eat. The third component is **Activity Thermogenesis**, which includes all physical activity, from structured exercise to daily tasks like walking or cleaning. In some cases, a fourth component called **Non-Exercise Activity Thermogenesis (NEAT)** is considered separately, which includes spontaneous movements such as fidgeting or posture changes. Together, these components determine how many calories a person burns each day, and they vary based on factors like age, body composition, activity level, and overall health.

## Basal Metabolic Rate (BMR)

BMR is a measure of basal energy expenditure each day; the energy needed to maintain vital functions, sustaining metabolic activities of cells and tissues, and maintaining processes such as blood circulation, respiration, gastrointestinal function, and renal function.

Several key factors influence an individual's BMR, the most significant factors include the following:

- 1. Body size and composition:** People with more muscle mass have a higher BMR because muscle tissue burns more calories at rest than fat tissue.
- 2. Age:** BMR is highest during periods of rapid growth and generally decreases with age due to a natural loss of muscle mass and hormonal changes.
- 3. Sex:** Males typically have a higher BMR than females because they often have more muscle mass and less body fat.
- 4. Genetics:** Some people naturally have a faster or slower metabolism due to inherited traits.
- 5. Hormones:** Hormones, especially those produced by the thyroid gland play a major role in regulating BMR.
- 6. Health status:** Illnesses, fever, or injuries can raise BMR as the body works harder to heal and maintain normal function.
- 7. Environmental temperature:** Being in a cold environment can increase BMR slightly as the body works to maintain a stable internal temperature. Tropical climates can also lead to an increase in BMR.

These factors interact in complex ways, and changes in any of them can affect how many calories the body needs to function at rest.

## Activity Thermogenesis

Activity thermogenesis is the component of total energy expenditure that includes all the energy used during physical movement. It can be divided into two main parts: **exercise activity thermogenesis**, which refers to planned and intentional physical activities like running, swimming, or strength training, and **non-exercise activity thermogenesis (NEAT)**, which includes unstructured movements such as walking to class, typing, fidgeting, or doing household chores. Activity thermogenesis varies the most among individuals as a component of daily energy expenditure and can significantly influence total energy expenditure depending on how active a person is. For example, someone with a physically demanding job or a regular exercise routine will have a higher activity-related energy expenditure compared to someone who is mostly

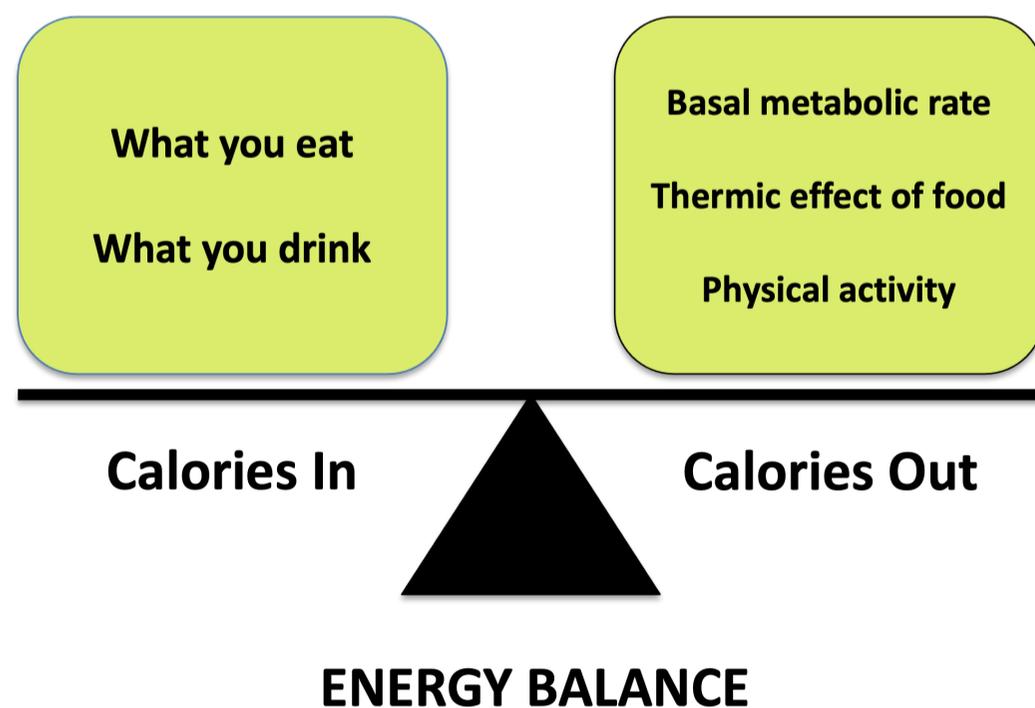
sedentary. Because it is a modifiable component, increasing daily physical activity is one of the most effective ways to boost total energy expenditure and support overall health.

## Thermic Effect of Food (TEF)

The Thermic Effect of Food, also known as the Specific Dynamic Action, refers to the increase in energy expenditure that occurs after eating, as the body works to digest, absorb, transport, metabolize, and store nutrients. TEF typically accounts for about 5–10% of total daily energy expenditure. Different types of nutrients have varying thermic effects—protein has the highest TEF, requiring more energy to process, followed by carbohydrates, and then fats, which have the lowest TEF. While TEF is a smaller component of total energy expenditure compared to basal metabolic rate or physical activity, it still plays a role in overall metabolism and can be influenced by factors such as meal size, composition, and timing. Eating frequent, balanced meals that include protein can slightly boost TEF and may contribute to energy balance and weight management.

## Energy Balance

Energy balance refers to the relationship between the number of calories consumed through food and beverages (energy in) and the number of calories the body uses for basic functions and physical activity (energy out). When energy intake equals energy expenditure, the body is in energy balance, and body weight tends to remain stable (Figure 2.5). A **positive energy balance** occurs when calorie intake exceeds expenditure, leading to weight gain. A positive energy balance may be desirable during periods of growth such as infancy, childhood, and pregnancy. An “unhealthy” positive energy balance is typically



characterized by being associated with an increase in fat tissue. Conversely, a **negative energy balance** — when calorie output is greater than input — results in weight loss. A negative energy balance could be a result of insufficient energy intake, excessive energy expenditure, or both. Achieving and maintaining energy balance is important for supporting growth, fueling daily activities, and managing body weight.

Figure 2.5 Energy balance is achieved when energy intake equals energy expenditure. Image by Author.

## **Application of Nutrient Standards**

Understanding nutrient standards, energy requirements, and total energy expenditure provides a foundation for making informed decisions about diet and health. Nutrient standards, such as the Dietary Reference Intakes (DRIs), offer guidance on the recommended intake of essential nutrients to support health and prevent deficiencies. Nutrition standards have a variety of applications and experts refer to the DRIs frequently. DRIs are used for developing nutrition labels, formulating dietary guidelines, and ensuring food and supplement safety. DRIs are also used to support the development of educational materials, marketing of products, counseling for consumers, and provide a framework for further research on the impact of dietary factors on health.

Energy requirements, based on individual factors like age, sex, weight, and activity level, help determine how many calories a person needs each day to maintain, lose, or gain weight. Total energy expenditure, which includes basal metabolic rate, the thermic effect of food, and physical activity, reflects the total number of calories burned daily. Applying this knowledge can help individuals plan balanced meals, maintain a healthy body weight, and support overall well-being. Whether for personal health goals or professional practice, understanding these concepts is key to promoting nutritional health across the lifespan.

# Chapter 3: Digestive System

The digestive system is the gateway through which our bodies receive the nutrients needed for energy, growth, and overall health. In the study of nutrition,



Figure 3.1 Eating and digesting an apple requires the coordination of the entire digestive system. [Image from pxhere](#); this image is released free of copyrights under [Creative Commons CC0 1.0](#).

understanding how the body breaks down food into usable components is essential. The digestive system is a complex network of organs and processes that work together to mechanically and chemically digest food, absorb nutrients, and eliminate waste. Digestion of even one apple (Figure 3.1) requires the full coordination of all parts of the digestive system. From the moment food enters the mouth to its final exit from the body, each step plays a vital role in making nutrients available for use.

This chapter explores the structure and function of the digestive system, the journey of food through the gastrointestinal tract, and how nutrients are absorbed and transported to where they are needed most. By understanding digestion, we can better appreciate the connection between what we eat and how our bodies function.

## Overview of the Digestive System

The digestive system is responsible for breaking down the food we eat into smaller components that the body can absorb and use for energy, growth, and repair. It has two main parts: the **gastrointestinal (GI) tract** and the **accessory organs** (Figure 3.2).

The GI tract, or alimentary canal, is a long, hollow, muscular tube that runs from the mouth to the anus. It includes major organs like the esophagus, stomach, small intestine, and large intestine. The accessory organs, which include the salivary glands, liver, pancreas, and gallbladder, are not part of the GI tract itself but play important roles by producing and releasing secretions for digestion into ducts that empty into the lumen (interior space) of the GI tract. Together, these components help the body get a steady supply of water, electrolytes, vitamins, and nutrients, turning what we eat into the materials our bodies need to thrive.

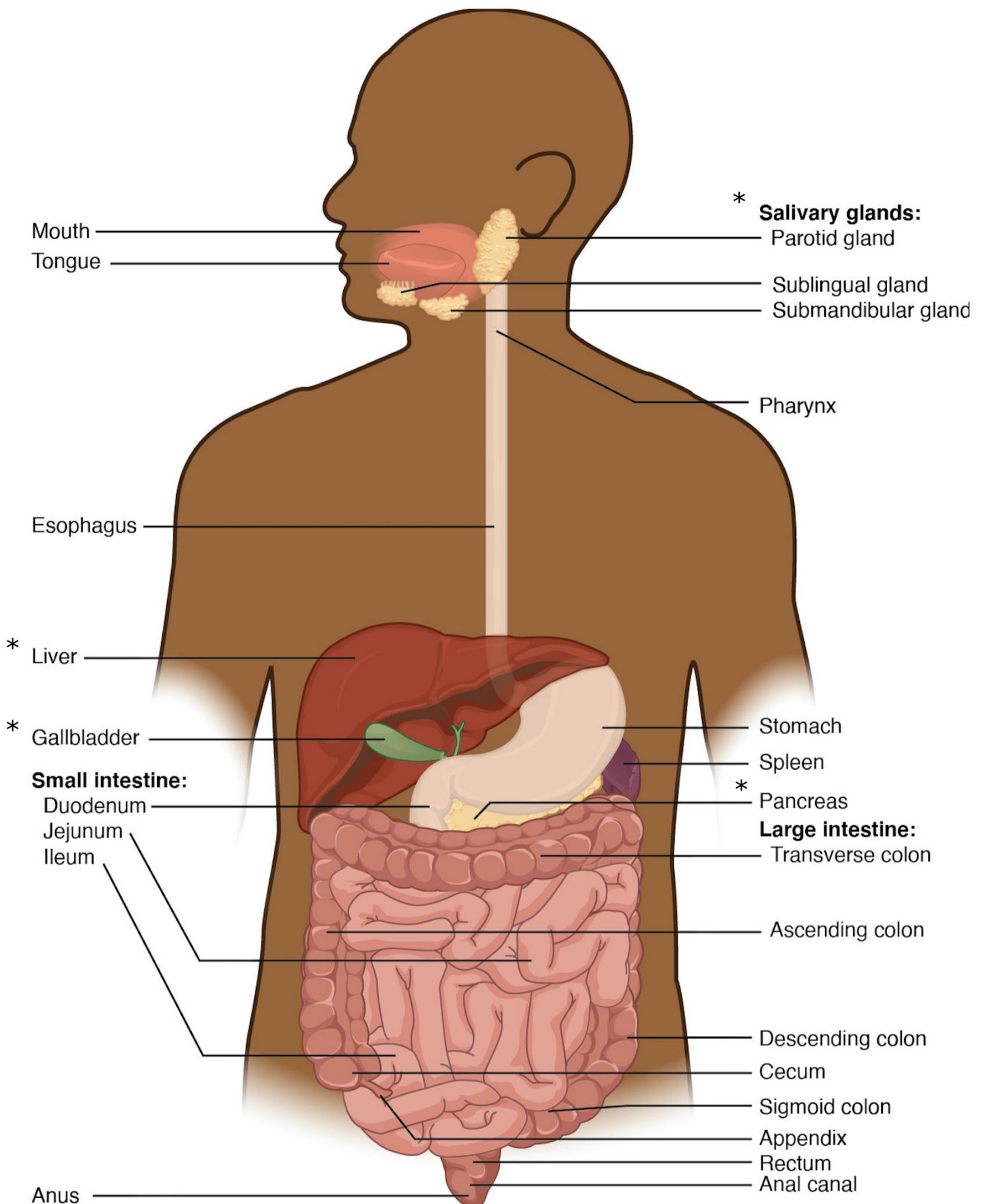


Figure 3.2 The digestive system is made up of the gastrointestinal (GI) tract and accessory organs. The GI tract is a hollow tube that runs from the mouth to the anus. The accessory organs (marked with \*) produce and store secretions to aid in digestion. [Figure 23.2](#), by J. Gordon Betts, Kelly A. Young, James A. Wise, Eddie Johnson, Brandon Poe, Dean H. Kruse, Oksana Korol, Jody E. Johnson, Mark Womble, Peter DeSaix, OpenStax from *Anatomy and Physiology 2e* (2022) is licensed under the Creative Commons Attribution 4.0 International license.

## Layers of the GI Tract

The GI tract is made up of four tissue layers — the mucosa, submucosa, muscularis, and serosa (Figure 3.3). All layers facilitate digestion and absorption of nutrients by providing secretions, movement, communication, and protection.

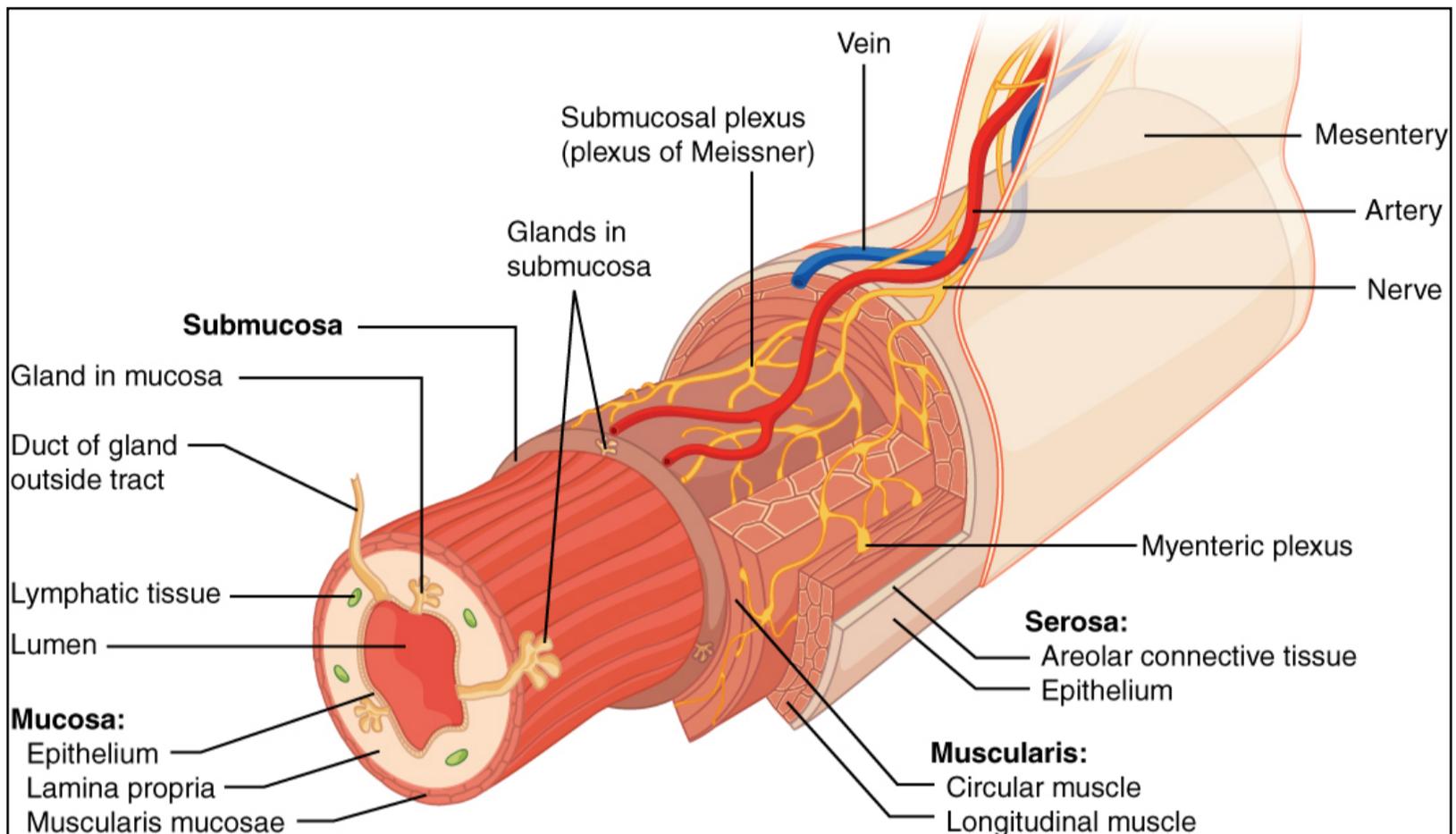


Figure 3.3 The GI tract has four basic tissue layers including the mucosa, submucosa, muscularis, and serosa. [Figure 23.3](#) by J. Gordon Betts, Kelly A. Young, James A. Wise, Eddie Johnson, Brandon Poe, Dean H. Kruse, Oksana Korol, Jody E. Johnson, Mark Womble, Peter DeSaix, OpenStax from *Anatomy and Physiology 2e* (2022) is licensed under the [Creative Commons Attribution 4.0 International license](#).

### Mucosa

The mucosa forms the innermost lining of the alimentary canal. It is referred to as a mucous membrane because mucus production is one of its important characteristics. It plays a central role in secretion, absorption, and immune defense. The mucosa consists of three components — the epithelium, lamina propria, and muscularis mucosae.

The **epithelium** is the layer in direct contact with the lumen, the internal space of the digestive tract through which food passes. Its structure varies by location. In the mouth, pharynx, esophagus, and anal canal, the epithelium is primarily non-keratinized stratified squamous epithelium, adapted to withstand mechanical stress. In the stomach and intestines, there is a transition to simple columnar epithelium, specialized for secretion and nutrient absorption. Scattered among the epithelial cells are two important cell types: goblet cells secrete mucus to lubricate the contents and protect the mucosal lining, and enteroendocrine cells release hormones to help regulate digestive processes.

Epithelial cells of the mucosa have a rapid turnover, with lifespans ranging from just a few days in the oral cavity to about one week in the intestines. This continuous renewal maintains mucosal integrity despite constant exposure to food and digestive substances.

**Table 3.1 Digestive organs and their main functions**

Organ	Main Functions
<b>Mouth</b>	Mechanical digestion (chewing) Chemical digestion begins with digestive enzymes (lipase, amylase) in saliva
<b>Salivary Glands</b>	Produce saliva to facilitate chewing, swallowing, speech, and taste perception. Secrete enzymes for digestion of carbs and lipids.
<b>Pharynx</b>	Passageway for food from mouth to esophagus Prevents food from entering the airway
<b>Esophagus</b>	Transports food from pharynx to stomach via peristalsis
<b>Stomach</b>	Mixes and churns food with gastric juices to form chyme Chemical digestion of (mainly) proteins Secretes hydrochloric acid to kill microbes
<b>Small Intestine</b>	Main site of nutrient digestion and absorption Enzymes from pancreas and bile from liver aid digestion
<b>Large Intestine</b>	Absorbs water and electrolytes Forms and stores feces Houses gut microbiota
<b>Liver</b>	Produces bile to emulsify fats Processes nutrients absorbed by the small intestine
<b>Gallbladder</b>	Stores and concentrates bile; releases bile into small intestine
<b>Pancreas</b>	Produces digestive enzymes (lipase, amylases, proteases) Secretes bicarbonate to neutralize stomach acid

The **lamina propria** lies beneath the epithelium. This is a layer of loose connective tissue that has an extensive network of blood and lymphatic vessels. These vessels facilitate the transport of absorbed nutrients. Additionally, the lamina propria contains immune components, including clusters of lymphocytes that form mucosa-associated lymphoid tissue (MALT). In the distal portion of the

small intestine (ileum), prominent lymphatic structures known as Peyer's patches provide targeted immune surveillance against ingested pathogens.

The **muscularis mucosae** is a thin layer of smooth muscle that maintains gentle tension in the mucosa, promoting the formation of small folds. These folds increase the surface area available for digestion and absorption.

### **Submucosa**

The submucosa lies directly beneath the mucosa and consists of dense, irregular connective tissue. It supports the mucosa and binds it to the underlying muscularis layer. The submucosa contains: blood and lymphatic vessels, which help distribute absorbed nutrients; submucosal glands, which secrete digestive fluids; and a network of nerves known as the Meissner's plexus that regulates glandular secretion and local blood flow.

### **Muscularis**

The muscularis, also known as the muscularis externa, is responsible for the mechanical processing and movement of food through the GI tract via peristalsis and segmentation (methods of GI motility). In most regions, including the small intestine, the muscularis consists of two layers of muscle: an inner, circular layer and an outer, longitudinal layer. The coordinated muscle contractions of these two layers with muscle fibers running in opposing directions help mix food with digestive secretions and propel it along the GI tract.

Structural modifications of the muscularis are seen throughout the GI tract. The stomach includes a third oblique muscle layer to facilitate churning and mechanical breakdown of foodstuffs. Furthermore, in the colon, the longitudinal layer is arranged into three distinct bands called teniae coli. These contribute to the formation of segmented pouches (haustra) along the colon.

### **Serosa**

The outermost layer of the alimentary canal is the serosa (or adventitia, depending on the region it's located in). The serosa primarily consists of a loose connective tissue that acts as an outer covering to protect the GI tract, reducing friction between digestive organs and surrounding structures.

## Gastrointestinal Motility

GI motility refers to the coordinated contractions of the smooth muscle layers in the digestive tract that move and mix contents along the lumen. The two main types of GI motility are **peristalsis** and **segmentation**.

- Peristalsis consists of rhythmic, wave-like contractions (of the longitudinal and circular muscularis layers) that propel food forward through the alimentary canal (Figure 3.4). It begins in the esophagus and continues through the stomach and intestines, ensuring the unidirectional movement of digestive contents.

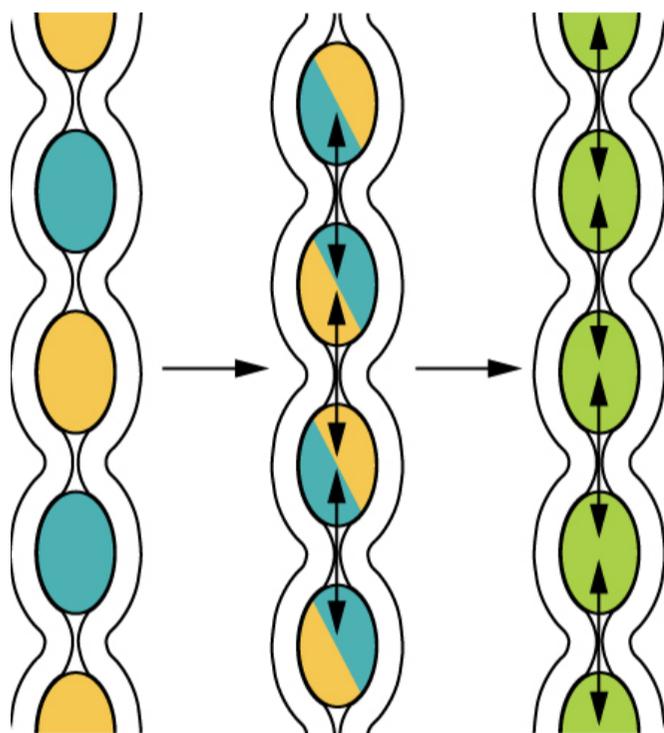


Figure 3.5 Segmentation is a type of GI movement that mixes food and digestive secretions. "Segmentation" J. Gordon Betts, Kelly A. Young, James A. Wise, Eddie Johnson, Brandon Poe, Dean H. Kruse, Oksana Korol, Jody E. Johnson, Mark Womble, Peter DeSaix, OpenStax from *Anatomy and Physiology* (2013) is licensed under the [Creative Commons Attribution 4.0 International license](#).

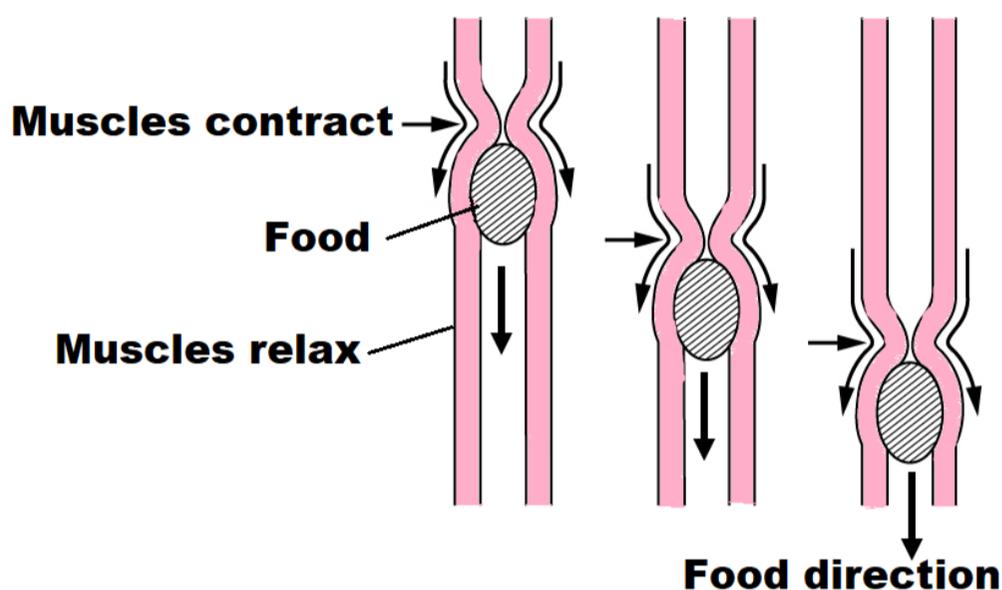


Figure 3.4 Peristalsis is a type of GI movement that propels food through the alimentary canal with wave-like motions. "Peristalsis" J. Gordon Betts, Kelly A. Young, James A. Wise, Eddie Johnson, Brandon Poe, Dean H. Kruse, Oksana Korol, Jody E. Johnson, Mark Womble, Peter DeSaix, OpenStax from *Anatomy and Physiology* (2013) is licensed under the [Creative Commons Attribution 4.0 International license](#).

- Segmentation (Figure 3.5) occurs mainly in the small intestine and involves alternating contractions of circular muscle that create a chopping motion, mixing and slowly moving food through the canal. This process enhances digestion and absorption by increasing contact time between food and secretions.

Peristalsis and segmentation both ensure that food particles are physically and chemically broken down and that food mass moves along the GI tract at the appropriate rate. Together, these motility patterns coordinate the mechanical processing of food, facilitate the mixing of digestive enzymes, and optimize nutrient absorption.

# Functions of the Digestive Organs

## Mouth

The mouth is the starting point of the digestive process and plays an important role in both mechanical and chemical digestion. When food enters the mouth, it is broken down into smaller pieces by **mastication**, or chewing, a mechanical process that increases the surface area of the food, making it easier to digest. At the same time, saliva is released from the salivary glands and begins the chemical digestion of carbohydrates through the enzyme salivary amylase and lipids through the enzyme lingual lipase. Digestive enzymes only act on the surfaces of food particles, so the rate of digestion is dependent on the total surface area of the food exposed to digestive secretions.

Saliva also moistens food, forming it into a soft mass called a **bolus** that can be easily swallowed. The tongue helps mix the food with saliva and pushes it toward the back of the mouth for swallowing, guiding it into the pharynx and then the esophagus. This initial step in digestion is essential for preparing food for further breakdown and nutrient absorption later in the digestive tract.

## Esophagus

The esophagus is a muscular tube that acts as conduit for the delivery of food from the mouth and pharynx to the stomach (Figure 3.6). The movement of the soft palate in the mouth (behind the teeth) during swallowing guides the bolus of food to the esophagus. There are copious amounts of mucus produced in the esophagus to aid in lubrication and protection.

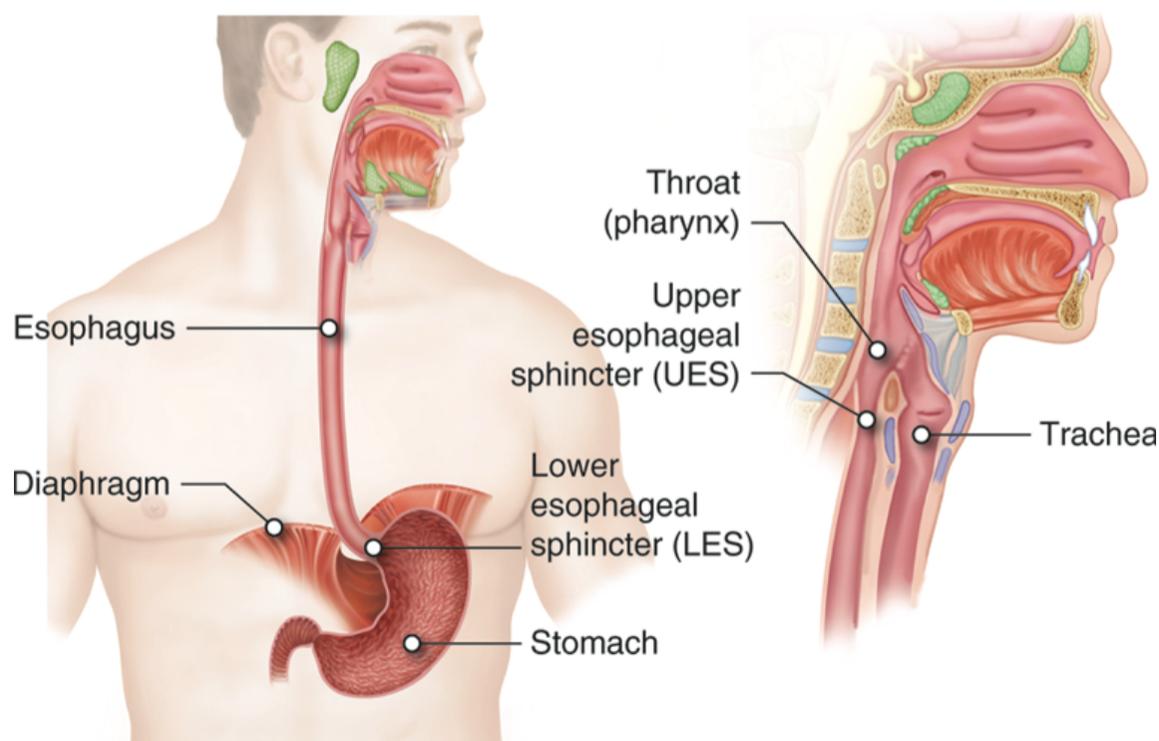


Figure 3.6 The esophagus is a muscular tube that connects the mouth and pharynx to the stomach. The lower esophageal sphincter regulates the passage of food into the stomach. "The Esophagus" by Cengage is licensed under [Creative Commons Attribution 3.0](https://creativecommons.org/licenses/by/3.0/).

## Stomach

The stomach is a glandular organ that plays a key role in both the mechanical and chemical breakdown of food. It receives food from the esophagus and churns it with powerful muscular contractions. This is possible due to the anatomical modification of the muscularis layer with the addition of the oblique muscle layer (Figure 3.7). The stomach also serves a role in the storage of food until it can be further processed. The stomach is suited for this job due to its mucosal layer being folded into convolutions called **rugae** (Figure 3.7). As food enters the stomach, the rugae allow the stomach to expand and accommodate increased volume.

Once food enters the stomach, it triggers a complex series of gastric secretions that begin the next phase of digestion. The presence of food stretches the stomach walls and stimulates the release of the hormone **gastrin** from G-cells, which in turn signals the gastric glands in the stomach lining to secrete several substances critical for digestion. One of the primary secretions is **hydrochloric acid (HCl)** from the parietal cells, which creates a highly acidic environment (pH around 1.5 to 3.5). HCl is

important for the denaturing of proteins, making them easier to break down. HCl also activates the inactive protease **pepsinogen** (released from chief cells) into its active form, **pepsin**, which begins protein digestion. The stomach also produces **mucus**, which coats and protects the mucosal lining from the corrosive effects of acid and enzymes. Additionally, **intrinsic factor** is secreted from the parietal cells to aid in the later absorption of vitamin B12 in the small intestine.

The combined action of muscular contractions and chemical secretions transforms food into a semi-liquid mixture called **chyme**, which is gradually released into the first portion of the small intestine (duodenum) through the pyloric sphincter (gastric emptying). This process is tightly regulated to ensure that the small intestine can effectively digest and absorb nutrients without being

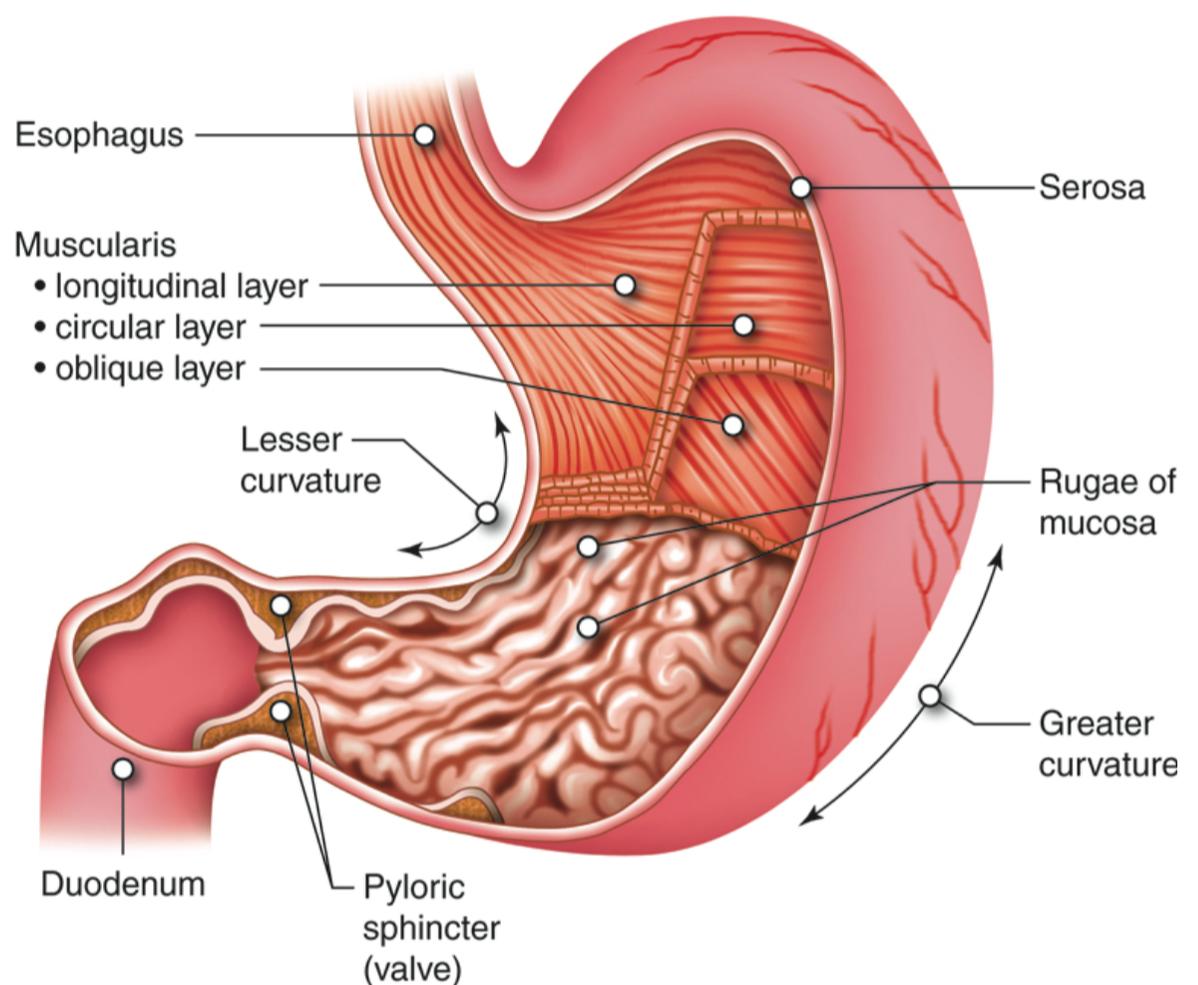


Figure 3.7 The stomach is a glandular, secretory organ with structural modifications to its mucosa and muscularis that reflect its function. This image by Cenevo is licensed with CC BY 3.0.

overwhelmed. Factors such as the type of food (fats and proteins slow emptying more than carbohydrates) and the volume and composition of the chyme influence the rate of gastric emptying. Ultimately, the goal is optimal digestion and nutrient absorption in the small intestine.

## Small Intestine

The small intestine is the primary site for digestion and **absorption** of nutrients. It is divided into three sections: the duodenum, jejunum, and ileum (Figure 3.8). When the acidic semi-liquid chyme mixture from the stomach enters the duodenum, it triggers a series of responses. One of the first reactions is the release of the hormone

secretin from the cells lining the duodenum. Secretin is released in response to the high acid content of chyme and signals the **pancreas** to secrete a bicarbonate-rich fluid. This bicarbonate neutralizes the acidic chyme, creating a more suitable environment for digestive enzymes to function and aiding in the protection of the intestinal lining from the acid.

In addition to bicarbonate, the pancreas also releases enzymes that break down carbohydrates, proteins, and lipids. Segmentation-mixing contractions promote the progressive mixing of food with these secretions.

The chyme also mixes with bile, which plays a crucial role

in the digestion and absorption of dietary fats. It is produced by the **liver** and stored in the **gallbladder**, then released into the duodenum of the small intestine in response to the hormone cholecystinin (CCK), which is triggered by the presence of fat in the chyme. Bile contains bile salts, which act as emulsifiers. Unlike enzymes, bile salts do not break chemical bonds but instead break large fat globules into smaller droplets, a process known as emulsification. This greatly increases the surface area of the fat, allowing pancreatic lipase, the enzyme responsible for fat digestion, to work more efficiently. Without bile, fats

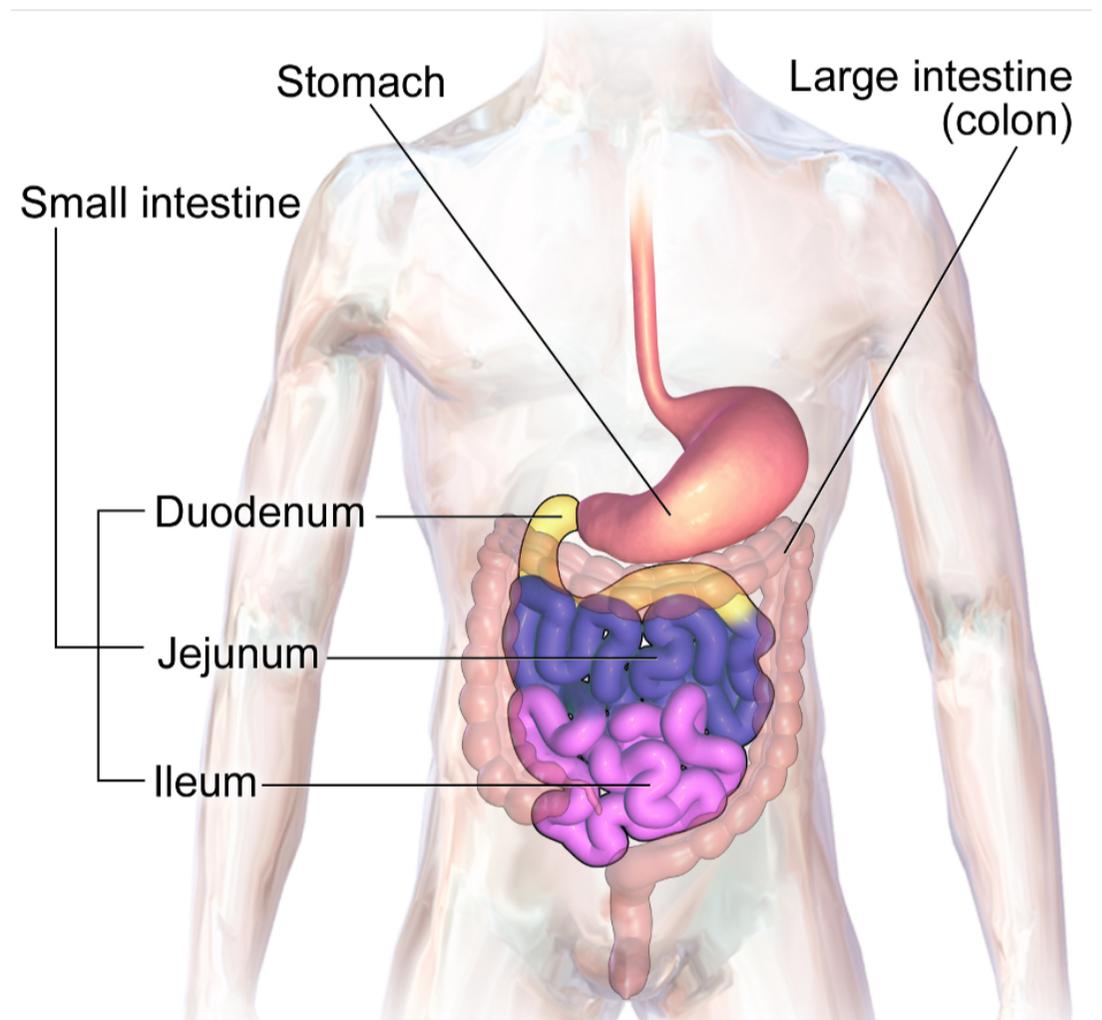


Figure 3.8 The small intestine consists of 3 parts — the duodenum, which connects to the stomach, the jejunum, and the ileum, which connects to the large intestine. “[Small Intestine Anatomy](#)” from the [Medical Gallery of Blausen Medical 2014](#) is licensed under the [Creative Commons Attribution 3.0 Unported license](#).

would remain in large clumps, making it difficult for enzymes to access and break them down.

As digestion continues, nutrients are absorbed across the enterocytes (epithelial cells of the small intestine) and through the intestinal walls, which are lined with villi and microvilli—tiny finger-like projections that dramatically increase the surface area for absorption (Figure 3.9). Microvilli increase the surface area exposed to intestinal materials at least 20-fold! In this way, the structure of the small intestine lends to its function in nutrient absorption. Nutrients pass through the walls of the small intestine and enter the bloodstream or lymphatic system to be transported throughout the body. Specifically, water-soluble nutrients enter the bloodstream and are transported directly to the liver for processing, while fat-soluble nutrients enter lymphatic vessels.

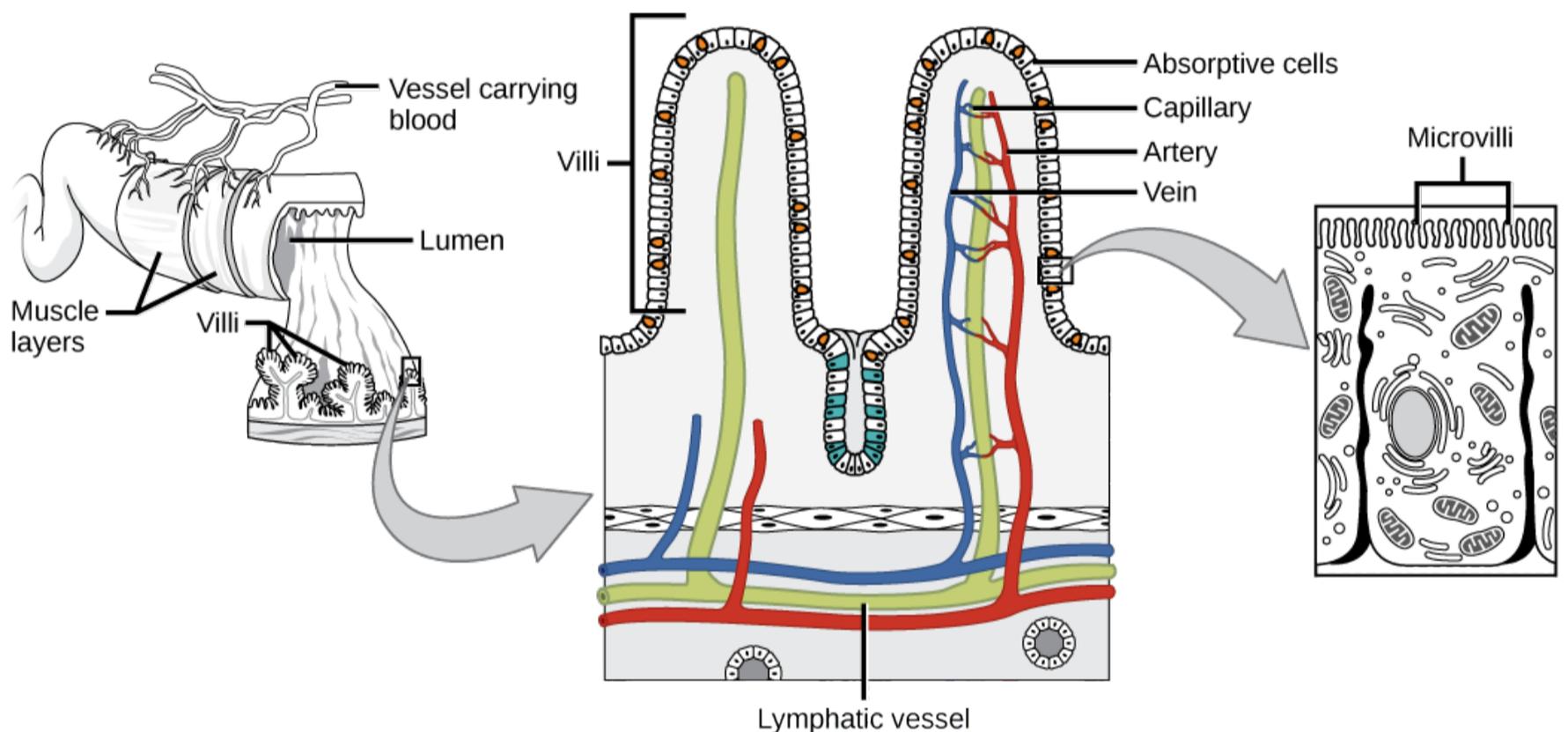


Figure 3.9 The mucosal layer of the small intestine is modified to have villi and microvilli, fingerlike projections that significantly increase surface area for maximal nutrient absorption. The villi are lined with enterocytes (absorptive cells), which have microvilli extensions on their surface. Image by Connie Rye, Robert Wise, Vladimir Jurukovski, Jean DeSaix, Jung Choi, Yael Avissar, OpenStax from *Biology* (2016) is licensed under the [Creative Commons Attribution 4.0 International license](https://creativecommons.org/licenses/by/4.0/).

## Large Intestine

The large intestine has three principal functions:

1. Absorption of water and electrolytes from chyme to form solid feces;
2. Storage of fecal matter until it can be expelled;
3. Microbial action.

After nutrient absorption is completed in the small intestine, the large intestine receives the remaining indigestible food matter (mainly fibrous material from

plants) and is responsible for absorbing water and electrolytes from it (Figure 3.10). In doing so, solid waste (feces) is formed. The large intestine has a unique method of GI motility called haustrations — circular constrictions that cause slow churning movements. The haustrations help expose undigested food residue to the absorptive mucosa of the large intestine so that water can be absorbed and fecal matter can become increasingly solid as the material moves through. The large intestine stores the fecal matter it forms until it can be expelled.

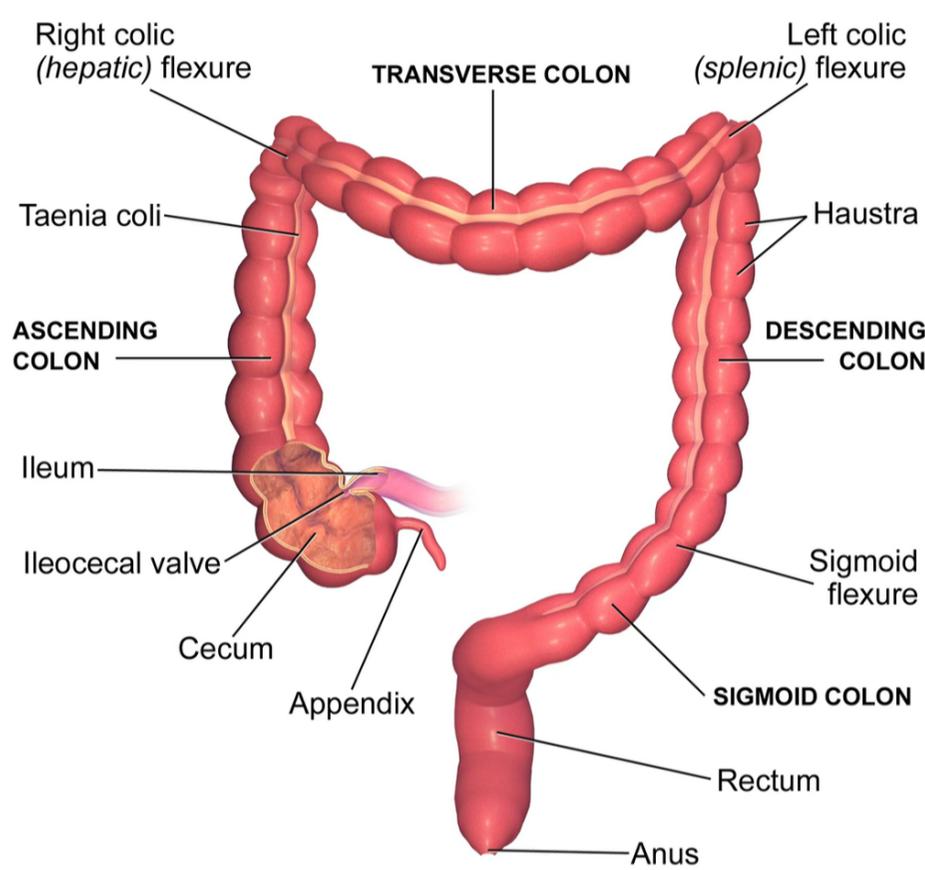


Figure 3.10 The large intestine is primarily responsible for water and electrolyte absorption and production of feces. "Large intestine" by BruceBlaus in the Wikijournal of Medicine is licensed under [CC BY 3.0](https://creativecommons.org/licenses/by/3.0/).

The large intestine also plays a role in housing a natural microbial population referred to as the microbiome. These hundreds of species of beneficial gut bacteria are important for an overall healthy colonic ecosystem. The bacteria help break down (ferment) some of the undigested food residue and produce certain nutrients, such as vitamin K and some B vitamins. The intestinal bacteria also help protect us from infection by competing with pathogenic bacteria for limited resources, namely nutrients and space.

## Sphincters

Sphincters are thick circular smooth muscle bands that act as valves to regulate the flow of material through all these different parts of the alimentary canal. They open and close at key points to control the movement of food and prevent backflow. The **gastroesophageal sphincter**, or lower esophageal sphincter, is located between the esophagus and stomach. It opens to allow food to pass from the esophagus into the stomach and closes to prevent stomach acid from refluxing into the esophagus. The **pyloric sphincter** located between the stomach and the small intestine regulates the passage of partially digested food (chyme), ensuring the small intestine receives manageable amounts for effective digestion and absorption. The **ileocecal valve** controls the flow from the small intestine to the large intestine, and the anal sphincters control the release of feces from the rectum. The sphincters are essential for maintaining the proper sequence and direction of the flow of materials through the GI system while ensuring that each part of the GI tract is able to function efficiently.

If there is a weakening of a sphincter, it may impact the ability of the muscle band to regulate. For example, the gastroesophageal sphincter relaxes briefly to allow food to enter the stomach. It then promptly contracts and closes after the food passes to the stomach to prevent the stomach contents from re-entering the esophagus. If the sphincter does not close tightly enough, stomach acid and food particles can reflux back up, causing heartburn. This is a major cause of gastroesophageal reflux disease (GERD).

## Phases of Digestion

Digestion occurs in three main phases — the cephalic, gastric, and intestinal phases. Digestion begins with the **cephalic phase**, which is triggered by the sight, smell, thought, or taste of food. In other words, this phase begins before food ever enters the mouth. During this time, the central nervous system is stimulated, which stimulates GI motility and the release of digestive secretions. The brain signals the stomach to prepare for digestion because next is the **gastric phase**, which starts once food arrives in the stomach. In this phase, the stomach stretches to accommodate the food, GI motility in the stomach increases and contractions become more powerful, and the release of gastric secretions increases. The gastric glands secrete hydrochloric acid and digestive enzymes, such as pepsin, to begin breaking down proteins. Finally, the **intestinal phase** begins as partially digested food (chyme) enters the small intestine. This phase involves the release of hormones like secretin and cholecystokinin, which regulate the release of bile from the gallbladder and digestive enzymes from the pancreas, ensuring continued digestion and nutrient absorption. Together, these phases coordinate the body's response to food and help ensure efficient digestion.

In summary, the digestive system is a highly coordinated network of organs and tissues that work together to break down food, absorb nutrients, and eliminate waste. From the mechanical and chemical processes that begin in the mouth to the intricate regulation of digestion, each component plays a vital role in maintaining nutritional balance and overall health. Understanding the structure and function of the alimentary canal and its accessory organs provides a foundation for recognizing how the body processes the food we consume.

# Chapter 4: Carbohydrates

Macronutrients are the fundamental building blocks of the human diet, providing the energy and raw materials our bodies need to function, grow, and thrive. These nutrients — carbohydrates, proteins, and fats — are required in large amounts and each plays a unique and vital role in maintaining health.

Carbohydrates are the body's primary energy source. Proteins support tissue growth and repair, and fats provide essential fatty acids and aid in the absorption of fat-soluble vitamins. Understanding how macronutrients work, how much we need, and how to choose high-quality sources is essential for making informed dietary decisions.

Carbohydrates are especially important for the brain and nervous system. Chemically, carbohydrates are organic compounds made up of carbon, hydrogen, and oxygen atoms, typically in a 1:2:1 ratio and represented by the formula  $(\text{CH}_2\text{O})_n$ , where  $n$  is the number of carbons in the molecule. This formula also explains the origin of the term "carbohydrate": the components are carbon ("carbo") and the parts of water (hence, "hydrate"). The basic building block of all carbohydrates is the sugar molecule, also known as a monosaccharide (Figure 4.1).

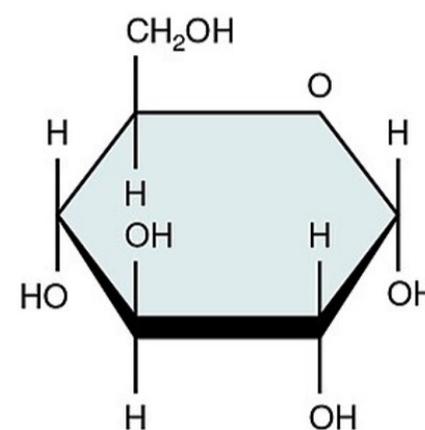


Figure 4.1 Glucose ( $\text{C}_6\text{H}_{12}\text{O}_6$ ) is an example of a monosaccharide. Cropped from [Figure 3.6](#) by Mary Ann Clark, Matthew Douglas, Jung Choi, OpenStax from [Biology 2e](#) (2018) is licensed under [Creative Commons Attribution 4.0 International license](#).

## Classification of Carbohydrates

Carbohydrates are categorized based on the number of sugar units they contain (Figure 4.2). Simple carbohydrates include monosaccharides and disaccharides. Monosaccharides are single sugar units and include glucose, fructose, and galactose. Disaccharides are two sugar units linked together through covalent glycosidic bonds and include sucrose, lactose, and maltose. Complex carbohydrates include oligosaccharides and polysaccharides. Oligosaccharides are chains of 3-10 monosaccharides, including raffinose and stachyose. Polysaccharides are long chains of monosaccharides, typically more than 10 units long. These include starch, glycogen, and dietary fiber.

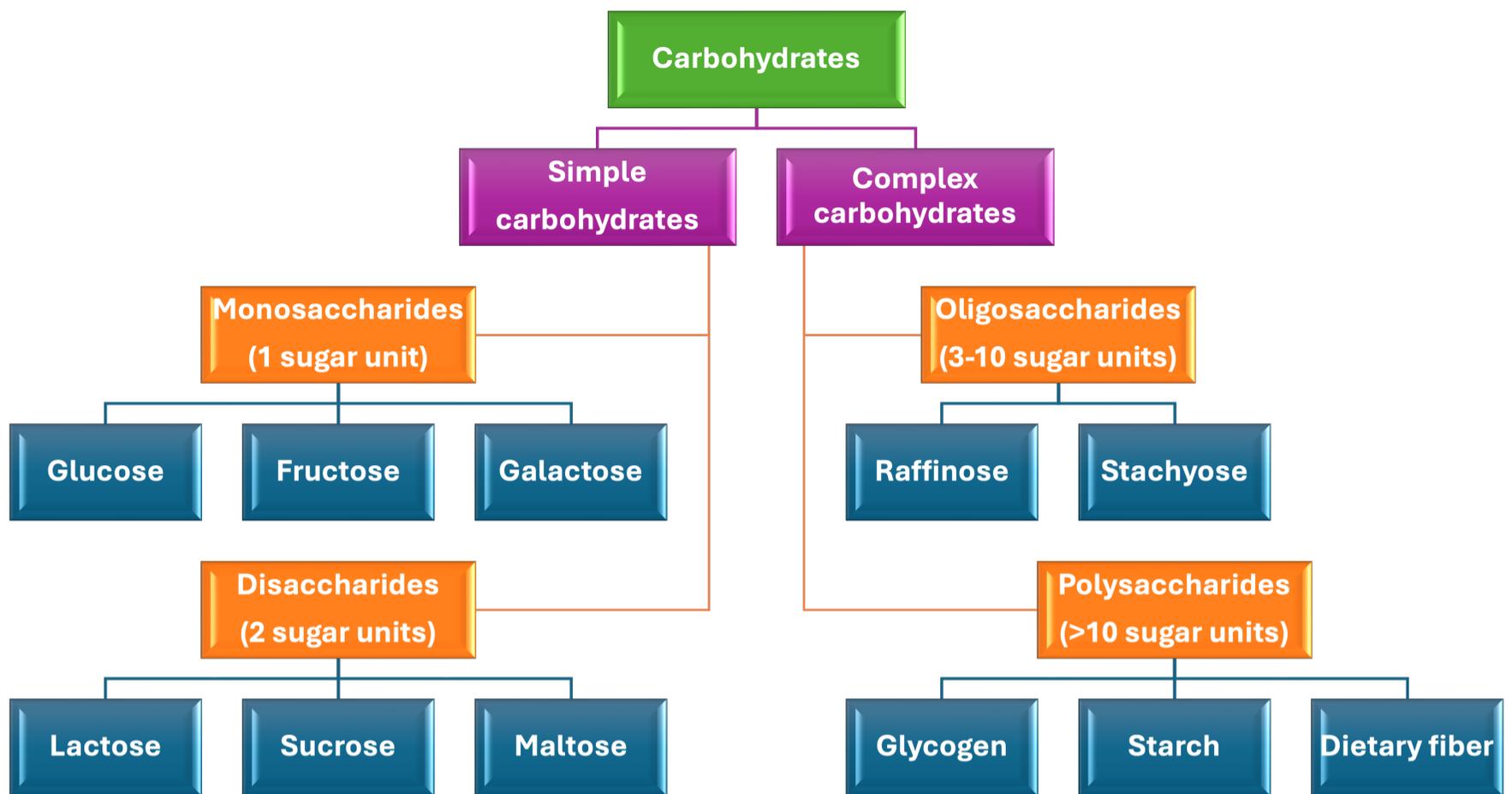


Figure 4.2 Classification of carbohydrates. Simple carbohydrates include monosaccharides and disaccharides, while complex carbohydrates include oligosaccharides and polysaccharides. Image by Author.

## Simple Carbohydrates

### Monosaccharides

Glucose is the most abundant monosaccharide in the body. It is produced through photosynthesis, which is a multi-step process that requires sunlight, carbon dioxide, and water as substrates (Figure 4.3). When chlorophyll-containing plants combine carbon dioxide and water in the presence of sunlight, oxygen is released and the energy from sunlight is stored as chemical energy in simple carbohydrate molecules. These sugar molecules contain energy and the energized carbon that all

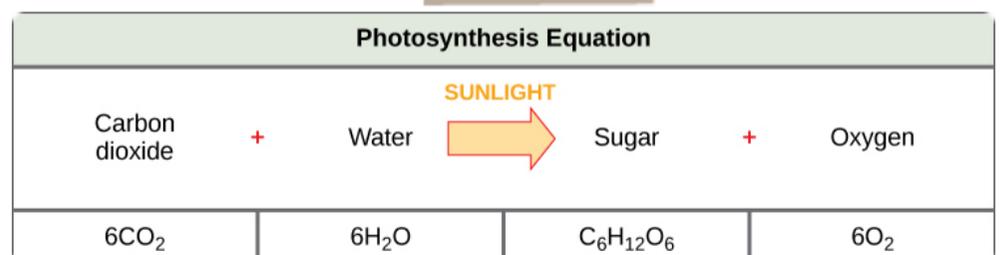
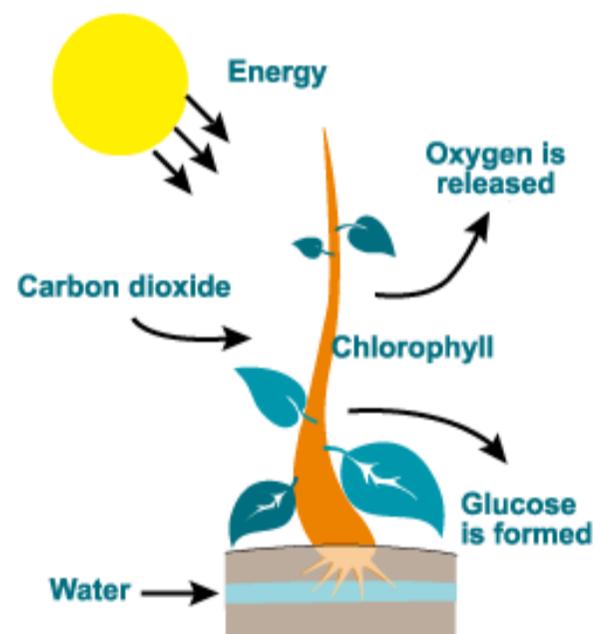
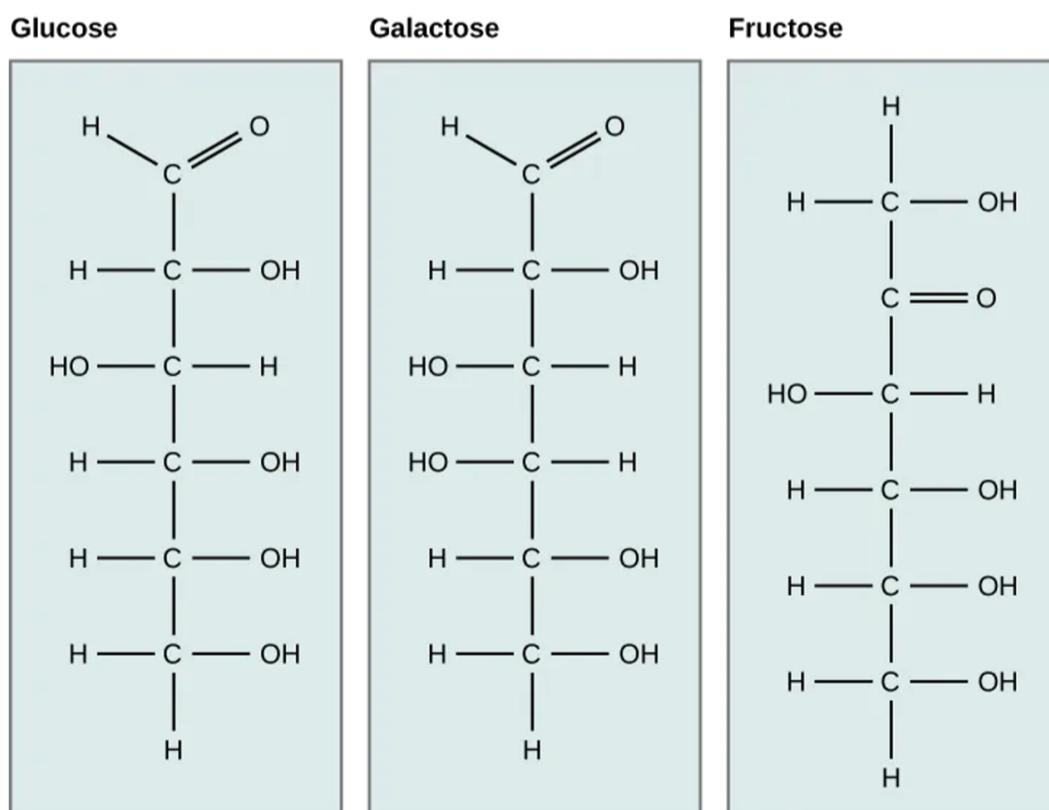


Figure 4.3 Photosynthesis uses solar energy, carbon dioxide, and water to produce carbohydrates. Oxygen is generated as a waste product of photosynthesis. Modified by Author from [Photosynthesis gif by Riyasachdeva250](#) licensed by [CC BY-SA 4.0 International license](#).

living things need to survive. This provides an energy source for plants, and when plant foods are consumed, the body breaks down and digests large carbohydrates into glucose, and the body's cells use it for energy.

The primary function of glucose is to provide cells with energy in the form of ATP. It is found naturally in many carbohydrate-rich foods like fruits, vegetables, and grains. Glucose is absorbed into the bloodstream following digestion. The hormone insulin, produced by the pancreas, helps transport glucose from the blood into cells, where it is used for energy. Unused glucose gets stored as glycogen (a complex carbohydrate) in the liver and skeletal muscles for future energy use. It can also be converted into amino acids and fat for energy storage. Maintaining balanced blood glucose levels is essential for overall health, as this monosaccharide is the preferred energy source for the nervous system and red blood cells.

Fructose and galactose are also simple sugars like glucose, though they differ in structure and function (Figure 4.4). Fructose, commonly referred to as "fruit sugar," is naturally found in fruits, honey, and some root vegetables. It is the sweetest naturally occurring carbohydrate and is also a component of sucrose (table sugar), which is a disaccharide composed of one molecule of glucose and one molecule of fructose. Fructose is often consumed in higher amounts through processed foods and beverages sweetened with high-fructose corn syrup, which has raised concerns about its potential contribution to metabolic disorders when consumed in excess.



Galactose has a similar chemical structure to glucose (Figure 4.4), and while less sweet than fructose, it is equally important in the human diet. It is most commonly consumed as part of lactose, the disaccharide found in milk and dairy products, which consists of glucose and galactose. During digestion, the enzyme lactase breaks down lactose into its monosaccharide components, which are then absorbed in the small intestine. The body uses galactose to make components of cell membranes and synthesize lactose, but the majority of it is transported to

Figure 4.4 Chemical structures of glucose, galactose, and fructose, each having a 6-carbon structure. [Figure 3.5](#) by Mary Ann Clark, Matthew Douglas, Jung Choi, OpenStax from *Biology 2e* (2018) is licensed under [Creative Commons Attribution 4.0 International license](#).

the liver, where it is converted into glucose to be used for energy or storage.

Especially when considering overall carbohydrate intake, understanding these sugars' sources and how they are processed by the body is essential for evaluating their roles in health and disease.

## Disaccharides

Disaccharides are defined as two monosaccharides joined by glycosidic linkage. Glycosidic linkages are covalent bonds that form between two monosaccharides

during a dehydration synthesis (or condensation) reaction. In this process, a hydroxyl group ( $-OH$ ) from one monosaccharide reacts with a hydrogen atom ( $-H$ ) from another, resulting in the release of a water molecule ( $H_2O$ ) and the formation of an oxygen bridge between the two sugar units (Figure 4.5). The position and orientation of the glycosidic bond—such as  $\alpha(1\rightarrow4)$  or  $\beta(1\rightarrow4)$ —determine the structural and functional properties of the resulting disaccharide (or polysaccharide). For example, an  $\alpha(1\rightarrow4)$  glycosidic bond between two glucose molecules forms maltose, while a  $\beta(1\rightarrow4)$  linkage between glucose and galactose forms lactose. The human digestive system has specific enzymes that recognize and break certain glycosidic bonds; for example, amylase breaks  $\alpha(1\rightarrow4)$  linkages in starch, while lactase is required to break the  $\beta(1\rightarrow4)$  bond in lactose. Glycosidic linkages are ultimately important in determining whether a carbohydrate is digested or not, and how it is digested.

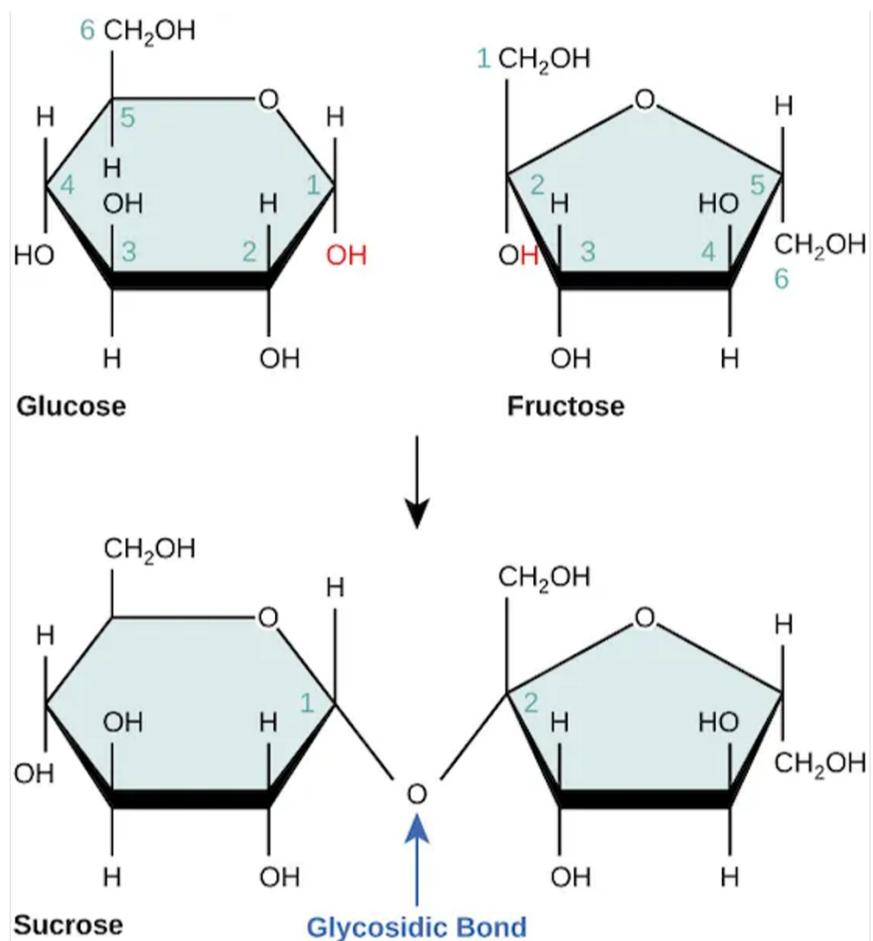
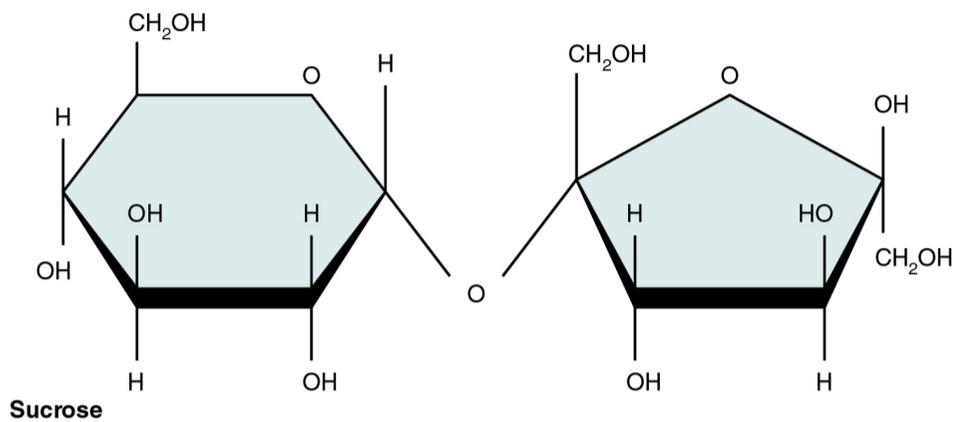


Figure 4.5 A glycosidic bond forms between glucose and fructose (monosaccharides) to form the disaccharide sucrose. *Dehydration Synthesis* by Mary Ann Clark, Matthew Douglas, Jung Choi, OpenStax from *Biology 2e* (2018) is licensed under [Creative Commons Attribution 4.0 International license](https://creativecommons.org/licenses/by/4.0/).

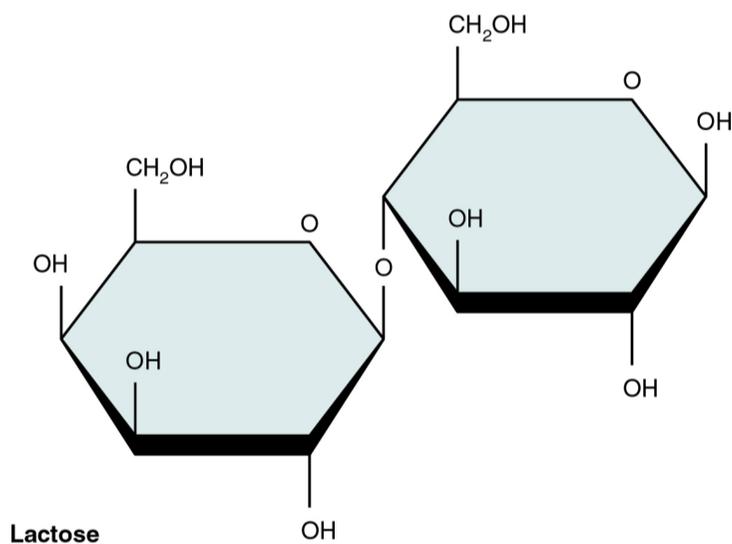
The most common disaccharides include lactose, maltose, and sucrose (Figure 4.6). Lactose consists of glucose bonded to galactose with a  $\beta(1\rightarrow4)$  linkage and is sometimes referred to as “milk sugar” because it is the most abundant carbohydrate found in milk and most products made from milk. Lactose serves as an important energy source, particularly for infants. During lactation, enzymes in the mammary glands combine glucose and galactose to produce lactose.

In the small intestine, lactose is broken down into its monosaccharide components by the enzyme lactase, which is produced by the enterocytes (the epithelial cells lining the intestinal wall). However, in many individuals, lactase production decreases after weaning (the transition from exclusively breastfeeding or formula-feeding to consuming other foods), leading to a condition known as lactose intolerance (Figure 4.7). Some people, however, do continue to produce lactase into adulthood, a trait known as lactase persistence.

(a) The monosaccharides glucose and fructose bond to form sucrose



(b) The monosaccharides galactose and glucose bond to form lactose.



(c) Two glucose monosaccharides bond to form maltose.

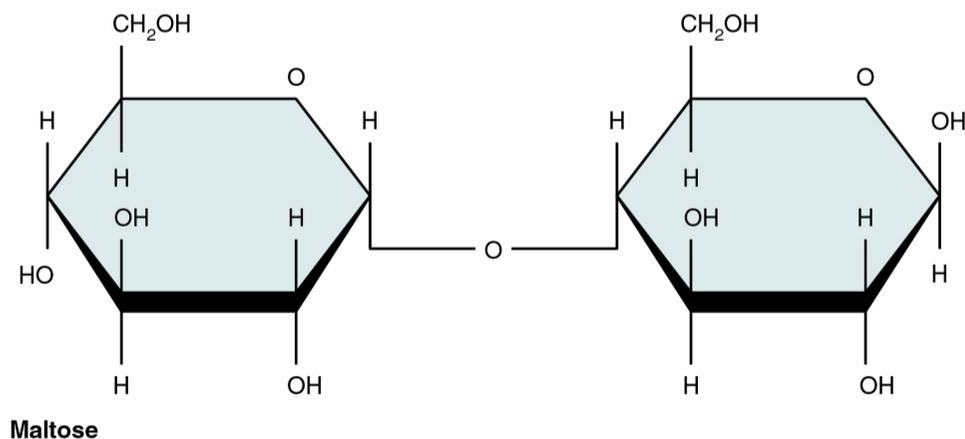


Figure 4.6 Three important disaccharides are sucrose, lactose, and maltose. Sucrose and maltose are bonded with alpha glycosidic bonds, while lactose is formed with a beta glycosidic bond. [Figure 3.8](#) by Mary Ann Clark, Matthew Douglas, Jung Choi, OpenStax from *Biology 2e* (2018) is licensed under [Creative Commons Attribution 4.0 International license](#).

People with lactose intolerance, however, are unable to fully digest lactose in the small intestine, resulting in the lactose reaching the large intestine undigested. Bacteria in the large intestine break down the lactose, leading to gastrointestinal symptoms such as bloating, gas, abdominal pain, and diarrhea. The severity of symptoms varies depending on the amount of lactose consumed and the individual's remaining lactase activity. Management typically involves reducing or eliminating lactose-containing foods, using lactose-free alternatives, or taking lactase enzyme supplements.

Sucrose and maltose are also disaccharides. Sucrose, commonly known as table sugar, is composed of one molecule of glucose and one molecule of fructose linked by an  $\alpha(1 \rightarrow 2)$  glycosidic bond. It is naturally found in many fruits and vegetables and is commercially extracted from sugar cane and sugar beets, processed to make molasses, and further treated to produce crystallized sucrose (table sugar) for widespread use as a sweetener. Sucrose is easily

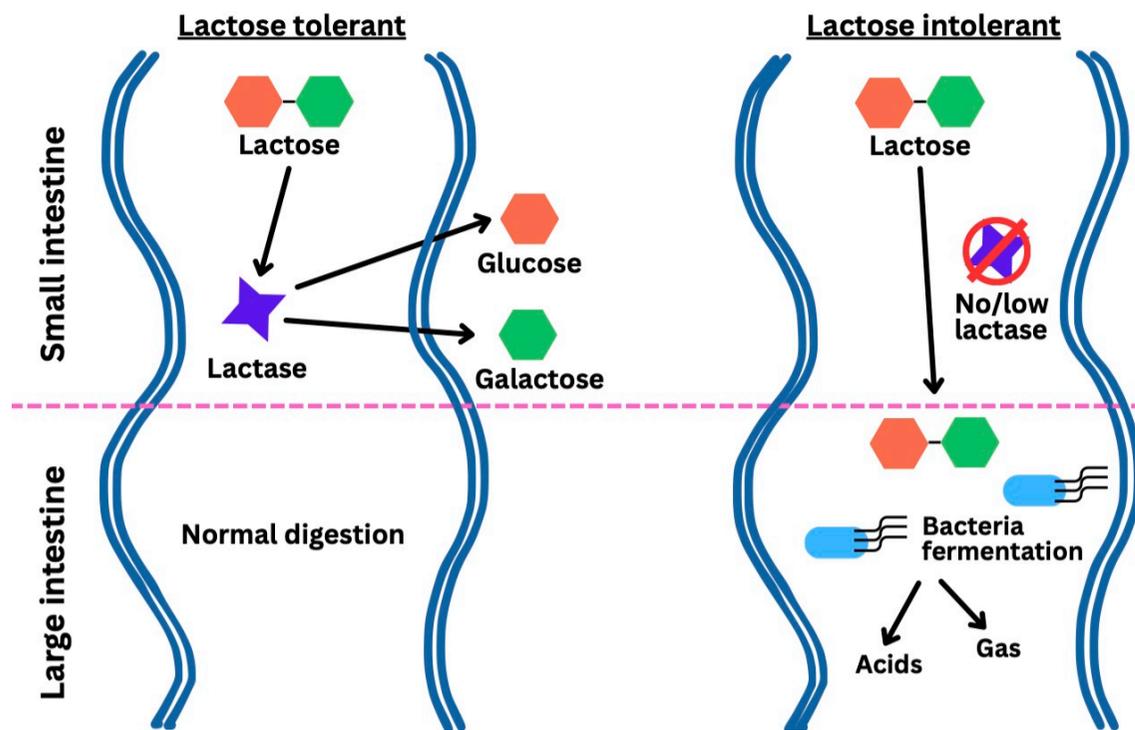


Figure 4.7 Lactose intolerant individuals do not have the enzyme lactase available to break down the disaccharide lactose in the small intestine. This results in the breakdown of lactose in the large intestine by bacteria, typically leading to gastrointestinal distress symptoms. Image by Author.

digested in the small intestine by the enzyme sucrase, which breaks it down into glucose and fructose for absorption. Sucrose is a significant source of added sugars in the modern diet.

Maltose, on the other hand, is composed of two glucose molecules joined by an  $\alpha(1\rightarrow4)$  glycosidic bond. It is not found in many foods, but is produced during the enzymatic breakdown of

starch, particularly during digestion or the malting process used in brewing beer. For example, enzymes convert starches from barley to maltose, which is then fermented by bacteria to produce alcohol. During digestion in the small intestine, the enzyme maltase hydrolyzes maltose into two glucose molecules, which can then be used for energy.

Naturally occurring sugars are found in whole, unprocessed foods such as fruits, vegetables, dairy products, and some grains. These sugars—primarily fructose, glucose, and lactose—are naturally integrated into the food's matrix, which also includes fiber, vitamins, minerals, and other beneficial compounds. For example, fruits have fructose but are also rich in vitamins, minerals, and fiber. In contrast, added sugars, though chemically identical to naturally occurring sugars, are those incorporated during food processing or preparation, such as sucrose or high-fructose corn syrup added to sodas, baked goods, and condiments. Baked goods with added sugars, for example, don't often have nutritional value beyond the calories they contain.

Excessive intake of added sugars has been associated with an increased risk of obesity, type 2 diabetes, cardiovascular disease, and dental caries. *The Dietary Guidelines for Americans* recommends that no more than 10% of one's daily caloric intake should come from added sugars. For example, for a 2,000 calorie diet, no more than 200 calories should come from added sugars. This equates to

approximately 12 teaspoons of added sugar from both food and beverages. Unfortunately, the average American consumes upwards of 20 teaspoons of added sugars each day.

In response to these recommendations and statistics, and amid growing health concerns, artificial sweeteners were developed (Figure 4.8). These synthetic or naturally derived compounds, such as aspartame, sucralose, saccharin, and stevia, provide intense sweetness with little to no caloric content. They are widely used in "diet" or "sugar-free" products and are regulated for safety by agencies like the FDA. While artificial sweeteners can help reduce added sugar intake, their long-term health effects continue to be a topic of research and debate, especially regarding their impact on appetite regulation, gut microbiota, and metabolic health.

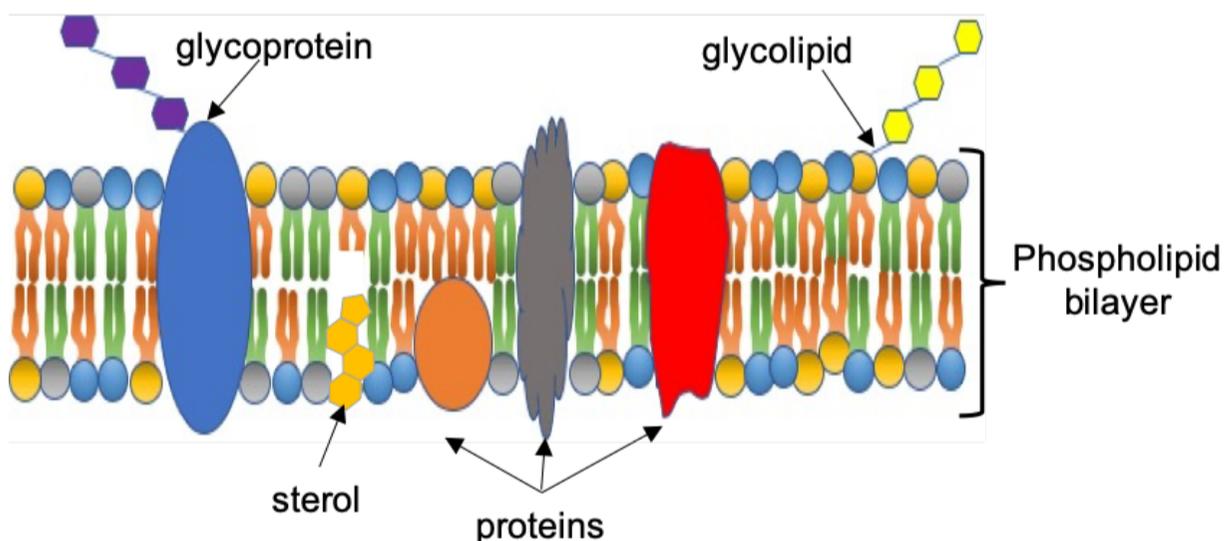


Figure 4.8 Artificial sweeteners. Image from Flickr by [abbyladybug](#) licensed by [CC BY-NC 2.0](#).

## Complex Carbohydrates

### Oligosaccharides

Oligosaccharides consist of between three and ten monosaccharides joined by glycosidic linkage. Raffinose and stachyose are the two most common oligosaccharides, found as components of glycoproteins and glycolipids in the cell



membrane and are important for cell-to-cell recognition and interactions (Figure 4.9). Raffinose and stachyose are found primarily in sources such as dried beans, soybeans, peas, and lentils. Humans lack the enzymes necessary to break these oligosaccharides down, therefore, they pass undigested into the large intestine

Figure 4.9 Oligosaccharides are found in the cell membrane as part of glycoproteins and/or glycolipids. "Fluid Mosaic Model" by [Connectivid-D](#) is licensed under the [Creative Commons Attribution Share-Alike 4.0 International license](#).

where they are broken down by bacteria. As a result, individuals often experience gastrointestinal symptoms such as bloating, cramps, or gas production when consuming common sources of these oligosaccharides.

## Polysaccharides

Though polysaccharides are classified as complex carbohydrates with more than 10 monosaccharides linked together, most polysaccharides are made of hundreds of monosaccharides bonded together in various arrangements. Ultimately, the types and arrangements of sugar molecules determine the shape and form of each polysaccharide. The three most common polysaccharides include starch, glycogen, and dietary fiber.

Starch is a complex carbohydrate most commonly found in plant-based foods such as grains like corn and wheat, pasta, bread, legumes, and potatoes. It is composed of two types of polysaccharides: amylose and amylopectin, both entirely made of glucose monomers. Amylose consists of long, unbranched chains of glucose molecules linked primarily by  $\alpha$ -1,4 glycosidic bonds, which makes it more resistant to digestion. In contrast, amylopectin is highly branched, containing both  $\alpha$ -1,4 and  $\alpha$ -1,6 glycosidic bonds ( $\alpha$ -1,6 bonds at the branch points of the structure). This extensive branching allows for quicker digestion and a faster rise in blood glucose levels when the structure is broken down. The ratio of amylose to amylopectin in a food affects its digestibility, glycemic response (how quickly and how much a food raises blood glucose levels after consumption), and texture.

Glycogen is another polysaccharide made entirely of glucose molecules, acting as the primary form of storage of glucose in animals and humans and serving as a readily available energy reserve. It is a highly branched polysaccharide composed of glucose units linked mainly by  $\alpha$ -1,4 glycosidic bonds, with branching occurring through  $\alpha$ -1,6 bonds approximately every 8 to 12 glucose units (Figure 4.10). This extensive branching allows for rapid mobilization of glucose when energy is needed, especially during periods of physical activity or between meals. Glycogen is primarily stored in the liver and skeletal muscles; liver glycogen helps maintain blood glucose levels, while muscle glycogen is used locally to fuel muscular activity. Because of its structure and function, glycogen plays a critical role in energy metabolism and blood sugar regulation.

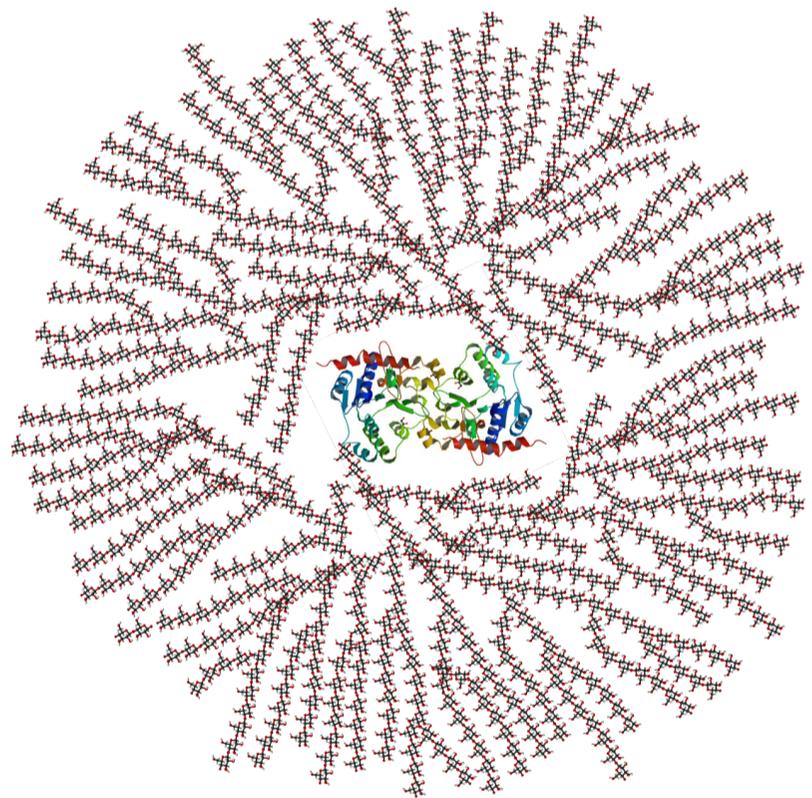


Figure 4.10 Glycogen is a highly branched arrangement of glucose molecules consisting of both  $\alpha$ -1,4 glycosidic bonds and  $\alpha$ -1,6 glycosidic bonds at branch points (shown in red). "Glycogen structure" by Mikael Häggström is made available under the [Creative Commons CC0 1.0 Universal Public Domain Dedication](#).

## Dietary Fiber

Dietary fiber is a type of complex carbohydrate found in plant-based foods that the body cannot digest. Fiber is made entirely of glucose molecules, though the bonds between the glucose molecules are different from what is seen in starch or glycogen. Fiber contains upward facing  $\beta$ -1,4 glycosidic bonds that are resistant to digestive enzymes. As a result, fiber passes from the small intestine to the large intestine relatively intact and is eventually broken down by the gut bacteria. Fiber promotes the growth of beneficial intestinal bacteria, playing a vital role in maintaining digestive health and preventing chronic diseases.

Fiber is not a required dietary component, however, many health benefits have been shown to be associated with a diet including fiber-rich foods. There are two main types of dietary fiber: soluble and insoluble. Soluble fiber absorbs water to form a gel-like substance in the intestines that protects the GI tract. This has been shown to slow digestion and help relieve constipation by softening fecal matter. It is found in foods such as oats, beans, lentils, apples, and citrus fruits. Insoluble fiber does not dissolve in water and adds bulk to the stool, promoting regular bowel movements and preventing constipation. Sources of insoluble fiber include whole grains, nuts, seeds, and the skins of fruits and vegetables (Table 4.1).

<b>Table 4.1 Common high-fiber foods</b>	
<b>Whole Grains</b>	Barley, oats, quinoa, whole wheat pasta, brown rice
<b>Legumes</b>	Lentils, split peas, black beans, garbanzo beans, kidney beans, edamame
<b>Vegetables</b>	Artichoke, green peas, broccoli, Brussels sprouts, sweet potato (with skin)
<b>Fruits</b>	Raspberries, blackberries, pear (with skin), apple (with skin), avocado
<b>Nuts &amp; Seeds</b>	Chia, flaxseed, almonds, pistachios

In addition to supporting digestive health, dietary fiber offers a range of health benefits. It helps regulate blood sugar levels by slowing digestion and allowing the body to properly absorb nutrients in food and prevent glucose spikes; this makes it especially beneficial for individuals with or at risk for type 2 diabetes. Fiber also contributes to heart health by lowering cholesterol levels by binding fats in the intestine and helping to eliminate them with stools. Furthermore, a high-fiber diet is associated with a reduced risk of developing colorectal cancer and can aid in achieving and maintaining a healthy weight by promoting a feeling of fullness and reducing overall calorie intake. Both types of fiber are essential for optimal health and should be included as part of a balanced diet.

Total fiber intake includes dietary fiber that exists naturally in plants plus any functional fiber added to a food. Functional fiber is typically derived from natural

fibrous plant sources and is added to food as an ingredient during manufacturing, though has also been shown to have beneficial physiological effects.

## **Nutrition And Diabetes Mellitus**

### **Hormonal Regulation of Glucose**

Blood glucose levels are typically lowest in the morning after an overnight fast, followed by a fluctuation in glucose levels throughout the day. Though in constant fluctuation, blood glucose levels are maintained within a homeostatic range at all times through the action of the pancreatic hormones insulin and glucagon (Figure 4.11).

Insulin and glucagon are released from the endocrine cells of the pancreas - beta cells and alpha cells, respectively. The pancreas has a rich blood supply, so these hormones are released directly into the bloodstream. Insulin is released in response to elevated blood glucose levels, such as after a meal. Insulin works to lower blood glucose levels by promoting its uptake into cells, especially in muscle and fat tissue, by stimulating the storage of excess glucose as glycogen in the liver or storage of excess glucose as fat in adipose tissue. Glucagon is released in response to low blood glucose levels, such as during fasting or in between meals. It raises blood glucose by stimulating the liver to break down glycogen stores in the liver into glucose (glycogenolysis) and to produce new glucose from non-carbohydrate sources (gluconeogenesis). While it is true that glycogen is also stored in the skeletal muscle, muscle lacks a glucagon receptor and is insensitive to glucagon. Rather, epinephrine released from the adrenal glands is important in muscle glycogenolysis and the glycogen in skeletal muscle helps fuel physical activity. Together, insulin and glucagon maintain blood glucose within a narrow, healthy range, ensuring a steady supply of energy for the body, particularly for the brain.

### **Diabetes Mellitus**

Diabetes mellitus is a metabolic disorder that affects how the body uses glucose. It is characterized by elevated blood glucose levels, or hyperglycemia. Diabetes has become a significant global health concern, with its prevalence rising sharply over the past few decades. As of 2022, approximately 830 million people worldwide are living with diabetes—a four-fold increase since 1990 . This surge is particularly pronounced in low- and middle-income countries, where access to healthcare and treatment options may be limited. In the United States, the Centers for Disease Control and Prevention (CDC) reports that about 38.4 million people, or 11.6% of the population, have diabetes. Notably, approximately 8.7 million adults are unaware they have the condition, highlighting the importance of regular screening and early detection . Furthermore, around 97.6 million U.S.

adults have prediabetes, a condition of elevated blood glucose levels that don't yet qualify for an official diabetes diagnosis.

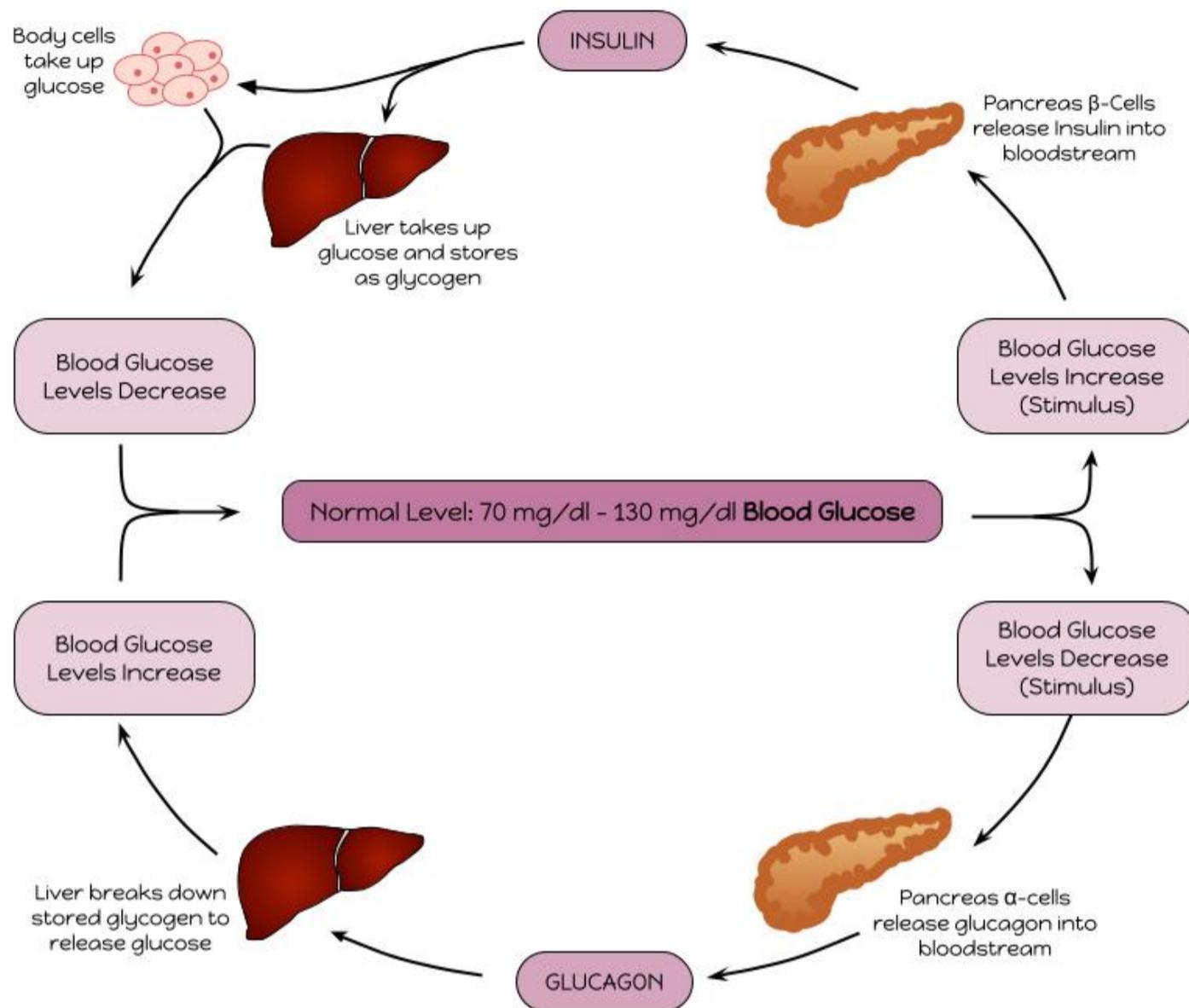


Figure 4.11 Blood glucose homeostasis is a balance achieved by the hormones insulin and glucagon. Insulin is released in response to high blood glucose levels, while glucagon is released in response to low blood glucose levels. "Glucose homeostasis" by Carogonz11 is licensed under the Creative Commons Attribution Share-Alike 4.0 International license. Read image transcript.

## Type 1 Diabetes Mellitus

Type 1 diabetes is an autoimmune condition in which the body's immune system mistakenly attacks and destroys the insulin-producing beta cells in the pancreas. As a result, individuals with type 1 diabetes are unable to produce sufficient insulin, leading to high blood glucose levels. This type of diabetes typically develops in childhood or adolescence, though it can occur at any age. Because insulin is essential for transporting glucose into cells for energy, people with type 1 diabetes must manage their condition through lifelong insulin therapy, either via injections or an insulin pump. Without treatment, glucose remains in the bloodstream, leading to serious complications such as nerve damage, kidney failure, and cardiovascular disease.

## **Type 2 Diabetes Mellitus**

Type 2 diabetes is a chronic metabolic disorder characterized by insulin resistance. In this condition, the pancreas produces sufficient insulin; however, the body's cells do not respond effectively to the insulin. Over time, it is commonly seen that the pancreas may also then produce less insulin. This form of diabetes is more common in adults but is increasingly seen in children and adolescents due to rising obesity rates and sedentary lifestyles. Risk factors include genetics, poor diet, physical inactivity, and excess body weight. Management typically involves lifestyle changes such as healthy eating, regular exercise, weight loss, and, in some cases, medication or insulin therapy. If left uncontrolled, type 2 diabetes can lead to complications similar to those seen in type 1 diabetes, including heart disease, vision problems, and nerve damage.

## Carbohydrate Recommendations

The Dietary Guidelines for Americans recommend that carbohydrates make up 45–65% of total daily calories for most people. This means that in a 2,000-calorie diet, about 900 to 1,300 calories should come from carbohydrates, which equals roughly 225 to 325 grams per day. At minimum, it is suggested to consume 130 grams of carbohydrates per day to support the requirements for the brain. It's important to focus on quality by choosing complex carbohydrates such as whole grains, fruits, vegetables, and legumes, which provide fiber, as well as vitamins, and minerals. Added sugars and refined grains should be limited, as they offer little nutritional value and can contribute to chronic health issues like obesity and type 2 diabetes. Adequate carbohydrate consumption supports vital physiological functions, including glucose metabolism, brain activity, and gastrointestinal health through fiber intake.

### Health Note

Carbs are the body's preferred source of energy - especially for the brain, which runs almost exclusively on glucose!

### Fun Fact

Even though they get a bad rap, carbs are essential for endurance athletes and brain performance.

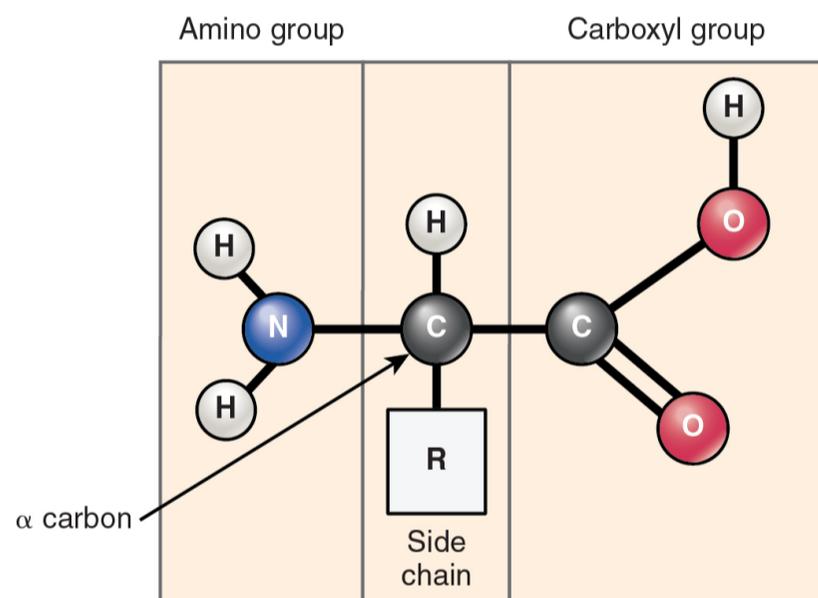
# Chapter 5: Proteins

Proteins are essential macronutrients that play a critical role in nearly every biological process in the human body. Composed of amino acids, proteins are required for the growth, maintenance, and repair of body tissues, including muscles, organs, skin, and hair. Beyond their structural functions, proteins also serve as enzymes, hormones, and immune system components, making them vital for metabolism and overall health.

## Protein Structure

Proteins are large, complex molecules made up of smaller monomeric units called **amino acids** (Figure 5.1), which are linked together in specific sequences by peptide bonds to form polypeptide chains. There are 20 different amino acids commonly found in proteins, each with a central carbon atom bonded to a hydrogen atom, an amino group, a carboxyl group, and a unique side chain (R

group) that determines its properties and makes it unique from others. Unlike carbohydrates and fats, proteins contain nitrogen, a key element that distinguishes them chemically and functionally.



The structure of a protein is organized into four levels: the primary structure is the linear sequence of amino acids; the secondary structure involves local folding into alpha helices and beta-pleated sheets; the tertiary structure refers to the overall three-dimensional shape of a single polypeptide chain; and the quaternary structure exists in proteins composed of multiple polypeptide subunits (Figure 5.2). The specific shape of a protein determines its function, and even slight changes in structure can significantly impact its biological activity.

Figure 5.1 Amino acid structure. The amino group, central (alpha) carbon, and carboxyl group are the same for all amino acids. The structure of the R-group makes amino acids different from one another. "Structure of an Amino Acid" by J. Gordon Betts, Kelly A. Young, James A. Wise, Eddie Johnson, Brandon Poe, Dean H. Kruse, Oksana Korol, Jody E. Johnson, Mark Womble, Peter DeSaix, OpenStax from *Anatomy and Physiology* (2013) is licensed under [CC BY 3.0](https://creativecommons.org/licenses/by/3.0/).

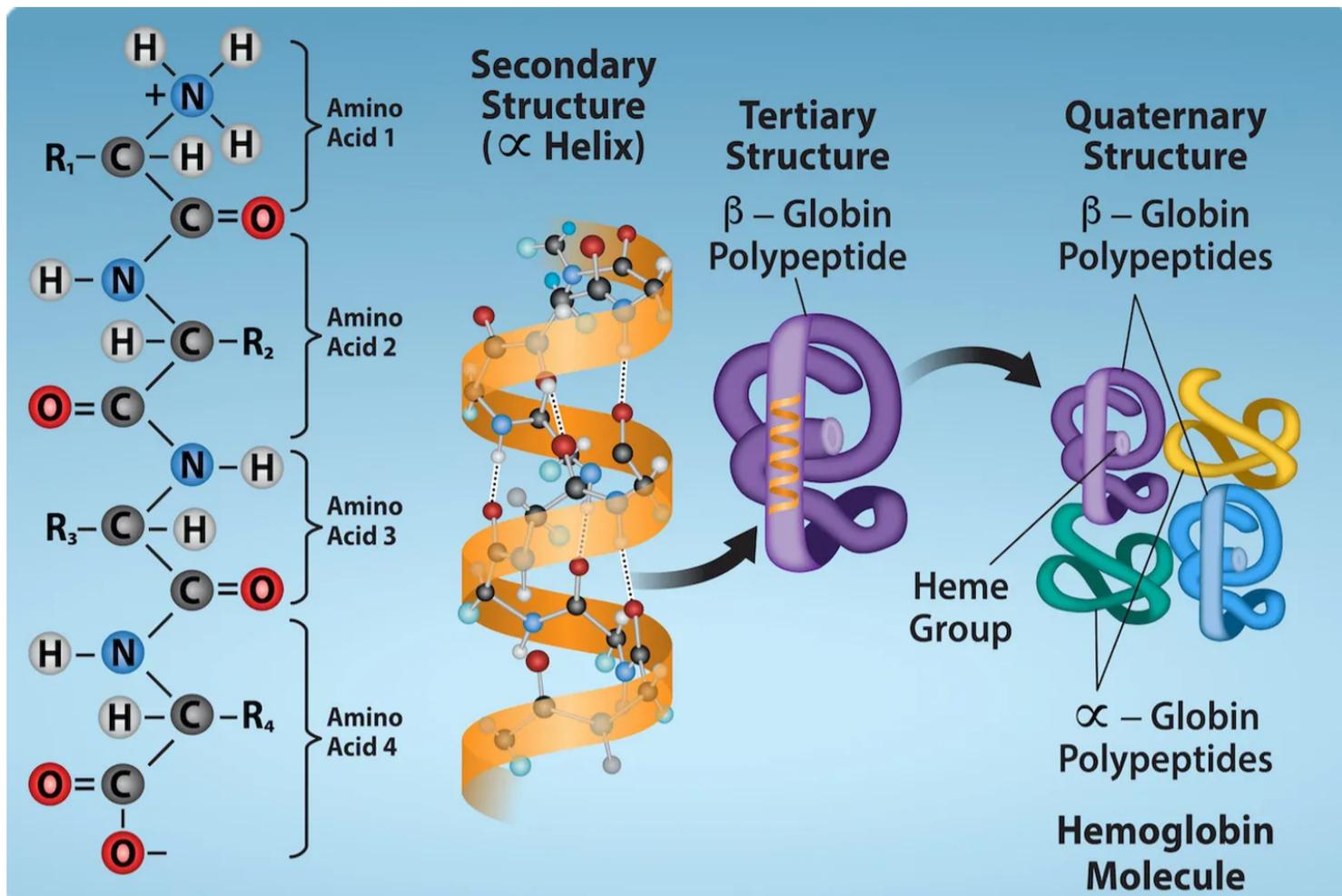


Figure 5.2 Protein structure is organized into four levels. A hemoglobin molecule is used as an example of a protein that has four polypeptide chains linked together to form a protein. [Image](#) by Mary Ann Clark, Matthew Douglas, and Jung Choi, OpenStax from *Biology 2e* (2018) is licensed under [Creative Commons Attribution 4.0 International license](#).

## Amino Acid Classification

Amino acids can be classified into three main categories based on the body's ability to synthesize them: essential, nonessential, and conditionally essential (Table 5.1) This classification highlights how amino acid needs can vary depending on physiological states and life stages.

- **Essential amino acids** cannot be synthesized by the human body or are not synthesized in ample amounts to meet physiological needs, and therefore must be obtained through the diet. Examples include leucine, isoleucine, lysine, and tryptophan. These are critical for processes like muscle protein synthesis and enzyme production.
- **Nonessential amino acids** are those that the body can produce on its own, even if they are not supplied by one's diet. Examples include alanine, aspartic acid, and glutamic acid.
- **Conditionally essential amino acids** are usually nonessential, but under certain conditions—such as illness, stress, or during infancy—the body's demand exceeds its ability to produce them. In such cases, dietary intake becomes necessary. Examples include arginine, glutamine, and tyrosine.

## Food Proteins

Meat, poultry, fish, eggs, dairy products and nuts provide more protein (per gram) than grains, fruits, and vegetables (Figure 5.3). The exception to this is legumes since leguminous plants have roots that are associated with bacteria that can take nitrogen from the air and incorporate it into amino acids. Those amino acids are used by the plant, so it then has higher protein content than other plants.

**Table 5.1 Classification of Amino Acids.**

Essential	Nonessential	Conditionally Essential
Histidine	Alanine	Arginine
Isoleucine	Asparagine	Cysteine
Leucine	Aspartic acid	Glutamine
Lysine	Glutamic acid	Glycine
Methionine	Serine	Proline
Phenylalanine		Tyrosine
Threonine		
Tryptophan		
Valine		

It is also important to remember that not all protein sources are created equal in terms of the types of amino acids they offer. Animal-derived foods tend to have greater amounts of essential amino acids. Dietary proteins come from both

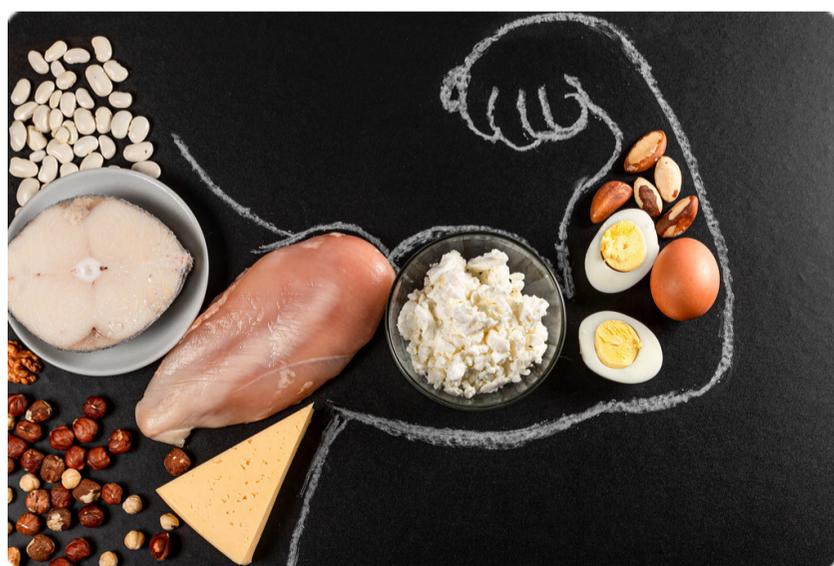


Figure 5.3 Meat, poultry, fish, eggs, dairy products, and nuts tend to offer more protein per gram than other food types. “[Protein food and hand drawn with muscles](#)” by [Marco Verch](#) is licensed under [CC-BY 2.0](#).

animal and plant sources, and the balance of amino acids they provide can vary significantly. Animal-based proteins—such as meat, poultry, fish, eggs, and dairy—are considered **complete proteins** because they contain all nine essential amino acids in proportions that closely match human needs. These sources are typically high in quality and bioavailability. In contrast, plant-based proteins—like beans, lentils, nuts, seeds, and grains—are often **incomplete proteins**, meaning they may lack one or more essential amino acids or have them in lower amounts. The amino acid(s) that are missing or in low amounts are

referred to as limiting amino acids. If a limiting amino acid is missing from one's diet, it is not possible to make the proteins the body needs that contain it. For example, grains are generally low in lysine, while legumes may be low in methionine.

However, by consuming a variety of plant-based proteins throughout the day, such as rice and beans (Figure 5.4), individuals can achieve a complementary balance of amino acids. Protein complementation allows a combination of two or more incomplete protein sources to be combined to supply all nine essential amino acids (Figure 5.5). Understanding the differences in amino acid profiles helps in planning balanced diets, especially for vegetarians and vegans.



Figure 5.4 Rice and beans as an example of protein complementation. [Congri](#) from Flickr by [Gloria Cabada-Leman](#) is licensed under [CC BY 2.0](#).

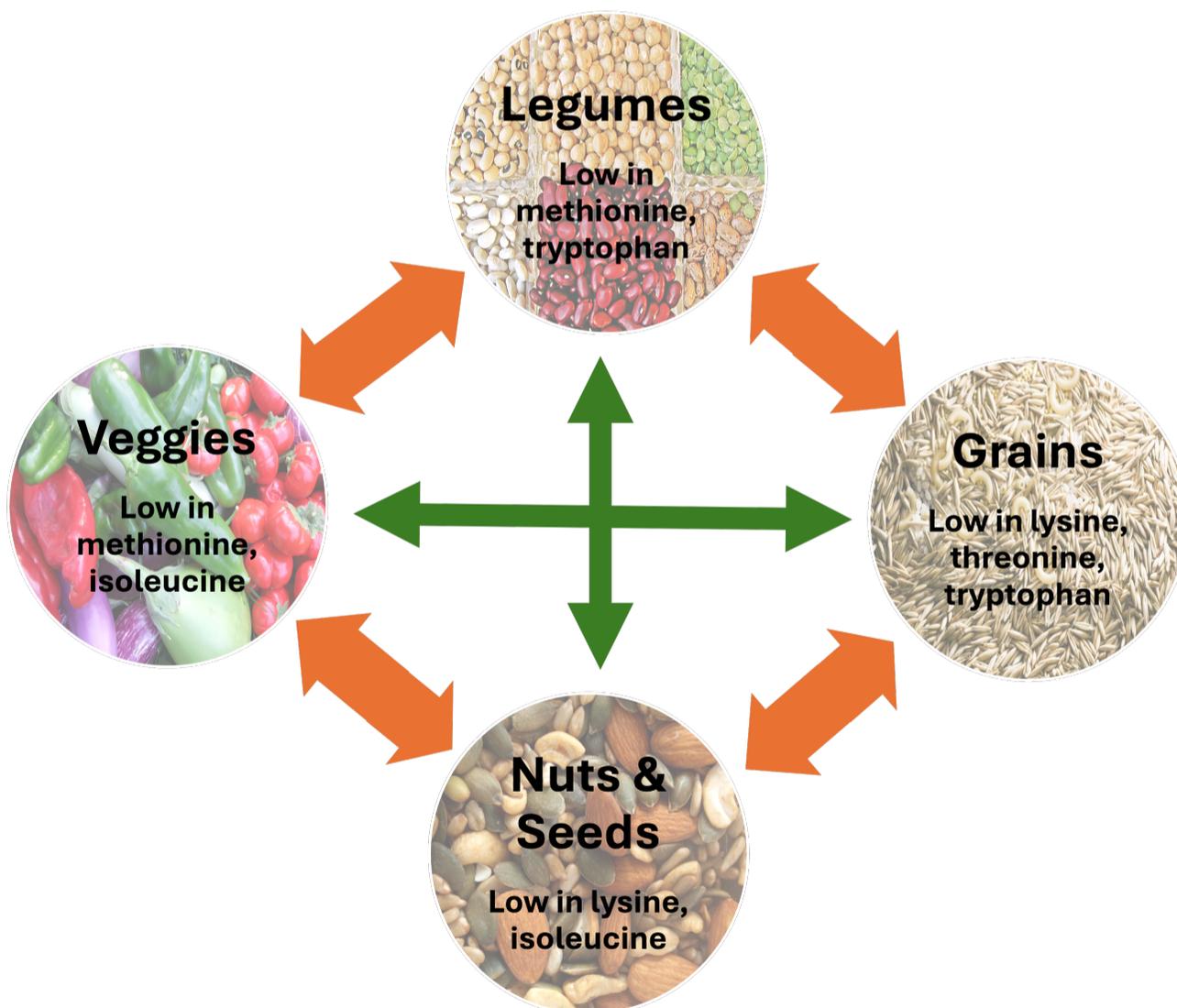


Figure 5.5 Protein complementation allows for the consumption of all 9 essential amino acids from incomplete protein sources. This is very common, particularly in places that rely heavily on plant sources for protein. Overall image is the work of the Author; image of [legumes](#) from [Wayback Machine](#) is licensed under [CC0](#); image of [grains](#) from [stock vault](#) licensed under [CC0](#); image of [veggies](#) by [Kenny Point](#) on [Flickr](#) is licensed under [CC BY-SA 2.0](#); image of [nuts and seeds](#) by [Martin Weller](#) from [Flickr](#) licensed under [CC BY-NC 2.0](#).

## Protein Quality

The quality of a protein indicates how well a protein source can meet the body's amino acid requirements. Protein quality depends upon whether the protein is complete versus incomplete as well as the body's ability to absorb the amino acids, or bioavailability. A high-quality protein is one that is a complete protein source and provides easily absorbed amino acids, therefore having high bioavailability. In contrast, a low-quality protein is one that is an incomplete protein source and has low bioavailability. Similar to completeness, animal-based foods are typically sources of high quality proteins, whereas plant-based proteins are typically lower quality.

To improve global nutrition, especially in regions where diets are primarily plant-based, scientists have turned to **genetic modification (GM)** to enhance protein quality in staple crops. This process involves altering the DNA of plants to increase the levels or balance of essential amino acids. Examples of genetic modification to improve protein quality include the following:

- **High-lysine corn:** Corn is naturally low in lysine and tryptophan, which limits its protein quality. Through genetic engineering, varieties have been developed to express higher levels of these amino acids, making corn a more complete protein source.
- **Genetically modified rice and legumes:** Rice has been engineered to express additional proteins rich in essential amino acids (like methionine), addressing its natural deficiencies. Similarly, efforts are underway to genetically modify soybeans and other legumes to boost their amino acid profiles.

Improving protein quality through genetic modification holds promise for things such as combating malnutrition in developing countries, supporting plant-based diets with more complete protein sources, and reducing reliance on animal proteins, potentially benefiting sustainability and food security. That said, concerns about GM crops, such as biodiversity loss, regulatory oversight, and public acceptance, must be considered alongside these innovations.

## Why We Need Protein

Proteins serve a wide range of essential functions in the body, making them vital to overall health and physiological processes. One of their primary roles is structural, as they are key components of muscles, skin, hair, and connective tissues, making them extremely important during periods of growth and development. Proteins also function as enzymes, which catalyze biochemical reactions necessary for digestion, energy production, and cell signaling. Additionally, proteins play a critical role in the immune system as antibodies that help defend against pathogens. They are also involved in transporting molecules,

such as hemoglobin carrying oxygen in the blood, and in maintaining fluid and pH balance. Some proteins act as hormones, like insulin, which helps regulate blood glucose levels. Because of these diverse functions, adequate protein intake is essential for growth, repair, and maintenance of body tissues.

In addition to consuming protein, our body is able to undergo protein turnover, the continuous process of breaking down and rebuilding proteins in the body. This dynamic cycle allows the body to replace damaged or old proteins, adapt to changing needs, and support growth and repair, without requiring enormous amounts of dietary protein. During protein turnover, the amino acids released from broken-down proteins can be reused to build new proteins or, if not needed, deaminated and used for energy or converted into other compounds. Closely related to protein turnover is nitrogen balance, which reflects the balance between nitrogen intake (mainly from dietary protein) and nitrogen loss (primarily through urine, feces, sweat, and other bodily processes). Because we are constantly breaking down and synthesizing protein, our bodies are always trying to maintain a balance of nitrogen. A person is in positive nitrogen balance when nitrogen intake exceeds loss, indicating that the body is building more protein than it is breaking down — a state common during growth, pregnancy, muscle building, or recovery from illness. Negative nitrogen balance occurs when nitrogen losses exceed intake, suggesting muscle or tissue breakdown, often seen during illness, injury, or malnutrition due to inadequate dietary protein intake or inadequate essential amino acid intake. Nitrogen balance means protein synthesis and breakdown are equal, which is typical for healthy adults who are maintaining their body weight and muscle mass.

## **Protein Recommendations**

The recommendations for dietary amino acid and overall protein intake reflect the ultimate reasons for protein consumption — to supply adequate amounts of essential amino acids, and to supply additional nitrogen needed to make nonessential amino acids and other non-protein, nitrogen-containing compounds (such as DNA). The recommendations do not distinguish between consumption of high-quality or low-quality proteins but are designed to support the body's needs for growth, maintenance, and repair.

**Table 5.2 Protein needs may vary slightly in different populations.**

<b>Population Group</b>	<b>Recommended Protein Intake</b>	<b>Reason for Increased Need</b>
<b>General Adults</b>	0.8 g/kg of body wt/day (RDA)	Supports basic maintenance and repair of body tissues
<b>Endurance Athletes</b>	1.2-1.4 g/kg of body wt/day	Supports muscle repair and energy needs due to prolonged activity
<b>Strength Athletes</b>	1.6-2.0 g/kg of body wt/day	Needed for muscle growth, repair, and recovery
<b>Older Adults (65+)</b>	1.0-1.2 g/kg of body wt/day	Helps preserve muscle mass and strength, supports immune function
<b>Pregnant Women</b>	+25 g/day above normal needs	Supports fetal growth and maternal tissue expansion
<b>Lactating Women</b>	+25 g/day above normal needs	Needed for milk production and nutrient transfer to the infant
<b>Recovering from Illness/ Injury</b>	1.2-2.0+ g/kg of body wt/day	Supports healing, tissue regeneration, and immune response
<b>Vegetarians/Vegans</b>	May need ~10% more than RDA (~0.9g/kg/day or more)	To compensate for lower digestibility and amino acid profile of plant foods

The Recommended Dietary Allowance (RDA) for protein is 0.8 grams per kilogram of body weight per day for healthy adults. This amount is considered sufficient to meet the needs of nearly all individuals in a given population. However, needs can vary depending on factors such as age, activity level, and health status (Table 5.2). For example, some athletes, older adults, and individuals recovering from illness or injury may require higher intakes of protein. In addition to the RDA, the Acceptable Macronutrient Distribution Range (AMDR) provides a broader guideline, suggesting that 10–35% of total daily calories should come from protein. This range allows for flexibility based on individual energy needs and dietary preferences, while still supporting optimal health.

### **Protein Excess**

Protein is often a macronutrient that individuals struggle to consume in adequate amounts. However, the continual increase in protein supplements in the form of powders, bars, ready-to-drink form, and others raises the question of whether a

person can consume “too much” protein. Overall, the body can tolerate higher levels of protein intake, and this has not been causally associated with adverse health outcomes. However, consuming protein well above the recommended levels for an extended period may have potential drawbacks. High protein diets can put extra strain on the kidneys, particularly in individuals with pre-existing kidney conditions. Excess protein intake may also displace other essential nutrients in the diet, leading to nutritional imbalances. Additionally, very high intake from animal sources may be associated with increased intake of saturated fat and cholesterol, potentially raising the risk of heart disease. For this reason, it is important to choose a variety of lean and low-fat protein foods in one’s diet. In healthy individuals, moderately high protein intake is generally well tolerated and may even support weight management and muscle maintenance.

## **Protein Deficiency**

Protein deficiency, on the other hand, can have serious health consequences, especially when it is prolonged. Inadequate protein intake can lead to muscle wasting, poor wound healing, weakened immunity, and delayed growth in children.

Protein-Energy Malnutrition (PEM) is a condition that arises from a deficiency in both protein and energy (calories), and it most commonly affects children in developing countries but can also occur in adults who are severely ill, elderly, or have eating disorders (Figure 5.6). PEM is not just a lack of protein alone; it involves insufficient overall nutrient intake, impacting growth, immunity, and organ function.

There are two primary forms of PEM:

- 1.** Marasmus – Caused by a severe deficiency in calories and protein. This leads to extreme weight loss, muscle wasting, and fat depletion. The individual appears very thin with prominent bones, and there's little to no edema (swelling).
- 2.** Kwashiorkor – Results from adequate or near-adequate calorie intake but insufficient protein. It is characterized by edema (swelling, especially in the abdomen), fatty liver, skin and hair changes, and a weakened immune system. Children with kwashiorkor may appear puffy despite being malnourished.

Both conditions can be life-threatening if not treated, and they often occur together in varying degrees. Even mild deficiencies can affect enzyme and hormone production, impair cognitive function, and lead to fatigue and increased risk of infections.

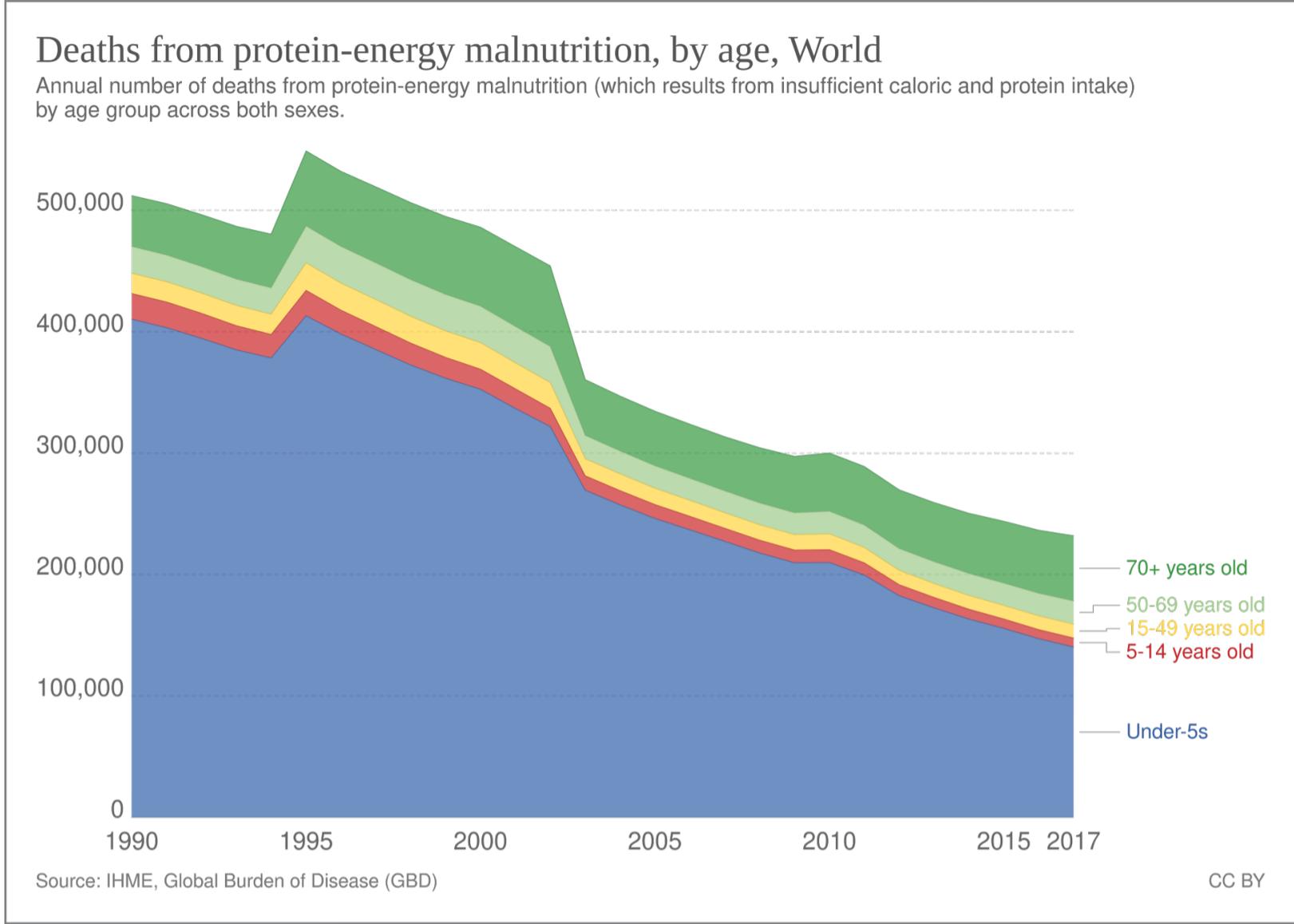


Figure 5.6 Protein Energy Malnutrition (PEM) results from insufficient caloric and protein intake. Though deaths from PEM have been on the decline since the 1990s, rates are still substantial and especially in children under the age of 5. [Image by Our World In Data from IHME, Global Burden of Disease](#) is licensed under the [Creative Commons Attribution 3.0 Unported license](#). [Access Interactive data from Our World in Data.](#)

**Health Note**

Protein is essential for building and repairing tissues—including muscles, skin, and even hormones.

**Fun Fact**

Your body can't store protein in the same way it does fat and carbs—so you need to eat it regularly!

# Chapter 6: Lipids

Lipids are a diverse group of water-insoluble, hydrophobic, organic compounds that play essential roles in the human body, far beyond simply serving as a dense source of energy. From forming the structural foundation of cell membranes to enabling the absorption of fat-soluble vitamins, lipids are involved in a wide array of physiological functions.

## Lipid Structures

### Fatty Acids

Fatty acids are the most abundant lipid in the body, mostly as components of larger molecules such as triglycerides and phospholipids, or bound to cholesterol. The human body has hundreds of unique fatty acids, though all have a similar structure that includes a methyl end and carboxylic end on either side of a carbon chain (backbone) (Figure 6.1).

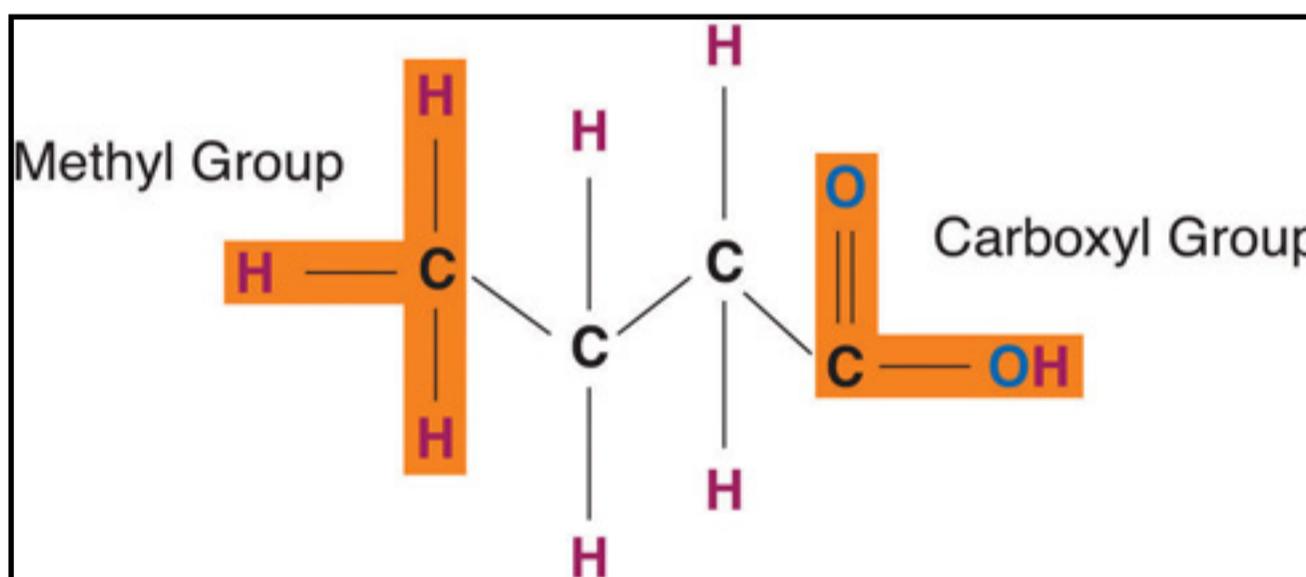


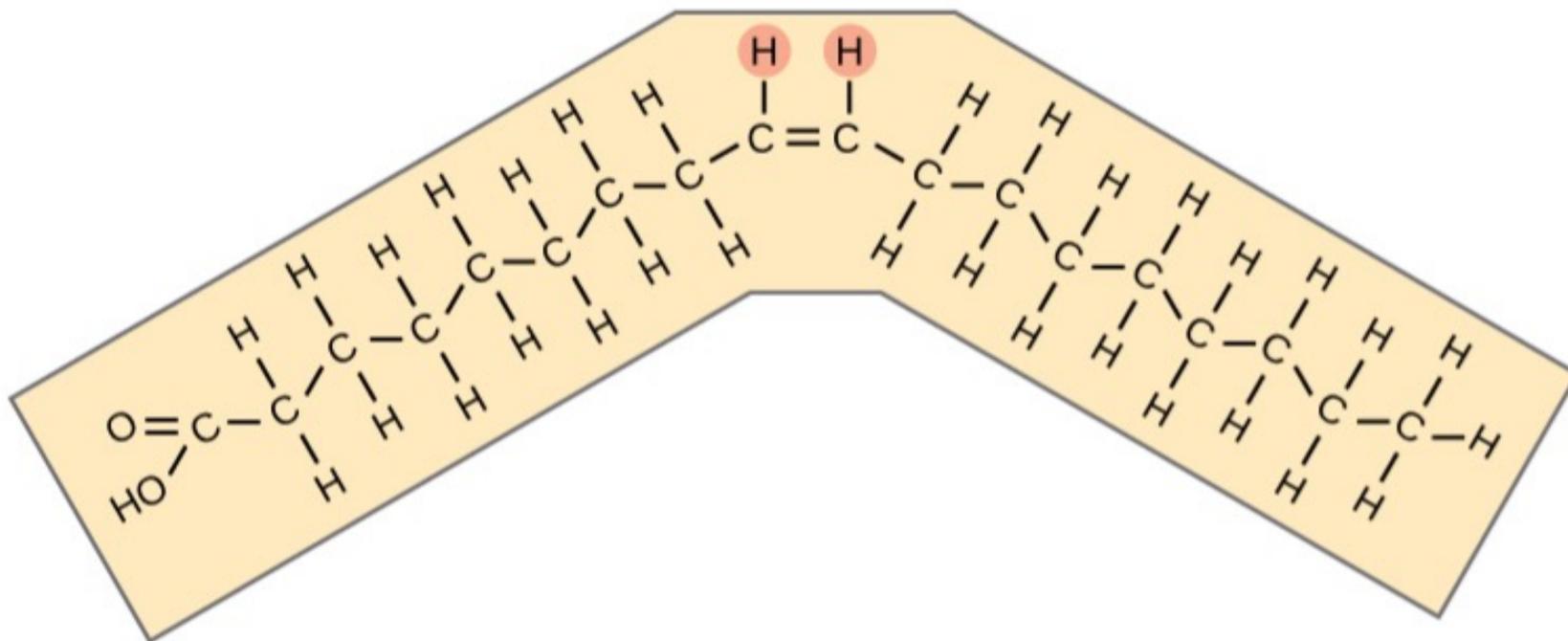
Figure 6.1 Fatty acid structure includes a carbon chain backbone of varying lengths with a methyl group on one end and a carboxylic acid group on the other end. *Image from 6.1 Triglycerides and Fatty Acids*, Pressbooks by Angela Harter Alger is licensed under a [Creative Commons Attribution 4.0 International License](https://creativecommons.org/licenses/by/4.0/).

The chain length of a fatty acid is determined by the number of carbon atoms in its hydrocarbon backbone. Short-chain fatty acids typically have less than eight carbons, medium-chain fatty acids have between eight and twelve carbons, and long-chain fatty acids have greater than 12 carbons in the backbone. This length significantly influences both the melting point and water solubility of the fatty acid. As the carbon chain increases in length, the melting point typically rises, making them more solid at room temperature, thus meaning that short-chain fatty acids are likely to be oils at room temperature. Conversely, water solubility decreases with longer chains, as the hydrophobic (nonpolar) portion of the molecule dominates, reducing its ability to interact with water molecules. Short-



## Unsaturated fatty acids

### *Cis* oleic acid



### *Trans* oleic acid

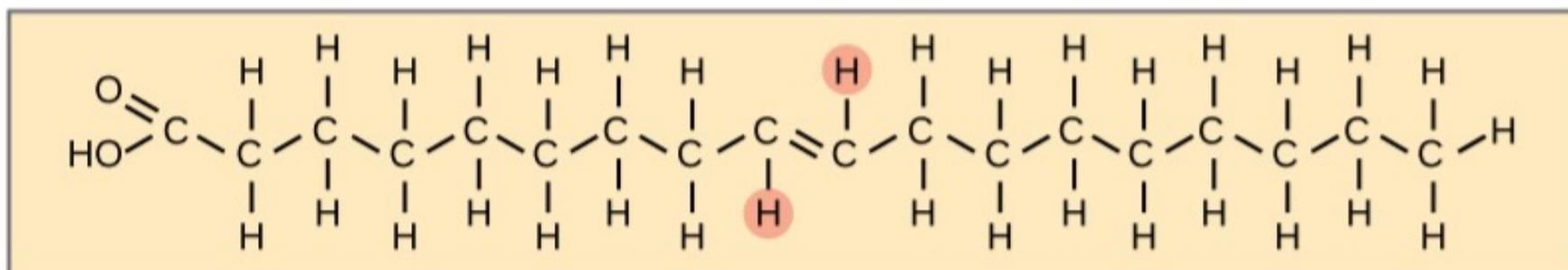


Figure 6.4 Unsaturated fatty acids can have *cis* or *trans* bonds between carbons in the hydrocarbon backbone. *Cis* bonds have hydrogens situated on the same side of the double bond, while *trans* bonds have hydrogens situated on opposite sides of the double bond. Cropped from [Figure 3.16](#) by Mary Ann Clark, Matthew Douglas, and Jung Choi, OpenStax from *Biology 2e* (2018) is licensed under [Creative Commons Attribution 4.0 International license](#).

*Trans* fats can be found naturally in small amounts in some animal products but are more commonly created through an industrial process called partial hydrogenation, which involves the infusion of hydrogen gas to solidify liquid oils. This makes them a consistency desirable for many processed food products. These artificial *trans* fats were widely used in processed foods, baked goods, and fried items to improve texture and shelf life. During the partial hydrogenation process, double bonds of the *cis*-conformation in the hydrocarbon chain may be converted to double bonds in the *trans*-conformation. Furthermore, double bonds may be converted to single bonds, creating a more saturated fat. Margarine and shortening are examples of artificially hydrogenated *trans* fats. However, research has suggested that *trans* fats raise low density lipoproteins (LDL; bad cholesterol) levels, while lowering high density lipoproteins (HDL; good cholesterol), increasing the risk of heart disease. Due to their harmful health effects, many countries have implemented regulations to reduce or eliminate *trans* fats from the food supply, and food labels are required to display the *trans* fat content.

## Essential Fatty Acids

Essential fatty acids are polyunsaturated fats that are vital for health but cannot be synthesized by the human body, making them essential to consume in one's diet. The two primary essential fatty acids are linoleic acid and linolenic acid (Figure 6.5). **Linoleic acid** is an omega-6 fatty acid, called omega-6 because the sixth carbon from the methyl end of the hydrocarbon chain is connected to a double bond. **Linolenic acid** is an omega-3 fatty acid, called omega-3 because the third carbon from the methyl end of the hydrocarbon chain is connected to its neighboring carbon by a double bond.

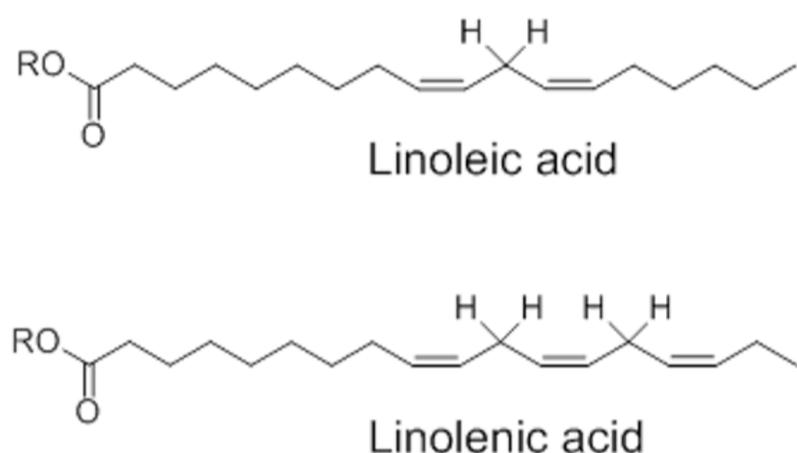


Figure 6.5. Linoleic acid and linolenic acid are both essential fatty acids, necessary to consume through the diet. Cropped from [Polyunsaturated fatty acids \(PUFAs\)](#) by [Oitio](#) is licensed under [Creative Commons CC0 1.0 Universal Public Domain Dedication](#).

These fatty acids are important for maintaining healthy cell membranes, supporting normal growth and development, and producing hormone-like substances called eicosanoids that help regulate inflammation, blood pressure, and immune function.

Dietary sources of essential fatty acids include plant oils (such as sunflower, soybean, and flaxseed oils), nuts, seeds, and fatty fish. Adequate intake of both omega-6 and omega-3 fatty acids is important for overall health, and thankfully they are usually abundant in the typical diet.

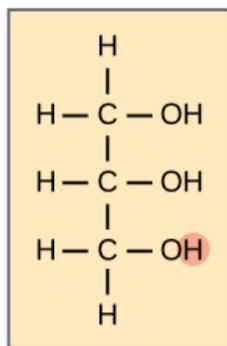
## Triglycerides

Most fatty acids don't exist in an unbound/free form in foods or in the body. Typically, they are part of larger, more complex molecules — such as tri-, di-, or monoglycerides (prefix indicating the number of fatty acids in the molecule).

Triglycerides are the most common type of lipid found in both the body and in food. They are made up of three fatty acids attached to a glycerol backbone by ester linkages; these fatty acids can be a mixture of fatty acid types such as saturated, monounsaturated, polyunsaturated, or a combination (Figure 6.6).

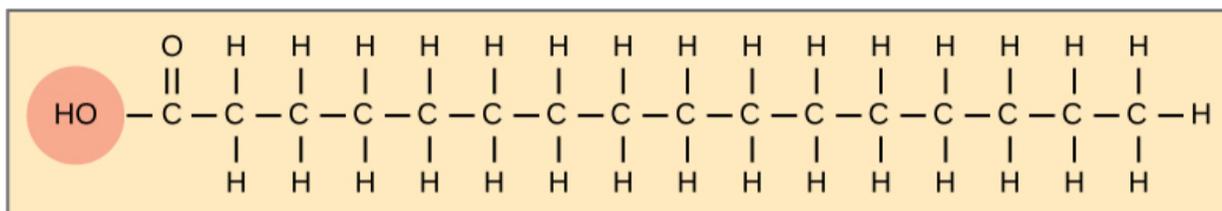
Triglycerides serve as a major energy reserve, stored primarily in adipose (fat) tissue, and they are our body's richest energy source, providing us with 9 kcal/gram (this is twice as much energy per gram than what carbohydrates or proteins provide, both 4 kcal/gram). When we consume more calories than we need, the body stores the excess energy as triglycerides in fat cells, where it can be used later during periods of fasting or increased energy demand.

### Glycerol



+

### Fatty Acid



### Triacylglycerol

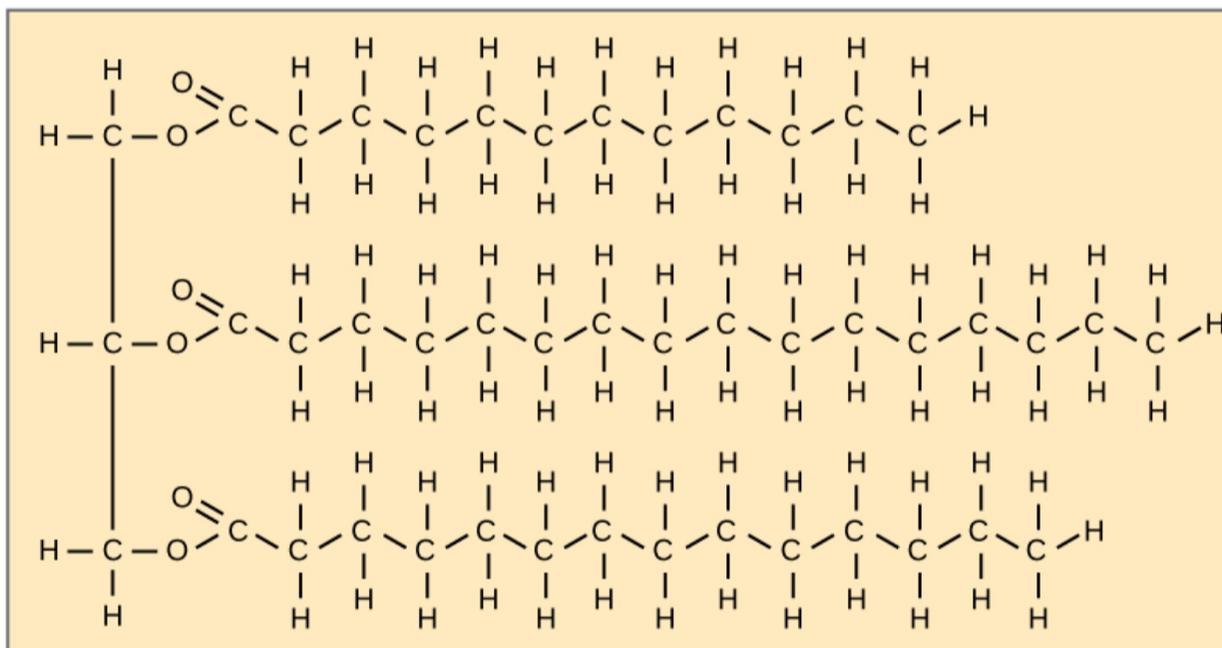


Figure 6.6 Triacylglycerol (triglyceride) is formed by the joining of three fatty acids to a glycerol backbone in a dehydration reaction. Three molecules of water are released in the process. [Image](#) by Connie Rye, Robert Wise, Vladimir Jurukovski, Jean DeSaix, Jung Choi, Yael Avissar, OpenStax from *Biology* (2016) is licensed under [Creative Commons Attribution 4.0 International license](#).

Whether triglycerides are being broken down from the diet or the adipose tissue, they must first be disassembled in order for the body to use them as a source of energy. The process by which triglycerides are disassembled into glycerol and fatty acids is known as **lipolysis**. Lipases — lipoprotein lipase and hormone-sensitive lipase — are crucial for the ester linkages to be broken. Together, these enzymes help regulate the balance between fat storage and fat use, depending on the body's energy needs.

- Lipoprotein lipase: an enzyme found on the walls of blood vessels, which removes fatty acids from triglycerides circulating in the blood (for example, after a meal).
- Hormone-sensitive lipase: enzymes activated by hormones during fasting or periods of increased energy demand — removes fatty acids from triglycerides in adipose tissue.

The type of fatty acids in a triglyceride — whether saturated, monounsaturated, or polyunsaturated — can influence its physical properties and its impact on health. While triglycerides are essential for providing energy and supporting certain bodily functions, elevated blood levels are associated with an increased risk of cardiovascular disease, making it important to balance intake and choose healthy fat sources.

## Phospholipids

Phospholipids are major constituents of the plasma membrane, the outermost layer of animal cells. They are composed of fatty acid chains attached to a glycerol backbone. Instead of three fatty acids attached to the backbone, as in triglycerides, phospholipids contain two fatty acids and a phosphate group attached to a glycerol backbone (Figure 6.7). This structure makes them both hydrophobic and hydrophilic, allowing them to form the bilayer of cell membranes — providing a flexible, protective barrier that regulates what enters and exits the cell. Phosphatidylcholine and phosphatidylserine are two important phospholipids that are found in plasma membranes. In addition to their structural role, phospholipids are involved in cell signaling and serve as precursors to eicosanoids, hormone-like compounds that influence inflammation, immunity, and other physiological processes. Phospholipids also act as emulsifiers and carriers, helping transport fat-soluble substances, such as vitamins and lipoproteins, through watery environments like blood and lymph. While the body can make phospholipids, they are also found naturally in foods such as egg yolks, soybeans, sunflower seeds, and some meats and fish.

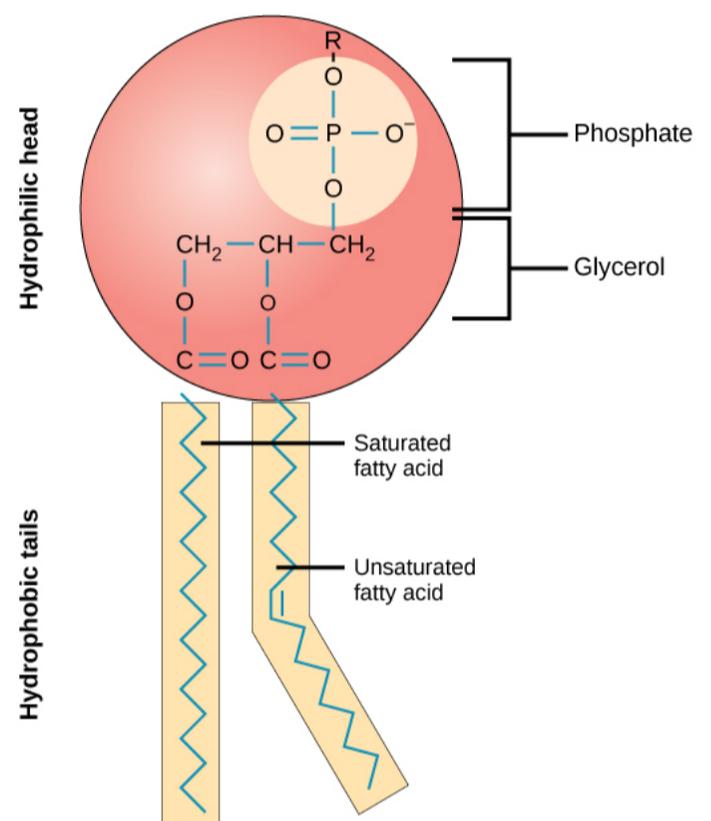


Figure 6.7 A phospholipid is a molecule with two fatty acids and a modified phosphate group attached to a glycerol backbone. Figure 3.2 by J. Gordon Betts, Kelly A. Young, James A. Wise, Eddie Johnson, Brandon Poe, Dean H. Kruse, Oksana Korol, Jody E. Johnson, Mark Womble, Peter DeSaix, OpenStax from *Anatomy and Physiology 2e* (2022) is licensed under [Creative Commons Attribution 3.0 Unported license](https://creativecommons.org/licenses/by/3.0/).

Unlike the lipids discussed up to this point, sterols have a fused ring structure. Although they do not resemble the other lipids, they are grouped with them because they are also hydrophobic and insoluble in water. Sterols are a subgroup of steroids, having four linked carbon rings and several of them, like cholesterol, have a short tail (Figure 6.8).

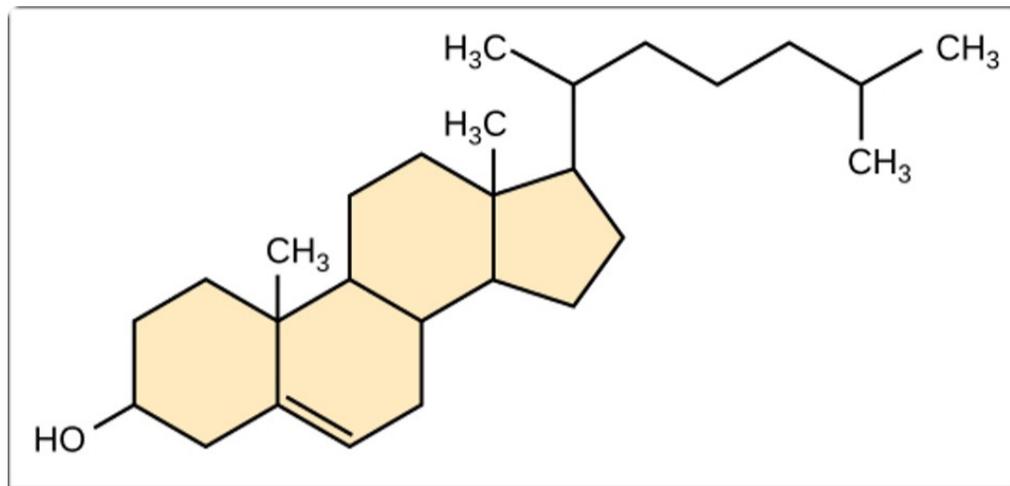


Figure 6.8 Cholesterol is a four-ring structure. Cropped from Figure 3.21 by Mary Ann Clark, Matthew Douglas, and Jung Choi, OpenStax (2018) from *Biology 2e* (2018) is licensed under [Creative Commons Attribution 4.0 International license](https://creativecommons.org/licenses/by/4.0/).

## Cholesterol

Cholesterol is the most common steroid. Cholesterol is mainly synthesized in the liver and is the precursor to many steroid hormones such as testosterone and estradiol, which are secreted by the gonads and endocrine glands. It is also the precursor to Vitamin D.

Cholesterol is also the precursor of bile salts, which help in the break down (emulsification) of

fats and their subsequent absorption by cells. Although cholesterol sometimes gets a negative connotation, it is absolutely necessary for the proper functioning of the body. It is a component of the plasma membrane of animal cells and is found within the phospholipid bilayer, regulating the fluidity and structural integrity of the membrane.

While cholesterol is found in animal-based foods such as meat, eggs, and dairy products, nearly every tissue in the human body is also capable of making all the cholesterol it needs; it is made primarily in the liver from glucose and fatty acids. In fact, the body typically produces more cholesterol than it absorbs from food. Because of this, even individuals who consume little or no dietary cholesterol can still have normal or elevated blood cholesterol levels. Furthermore, genetic factors can influence how much cholesterol a person makes.

The balance between cholesterol production and dietary intake is important for health, as high levels of cholesterol in the blood, especially low-density lipoprotein (LDL) cholesterol, can contribute to the development of atherosclerosis (the buildup of fats, cholesterol in and on the artery walls) and increase the risk of heart disease.

# Lipid Transport

## Lipoproteins

Cholesterol and other lipids are transported throughout the body with the help of lipoproteins. Lipoproteins are complexes of lipids and proteins that transport cholesterol, triglycerides, and other fats through the bloodstream since lipids are not water-soluble. There are several types of lipoproteins, classified by their density and function: chylomicrons; very-low-density lipoproteins (VLDL); low-density lipoproteins (LDL); and high-density lipoproteins (HDL).

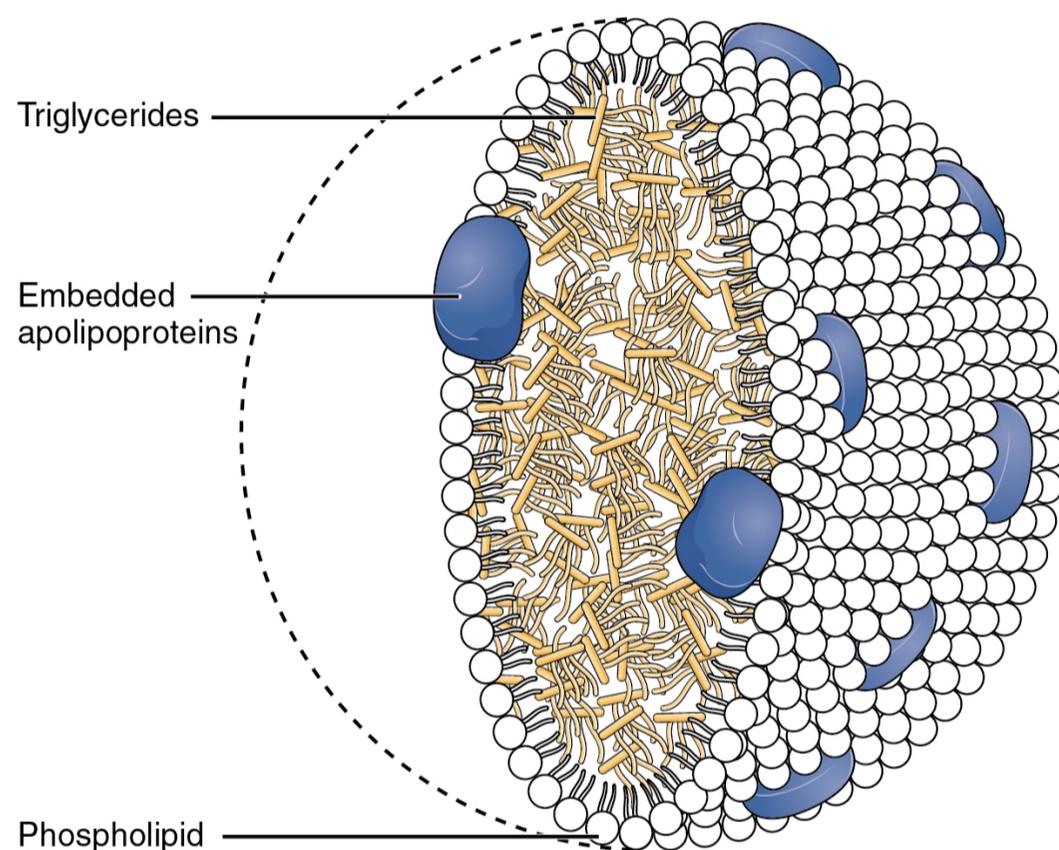


Figure 6.9. Chylomicrons (and other lipoproteins) consist of similar structures, with hydrophilic components such as apoproteins and polar head groups of phospholipids situated on the outer surface of the shell, and hydrophobic components like triglycerides situated inward. [Image](#) by J. Gordon Betts, Kelly A. Young, James A. Wise, Eddie Johnson, Brandon Poe, Dean H. Kruse, Oksana Korol, Jody E. Johnson, Mark Womble, Peter DeSaix, OpenStax from *Anatomy and Physiology* (2013) is licensed under [CC BY 3.0](#).

Chylomicrons (Figure 6.9) are synthesized in the cells of the small intestine (enterocytes) and are responsible for transporting exclusively dietary triglycerides and cholesterol from the intestines to other tissues. VLDL is produced by the liver and carries endogenous triglycerides to tissues; as triglycerides are removed, VLDL is gradually converted to LDL.

LDL, often referred to as "bad cholesterol," is produced by the liver and delivers cholesterol to cells for use (Figure 6.10). LDL receptors, especially on the cell membranes of liver cells, adipose, and muscle cells, bind to the apoproteins in the lipoprotein structure, allowing

cholesterol to be delivered to tissues that use it for structural and metabolic purposes. However, uptake of too much LDL can contribute to atherosclerosis plaque buildup in arteries if levels are too high. Certainly, the composition of one's diet can affect the concentration of LDL cholesterol in the blood.

In contrast, HDL, known as "good cholesterol," is synthesized in the liver and helps remove excess cholesterol from tissues and blood vessels, transporting it back to the liver for excretion or recycling (Figure 6.10). This process is known

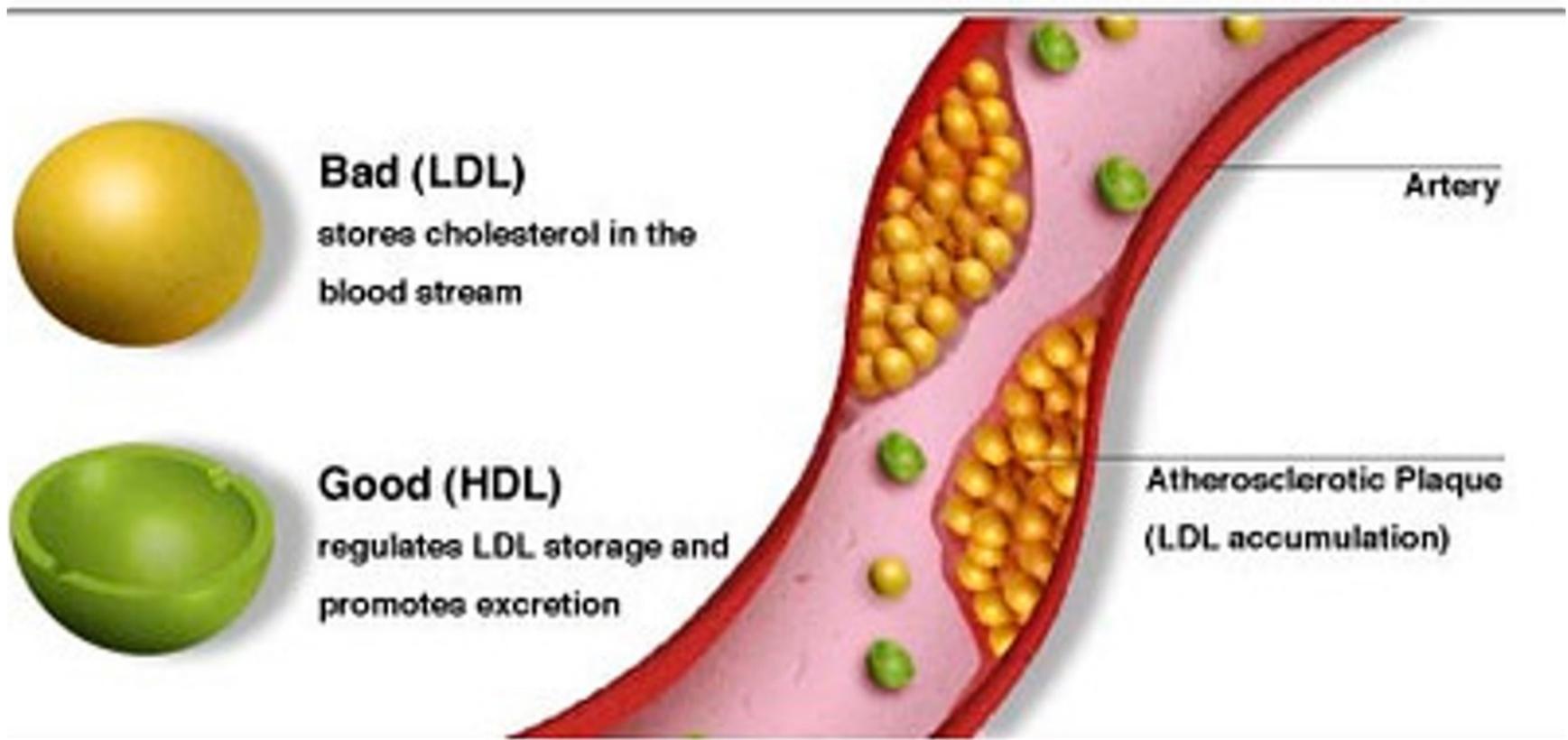


Figure 6.10 Low-density lipoprotein (LDL) transports cholesterol to tissues for use, but is referred to as “bad cholesterol” because it can build up in the arteries. High-density lipoprotein (HDL) participates in reverse cholesterol transport, taking excess cholesterol back to the liver. “Bad vs. Good Cholesterol” from Flickr by Le Van Thao is licensed under [CC BY-SA 2.0](https://creativecommons.org/licenses/by-sa/2.0/)

as reverse cholesterol transport. The proper balance and function of these lipoproteins are critical for maintaining cardiovascular health.

## Dietary Recommendations for Lipids

Current dietary guidelines recommend that total fat intake should make up 20–35% of total daily calories, with a focus on consuming healthy fats. For example, an individual with a 2,000-calorie diet should have 400-700 kcal come from lipids (44-78 g). It is highly suggested that saturated fat be limited to less than 10% of daily calories, and *trans* fats should be avoided as much as possible due to their association with an increased risk of heart disease. Instead, individuals are encouraged to consume unsaturated fats, particularly monounsaturated and polyunsaturated fats, which can be found in foods such as avocados, nuts, seeds, and fatty fish. Omega-3 fatty acids should be consumed twice per week, with increased consumption if an individual has cardiovascular disease. There are no Dietary Reference Intakes established for cholesterol intake, though the American Heart Association has classically recommended less than 300 mg of cholesterol daily.

Replacing saturated and *trans* fats with these healthier unsaturated and essential fats can support cardiovascular health and help manage blood cholesterol levels. Additionally, keeping total fat intake within recommended levels supports overall energy balance.

## **Health Note**

Dietary fat supports hormone production, absorbs fat-soluble vitamins, and cushions vital organs.

## **Fun Fact**

Your brain is nearly 60% fat by dry weight—healthy fats literally help you think!

# Chapter 7: Water

## Water Is the Essence of Life

Water is the most important substance in all living organisms. It is frequently classified as a macronutrient because water needs to be consumed in relatively large quantities in order to survive (Figure 7.1). However, unlike carbohydrates, protein, and fat, water does not provide any energy (kilocalories). Because of this, it is rarely brought up when macronutrients of a particular diet are discussed.



Figure 7.1 Glass of drinking water. [Image from Negative Space](#) is licensed under the [CC0 1.0 Universal license](#).

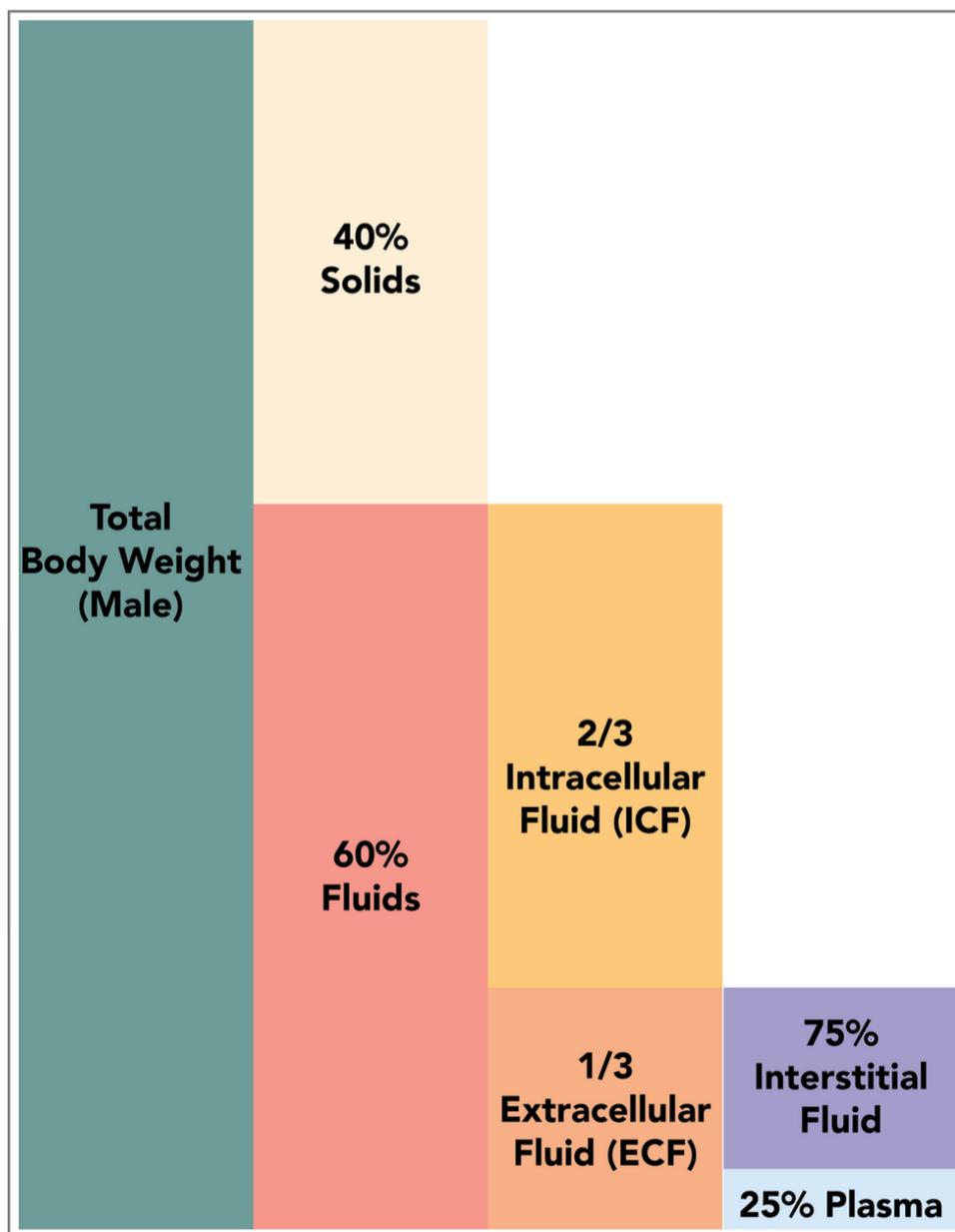


Figure 7.2 Fluid composition in an average individual (male). Water (red block) comprises approximately 60% of total body weight, on average. Fluid composition is similar in a female. [Image by Alan Sved](#) is licensed under [Creative Commons Attribution Share-Alike 4.0 International](#).

Water is the most abundant molecule in the body, comprising between 50-70% of our total body weight (Figure 7.2). It is the principal component of biological fluids. In a typical male, for example, approximately 60% of body weight is due to water — 2/3 existing as intracellular fluid (ICF, fluid within the cells) and 1/3 as extracellular fluid (ECF) outside of the cells. The majority of the ECF is interstitial fluid (fluid found between cells) and the rest is intravascular fluid (primarily plasma).

Water is abundant but also has unique and vital roles in the body. As a universal solvent, water dissolves a wide range of substances, enabling essential biochemical reactions and the transport of nutrients, gases, and waste products. It serves as a transport medium, allowing blood and other bodily fluids to move substances efficiently throughout

the body. Water also plays a key role in hydrolysis and condensation reactions, which are critical for breaking down and building up macromolecules like proteins and carbohydrates. Additionally, water helps maintain body temperature regulation through the process of sweating and evaporation, preventing overheating. Lastly, water acts as a lubricant, cushioning joints and tissues, and aiding in smooth movements and proper organ function. These functions highlight water's irreplaceable contribution to sustaining life and health.

**Table 7.1 Intracellular and Extracellular Fluid Concentrations of Ions**

Ion	ICF concentration (mmol/L)	ECF concentration (mmol/L)
Sodium	10	142
Potassium	149	4
Calcium	0.0001	2.4
Chloride	5	103
Magnesium	58	1.2
Bicarbonate	10	28
Phosphate	75	4

## Fluid Balance

Maintaining proper fluid balance is essential for physiological function, and water plays a central role in this regulation. Electrolytes are also vital for fluid balance, because where electrolytes go, water will follow. In the extracellular fluid, sodium and chloride predominate, whereas potassium and phosphate predominate in the intracellular fluid (Table 7.1). In the gastrointestinal tract, particularly the colon, fluid absorption is closely linked to sodium transport. For example, sodium is actively transported into colonic epithelial cells, creating a concentration gradient. This increased sodium concentration inside the cells drives osmosis, causing water to move from the intestinal lumen into the epithelial cells. This mechanism is critical for water reabsorption, and without it, the body would lose significant amounts of water in the feces, leading to dehydration.

Fluid balance also plays a major role in the regulation of blood volume and blood pressure. A high intake of sodium chloride (salt) can disrupt this balance. When sodium is not efficiently reabsorbed by the kidneys, it accumulates in the bloodstream. Water then follows sodium into the intravascular space, increasing blood volume. This expanded volume exerts greater pressure on blood vessel walls, leading to elevated blood pressure. Therefore, dietary sodium and the body's ability to regulate water movement are closely intertwined in maintaining overall fluid homeostasis.

## Dehydration

Dehydration occurs when the body loses more fluids than it takes in, resulting in an insufficient amount of water to carry out normal physiological functions. This imbalance can arise from inadequate fluid intake, excessive fluid loss (through sweating, vomiting, diarrhea, or urination), or a combination of both. Symptoms of dehydration range from mild to severe and can include thirst, dry mouth, fatigue, headache, dizziness, decreased urine output, and dark-colored urine. In more severe cases, dehydration can lead to confusion, rapid heart rate, low blood pressure, and even organ failure. The consequences of dehydration are particularly concerning because they can impair cognitive performance, physical endurance, thermoregulation, and kidney function. Certain populations are especially at risk, including infants and young children (due to their higher body water turnover), older adults (who may have a diminished sense of thirst), athletes (because of fluid loss through sweat), and individuals with chronic illnesses or those experiencing fever, diarrhea, or vomiting. Recognizing the signs

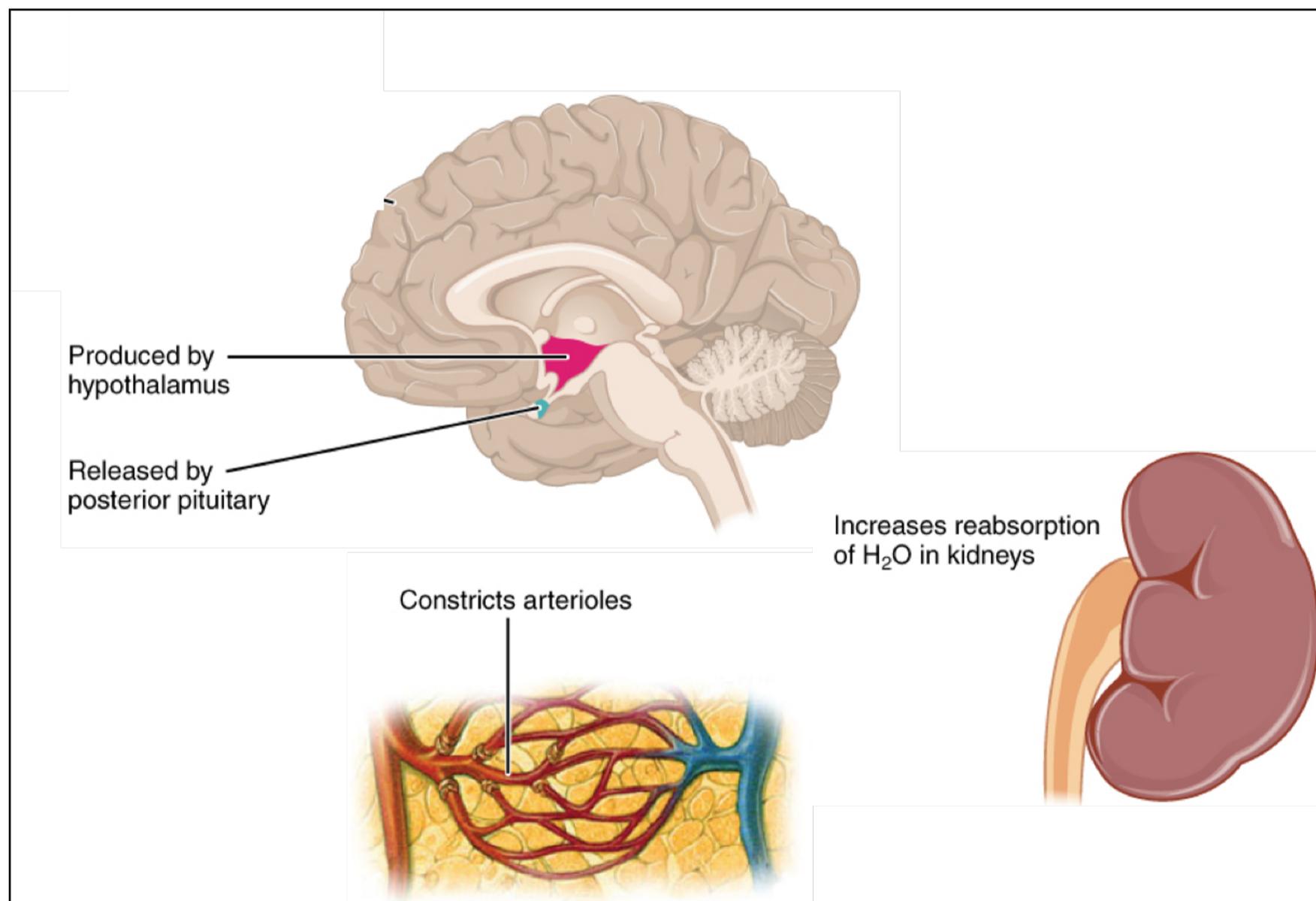


Figure 7.3 Antidiuretic hormone (ADH) action in response to dehydration. ADH is produced by the hypothalamus and released by the posterior pituitary gland in response to a decrease in blood volume and/or increase in blood osmolality. Adapted from [Figure 26.11](#) by J. Gordon Betts, Kelly A. Young, James A. Wise, Eddie Johnson, Brandon Poe, Dean H. Kruse, Oksana Korol, Jody E. Johnson, Mark Womble, Peter DeSaix, OpenStax from *Anatomy and Physiology 2e* (2022) is licensed under [Creative Commons Attribution 3.0 Unported license](#).

and risks of dehydration is key to preventing serious health outcomes and maintaining overall hydration and well-being.

## **The Body's Response to Dehydration**

When the body experiences dehydration, it initiates a complex hormonal response to conserve water and restore fluid balance. Ultimately, the body tries to retain as much fluid as possible.

Body water losses are rapidly reflected in the blood. Changes in blood volume and electrolyte concentrations in response to decreased blood water content (and therefore increased blood osmolality) trigger the hypothalamus in the brain to stimulate the release of antidiuretic hormone (ADH) from the pituitary gland. ADH then signals to the kidneys to conserve water by increasing reabsorption of water into the blood and concentrating the urine (Figure 7.3).

Decreased blood volume due to dehydration also results in a complex series of steps. One of the first steps involves the release of renin from the kidneys, which catalyzes a cascade of reactions. Renin converts angiotensinogen, a protein produced by the liver, into angiotensin I, which is then converted into angiotensin II by an enzyme released from the lungs (angiotensin-converting enzyme, ACE). Angiotensin II plays multiple critical roles: it stimulates the adrenal glands to release aldosterone, promotes the release of ADH, and triggers the sensation of thirst. Aldosterone acts on the kidneys to increase the reabsorption of sodium and chloride, which in turn promotes water retention, as water follows sodium back into the bloodstream via osmosis. Meanwhile, ADH signals the kidneys to conserve water directly by concentrating urine, as previously noted. Together, these actions help increase blood volume and stabilize blood pressure, allowing the body to correct for water loss and prevent further complications from dehydration (Figure 7.4).

## **How Much Water Do We Need?**

The amount of water a person needs to consume each day can vary depending on factors such as age, body size, activity level, climate, and overall health. General guidelines suggest that adult women should aim for about 2.7 liters (91 ounces) and adult men about 3.7 liters (125 ounces) of total water per day, according to the National Academies of Sciences. However, this total includes water from all dietary sources, not just beverages. In fact, approximately 20% of daily water intake comes from food, especially fruits and vegetables, while the remaining 80% is typically obtained through fluids, such as water, milk, juice, coffee, and tea (Figure 7.5).

Even though individual needs can differ, a good rule of thumb is to drink when thirsty and monitor urine color — pale yellow usually indicates adequate hydration. Additionally, during periods of intense physical activity, hot weather,

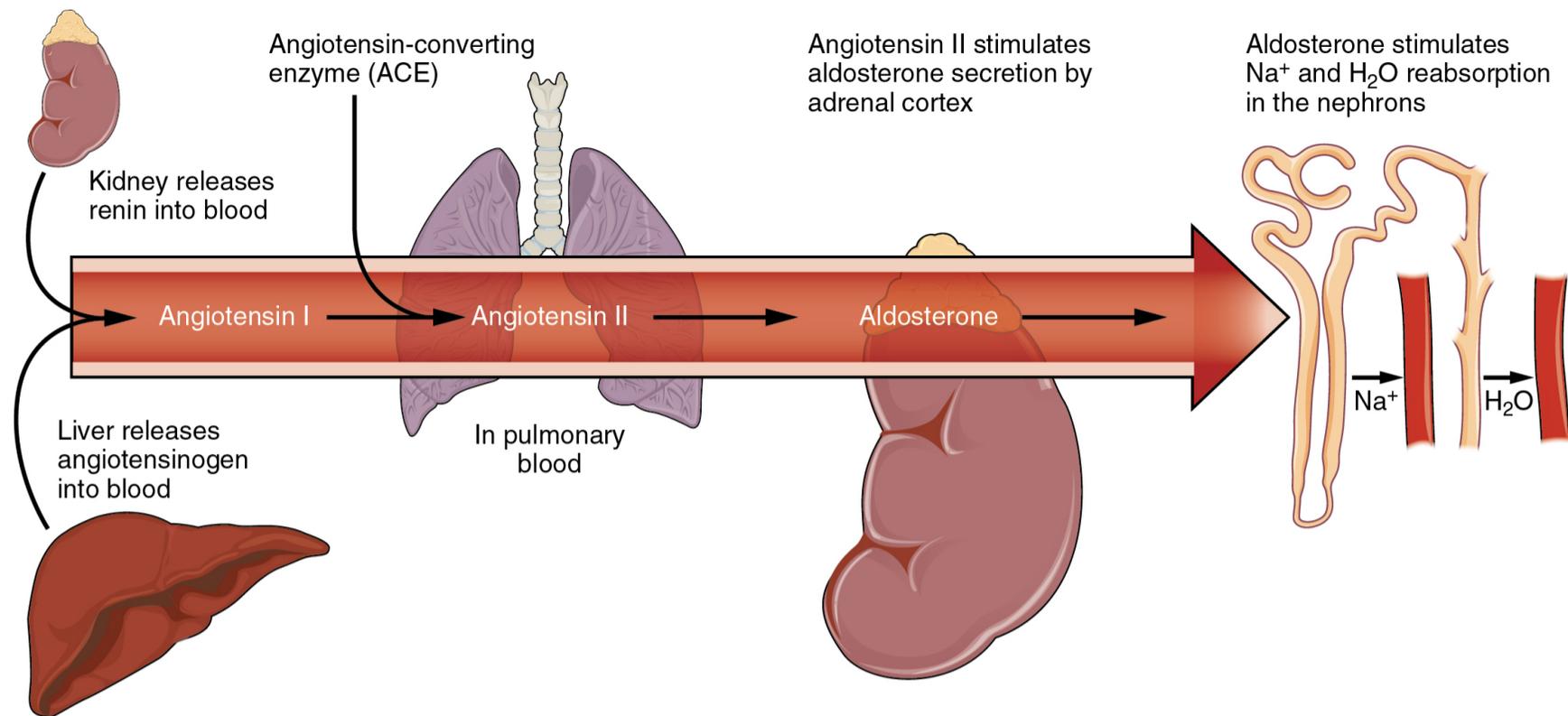


Figure 7.4 The renin-angiotensin-aldosterone system is initiated in response to dehydration to restore blood volume. Image by J. Gordon Betts, Kelly A. Young, James A. Wise, Eddie Johnson, Brandon Poe, Dean H. Kruse, Oksana Korol, Jody E. Johnson, Mark Womble, Peter DeSaix, OpenStax from *Anatomy and Physiology* (2013) is licensed under CC BY 3.0.

illness, or pregnancy and breastfeeding, fluid needs can increase significantly, making it important to adjust intake accordingly.

Water is an essential nutrient that plays a critical role in nearly every physiological function, from regulating temperature and transporting nutrients to facilitating chemical reactions and maintaining fluid balance. Its unique properties as a universal solvent and its involvement in vital processes like osmosis, hormone signaling, and cellular hydration underscore its importance to overall health. Understanding how the body conserves water, responds to dehydration, and regulates blood pressure through complex systems helps

highlight the body's remarkable ability to maintain homeostasis. Meeting daily fluid needs through a combination of beverages and water-rich foods is key to preventing dehydration and supporting optimal body function. Staying hydrated is a simple but powerful way to promote well-being across the lifespan, so consume your water!



Figure 7.5. Coffee is a caffeinated beverage. Image by [shixugang](#) from Pixabay.

- Caffeine has a mild diuretic effect, especially in large doses.
- Moderate consumption of caffeinated beverages does not cause dehydration in people who regularly consume them.
- Your caffeinated beverage consumption

contributes to your daily fluid needs!

- The water content in coffee, tea, soda, etc. more than offsets any slight increase in urine output.
- Caffeinated drinks hydrate you too — just don't rely on them exclusively!

## **Health Note**

Water makes up about 60% of the human body and is vital for temperature regulation, digestion, and nutrient transport.

## **Fun Fact**

Feeling thirsty? You may already be mildly dehydrated—drink water before you feel it!

# Chapter 8: Vitamins

Vitamins are organic compounds found in plant- and animal-derived foods that are essential for health. Vitamins are considered micronutrients, as they are required in small amounts to support a wide range of physiological processes. Unlike macronutrients such as carbohydrates, fats, and proteins, vitamins do not provide energy (kilocalories), but they are crucial in helping the body convert food into energy and in supporting functions like immunity, vision, blood clotting, and tissue repair. Each vitamin has specific roles and is essential — they must be obtained from the diet, as the body either cannot produce them at all or cannot produce them in sufficient quantities to meet physiological needs.

Vitamins are generally classified into two groups: **fat-soluble** (A, D, E, and K), which are stored in the body's fatty tissues, and **water-soluble** (B-complex vitamins and vitamin C), which circulate easily through the body and are excreted in urine if not used (Table 8.1). This chapter explores the unique functions, dietary sources, deficiency symptoms, and potential toxicities of each vitamin, highlighting their importance in maintaining overall health and preventing disease.

## Fat-Soluble Vitamins

Fat-soluble vitamins (vitamins A, D, E, & K) all share similar characteristics (Figure 8.1). As micronutrients, small amounts of the fat-soluble vitamins daily are necessary for optimal health. They can often be found in the fatty portions of foods, but are also present in a wide variety of plant- and animal-based foods. The digestion of fat-soluble vitamins requires the presence of dietary lipids as well as the action of bile for breakdown. Fat-soluble vitamins are absorbed in the small intestine, and once absorbed, they are circulated to the lymph by chylomicrons prior to eventually entering the blood. Toxicity can be a concern with these vitamins, as the body can store the fat-soluble

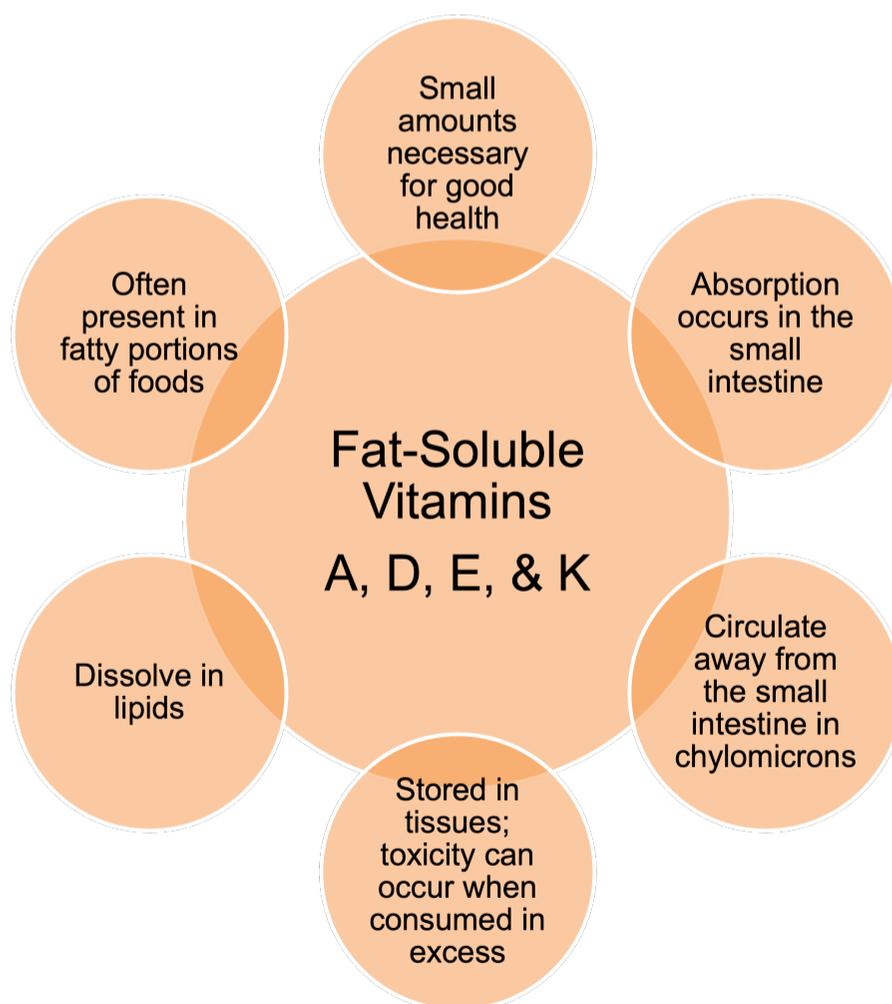


Figure 8.1 Fat-soluble vitamins share some common characteristics. Image by Author.

vitamins. Therefore, consuming large amounts of them, particularly through supplementation, can result in toxicity.

**Table 8.1 Characteristics of fat-soluble and water-soluble vitamins.**

Category	Vitamins	Key Functions	Characteristics
<b>Fat-Soluble</b>	A, D, E, K	-Vision (A) -Bone health (D) -Antioxidant (E) -Blood clotting (K)	-Stored in liver and adipose -Risk of toxicity if consumed in excess
<b>Water-Soluble</b>	B-complex, C	-Energy metabolism (B vitamins) -Red blood cell formation (B12, folate) -Collagen synthesis, immune support (C)	-Not stored in large amounts -Excess excreted in urine -Must be consumed regularly

## Vitamin A

Vitamin A consists of a family of compounds called retinoids. Retinoids are also referred to as preformed vitamin A and include retinol, retinal, and retinoic acid. The body is able to convert retinol to retinal in a reversible fashion, and retinal to retinoic acid in an irreversible manner. The vitamin A family also includes carotenoids — provitamin A and nonprovitamin A carotenoids. Provitamin A carotenoids can be converted to vitamin A. For example, beta-carotene is one of the most common provitamin A carotenoids found in food and can form two molecules of retinal. Nonprovitamin A carotenoids cannot be converted into vitamin A, but are still beneficial for health even though they don't contribute to vitamin A levels. For example, lycopene is a nonprovitamin A carotenoid found in red fruits and vegetables and is known for its beneficial antioxidant properties.

Retinoids are mainly found in animal foods, while provitamin A carotenoids are found mainly in plants. Retinol activity equivalent (RAE) is used to describe the overall vitamin A content of foods since there are these various forms of vitamin A, each with its own biological potency. RAE makes it possible to compare the nutritional content of foods containing preformed vitamin A to foods with provitamin A carotenoids.



Figure 8.2 Examples of food sources of vitamin A. [Image](#) from [R3genHealth](#) is licensed under [CC BY-NC 4.0](#).

## Dietary Sources

The RDA for vitamin A is 700  $\mu\text{g}$  RA/day for women and 900  $\mu\text{g}$  RAE/day for men. Preformed vitamin A is found in animal products such as liver and organ meats, eggs, fatty fish, and dairy. Provitamin A carotenoids are frequently found in orange and dark green vegetables such as carrots, sweet potatoes, spinach, and kale (Figure 8.2).

## Important Roles

Vitamin A is important in supporting vision, immune function, reproductive health, and cellular growth and differentiation. It also helps maintain healthy skin and mucous membranes.

Vitamin A is essential for vision, particularly in low light conditions. When light enters the eye, it strikes the rod and cone cells that make up the retina at the back of the eye (Figure 8.3). Vitamin A is essential for the production of rhodopsin, a pigment in the rod cells of the retina that allows us to see in low light. Specifically, retinal and the protein opsin combine to form rhodopsin. Night blindness is a common symptom of Vitamin A deficiency because the eye cannot produce enough rhodopsin for proper function in the dark.

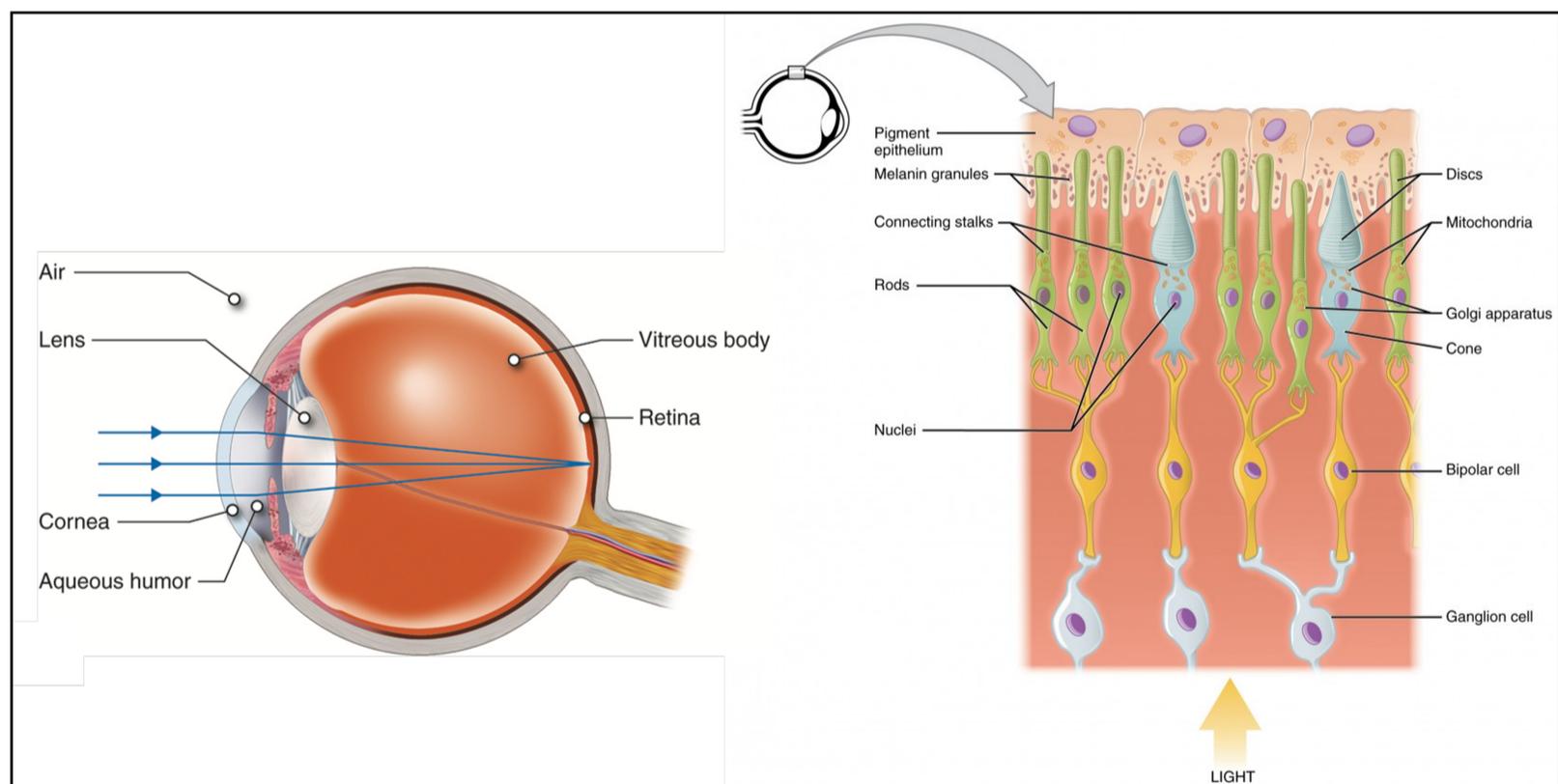


Figure 8.3 Rod and cone cells in the retina allow us to see color and black and white, respectively. Rod cells are important for night vision, consisting of a rhodopsin pigment that contains retinal. Image on the left by Cenevo is licensed under a Creative Commons Attribution 3.0. Cropped Image on the right by Elizabeth D. Kirby, Melissa J. Glenn, Noah J. Sandstrom, Christina L. Williams, OpenStax from *Introduction to Behavioral Neuroscience* (2024) is licensed under CC BY-SA 4.0.

Vitamin A is also important for cellular growth and differentiation, and the maintenance of healthy skin and mucous membrane barriers. Retinoic acid is specifically important for cell differentiation, as it up regulates genes that encode

for proteins that cause a cell to differentiate into an epithelial cell. Old epithelial cells are constantly sloughed off, such as in the gastrointestinal tract and skin, so a steady supply of vitamin A is needed to make new epithelial cells. This is important in the maintenance of our protective barriers.

### **Consequences of Deficiency or Toxicity**

Vitamin A deficiency — caused by inadequate vitamin A intake or impaired vitamin A utilization by the body — is the leading cause of preventable blindness in children worldwide. It leads to a spectrum of ocular issues, known as xerophthalmia, that can cause anything from dryness of the eyes to potential vision loss. Given the importance of vitamin A in the rhodopsin molecule of the rod cells, one of the initial symptoms of vitamin A deficiency is often night blindness, where individuals have difficulty seeing in low light conditions. More severe vitamin A deficiency can lead to dry and damaged conjunctiva (the membrane lining the eyelids and white part of the eye), drying, ulceration, and scarring of the cornea (outer layer of the eye), or the accumulation of dead cells on the surface of the eye (known as Bitot's spots).

Vitamin A deficiency can cause a range of skin problems as well, including dryness, itching, and scaling. Vitamin A is crucial for skin cell growth and repair, so its deficiency can lead to the aforementioned symptoms as well as impair the skin's ability to heal, increasing susceptibility to infections and inflammation.

While getting adequate vitamin A in our daily diet is essential for health, it is also important to avoid excessive intake. Chronic consumption of 3-4x the RDA can lead to hypervitaminosis A. This occurs when the body has too much vitamin A, usually from excessive supplementation or very high intake of foods rich in preformed vitamin A, such as liver. Symptoms often include headaches, blurred vision, liver abnormalities, and decreased bone strength. Carotenodermia can also result from the chronic overconsumption of carotenoids, and this typically results in the skin becoming yellow-orange in color.

#### **Health Note**

Vitamin A is important for vision, immunity, and skin health.

#### **Fun Fact**

The "A" in Vitamin A could stand for "Animal and Orange"—it's found in liver and carrots!

## Vitamin D

Vitamin D is considered both a nutrient and a prohormone — a nutrient because it is found in food, and a prohormone because the body uses it to produce an active hormone. There are two dietary forms of vitamin D: ergocalciferol (vitamin D<sub>2</sub>) found in plant sources and cholecalciferol (vitamin D<sub>3</sub>) found in animal sources. Vitamin D<sub>3</sub> is also the form of vitamin D made in the body.

Vitamin D is known as the sunshine vitamin, as exposure of the skin to ultraviolet rays from sunlight converts a cholesterol metabolite (7-dehydrocholesterol) to previtamin D<sub>3</sub> (precalciferol). In the skin, previtamin D<sub>3</sub> is then converted to vitamin D<sub>3</sub> (cholecalciferol). Vitamin D<sub>3</sub> then diffuses into the blood and circulates to the liver. Vitamin D<sub>3</sub> is then further metabolized and converted to 25-hydroxyvitamin D in the liver, and this is converted to calcitriol in the kidneys. Calcitriol is the active form of vitamin D in the body (Figure 8.4).

### Dietary Sources

The RDA of vitamin D for both women and men is 15 µg/day. Though vitamin D is not found naturally in a large amount of foods, it can be found in dietary sources such as fatty fish, cod liver oil, whole milk, and egg yolks. The most common sources of vitamin D are foods fortified with it, such as dairy products like milk, cereals, and orange juice (Figure 8.5).

In addition to being consumed through the diet, Vitamin D is unique because the body can synthesize it when the skin is exposed to ultraviolet B rays from sunlight. The resulting vitamin D<sub>3</sub> is chemically the same as what is consumed

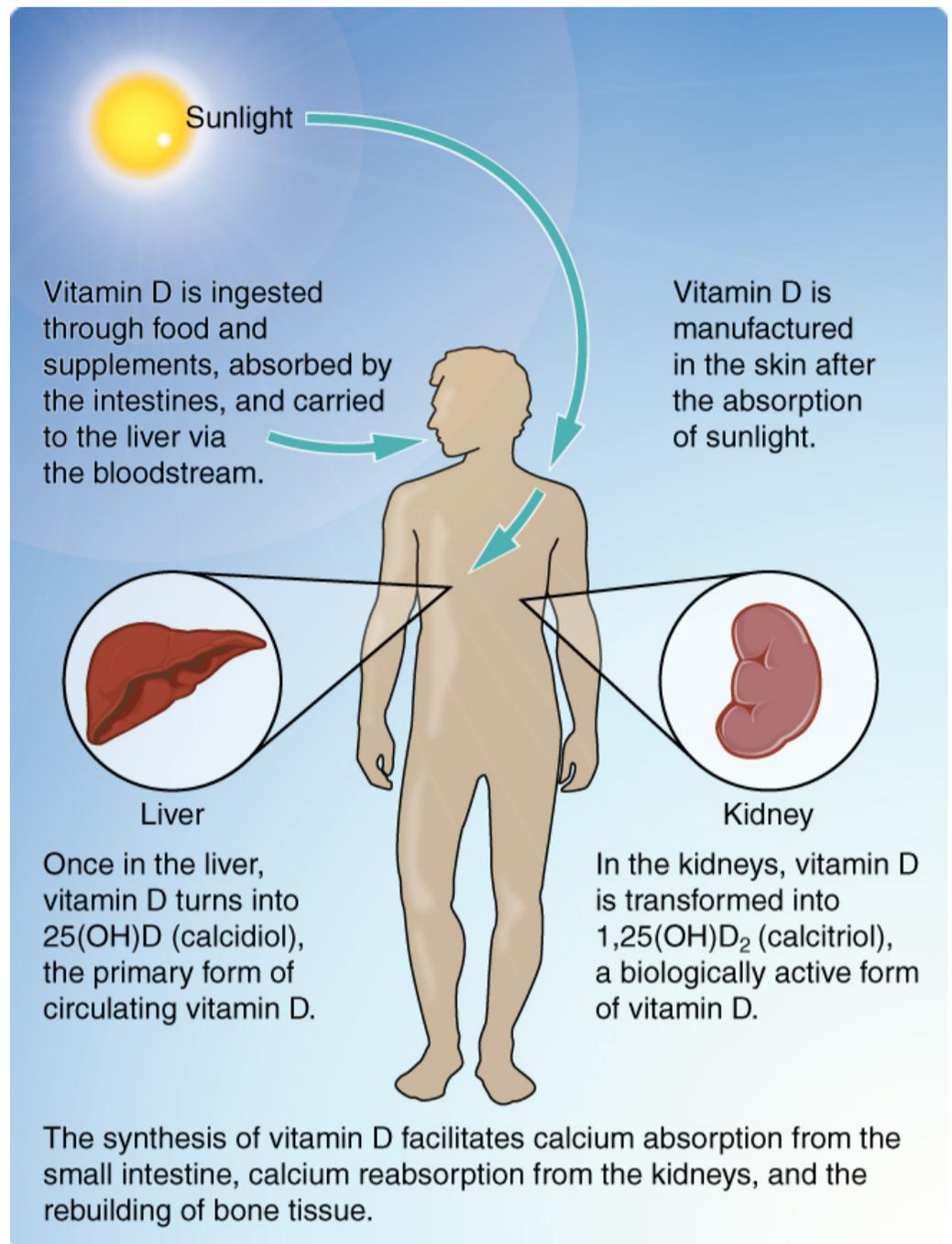


Figure 8.4 Synthesis of vitamin D. Figure 6.22 by J. Gordon Betts, Kelly A. Young, James A. Wise, Eddie Johnson, Brandon Poe, Dean H. Kruse, Oksana Korol, Jody E. Johnson, Mark Womble, Peter DeSaix, OpenStax from *Anatomy and Physiology 2e* (2022) is licensed under [Creative Commons Attribution 3.0 Unported license](https://creativecommons.org/licenses/by/3.0/).

from animal foods. For the body to produce vitamin D, it is suggested that people have approximately 5-30 minutes of midday sun exposure at least two times per week to the face, arms, legs, or back. Many environmental, genetic, and lifestyle factors can influence how much vitamin D a person can make endogenously.

Therefore, people with darker skin or those who live in persistent smog or overcast skies may require additional sun exposure to make adequate vitamin D.



Figure 8.5 Vitamin D-rich food sources include items such as fatty fish, dairy, eggs, and mushrooms. We can also get vitamin D from the sun! Image by [pch.vector](#) and designed by [Freepik](#).

### Important Roles

Vitamin D is essential for calcium and phosphorus absorption, which supports the development and maintenance of strong bones and teeth. Unlike most vitamins, vitamin D functions more like a hormone, with receptors found in nearly every cell of the body.

Calcium needs to always be available to the body's tissues. Not only is calcium the primary mineral component of our bones providing the structural foundation of our bodies. It is also for processes such as muscle contraction, blood pressure regulation, and conduction of neural impulses. Vitamin D (calcitriol) is crucial for maintaining healthy levels of calcium in the

blood, by modifying activity at the small intestine, kidneys, and bone.

If blood calcium levels were low, this would result in increased vitamin D activation in the kidneys. The following would then occur to raise blood calcium concentration:

- Small intestine — calcitriol upregulates genes that code for calcium transport proteins, allowing for absorption of calcium.
- Kidneys — calcitriol and parathyroid hormone (PTH) cause the kidneys to reduce excretion of calcium into the urine.
- Bone — calcitriol and PTH stimulate activity of osteoclasts, cells responsible for breaking down bone, and calcium is released from the bone into the blood.

In a condition of hypercalcemia, where blood calcium levels are too high, the opposite would occur — absorption in the small intestine would decrease, kidneys would excrete more calcium, and osteoclast activity in the bone would be inhibited.

## Consequences of Deficiency or Toxicity

Vitamin D deficiency is relatively common, especially in individuals with limited sun exposure, darker skin, older age, or fat malabsorption disorders. It is estimated that more than 1 billion people worldwide have insufficient levels of vitamin D. Deficiency can lead to inadequate bone mineralization during early life and increased demineralization of bone later in life.

Vitamin D deficiency can lead to rickets in children. Rickets is a result of improper bone mineralization, leading to soft and deformed bones. Long bones cannot support the stress of weight-bearing activities, and result in characteristically bowed legs and/or slower growth. In adults, vitamin D deficiency results in osteomalacia and osteoporosis. Osteomalacia often causes diffuse bone pain and muscle weakness as a result of soft and weak bones. Osteoporosis involves the demineralization of previously healthy bone, making it overall weaker and more prone to fracture (Figure 8.6). Due to this risk, the RDA for vitamin D increases to 20  $\mu\text{g}/\text{day}$  for individuals over the age of 70.

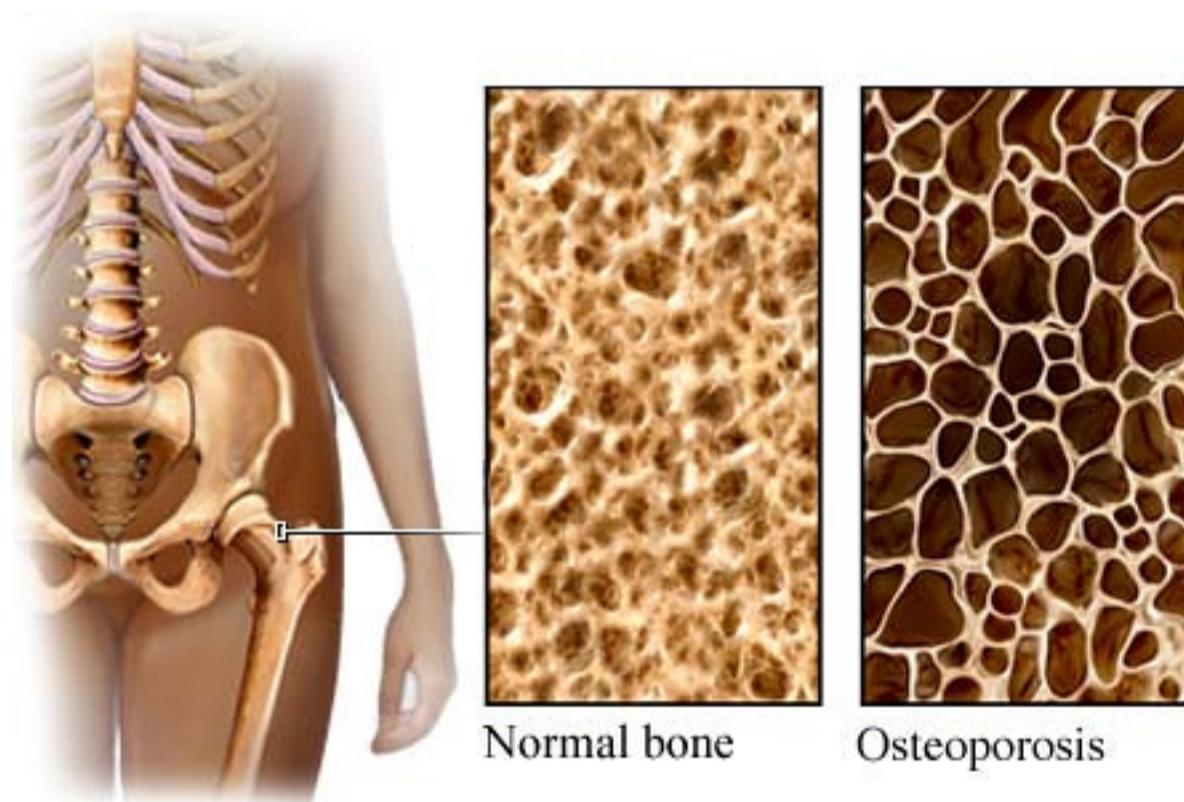


Figure 8.6 Osteoporosis due to increased demineralization of healthy bone leads to bones with thin walls and large spaces. Image by [goelsewhere](#) on [Flickr](#) is licensed under a [CC BY-NC 2.0 license](#).

Vitamin D toxicity is rare but can occur with excessive supplementation. Because of vitamin D's role in calcium absorption, excretion, and mobilization, chronic high levels of vitamin D leads to high calcium levels in the blood and urine. This may cause nausea, vomiting, weakness, kidney stones, and calcification of soft tissues like the heart and lungs.

## Health Note

Vitamin D helps the body absorb calcium and supports immune health.

## Fun Fact

Your skin can make vitamin D when exposed to sunlight—it's the only vitamin your body produces from a non-food source!

## Vitamin E

Vitamin E is a group of eight different compounds related in molecular structure, of which alpha-tocopherol is the most biologically active compound. Vitamin E acts as an antioxidant, helping to protect cell membranes from oxidative damage from reactive oxygen species. It also supports immune function and helps maintain healthy skin and eyes.

### Dietary Sources

The RDA for vitamin E is 15 mg/day for both women and men. Vitamin E is particularly abundant in vegetable oils, nuts, seeds, leafy greens, and fortified cereals (Figure 8.7).

### Important Roles

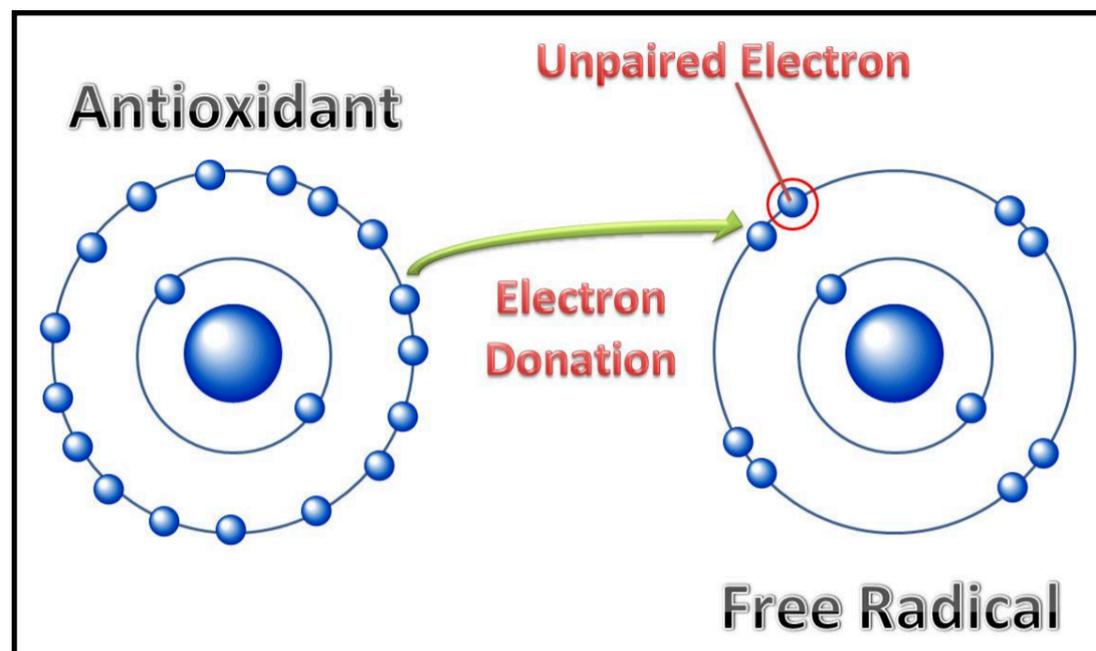
Free radicals are unstable molecules because they have unpaired electrons in their outer shells. They are capable of damaging (oxidizing) fatty acids in the phospholipid bilayers of cell membranes. Vitamin E plays an important role in acting as an antioxidant and protecting biological membranes. Vitamin E does so by donating electrons to free radicals, thereby stabilizing them and preventing them from damaging the fatty acids embedded in membranes (Figure 8.8).

Vitamin E may also help to prevent the formation of cataracts, an opacity of the normally clear lens of the eye. Smokers and individuals exposed to excessive amounts of sunlight are at an increased risk of cataract formation due to free radical damage. Increased vitamin E consumption through the diet or supplementation may decrease the risk of developing cataracts, particularly in more at-risk populations.



Figure 8.7 Examples of food sources of vitamin E. Image modified from [photo](#) by [Towfiqu barbhuiy](#) on [Pexels](#).

## Consequences of Deficiency or Toxicity



Deficiencies in vitamin E are rare, and are typically reported in people who have an underlying condition that impairs fat absorption and/or the absorption of fat-soluble vitamins. Deficiency may result in muscle weakness, vision issues, nerve damage causing numbness and tingling, and a weakened immune system. Hemolytic anemia may also occur as a result of a vitamin E deficiency, due to weakened and ruptured red blood cells. This is likely

Figure 8.8 An antioxidant, such as vitamin E, is able to donate an electron to stabilize a free radical and prevent oxidative damage from that free radical. Image by Lobo et al. (2010) is licensed under the [Creative Commons Attribution Share-Alike 4.0 International license](https://creativecommons.org/licenses/by-sa/4.0/).

due to the lack of vitamin E available to protect red blood cell membranes from oxidative damage. This ultimately leads to the cells breaking down, diminishing their capacity to carry oxygen and causing weakness and fatigue.

Vitamin E toxicity is rare, as the tolerable upper limit is 1,000 mg/day. High-dose supplementation can increase the risk of bleeding, as it can interfere with blood clotting. This is especially true for individuals also taking blood thinners.

### Health Note

Vitamin E acts as an antioxidant, protecting cells from damage.

### Fun Fact

Vitamin E helps keep your skin youthful by fighting free radicals.

## Vitamin K

Vitamin K is a family of structurally similar compounds. Phylloquinone (vitamin K1) is found in plant foods. Vitamin K1 is also found in some supplements and is given to infants at birth to prevent bleeding. Menaquinone (vitamin K2) is found in fermented foods and some animal products. It is also produced in small amounts by bacteria in the large intestine. Menadione (vitamin K3) is produced commercially. Interestingly, vitamin K was discovered by physiologist Henrik Dam

when he determined that vitamin K deficiency in chickens caused excessive bleeding.

## Dietary Sources

The Adequate Intake level established for vitamin K is 90 µg/day for women and 120 µg/day for men. Vitamin K is found mainly in leafy green vegetables (such as kale, spinach, and broccoli) (Figure 8.9), vegetable oils, and fermented foods. It is also produced in small amounts by gut bacteria.



Figure 8.9 Examples of food sources of vitamin K. Modified from [Image](#) by [Viktoria Slowikowska](#) from [Pexels](#).

## Important Roles

Vitamin K is essential for blood clotting (coagulation). It acts as a cofactor for enzymes that modify clotting factors produced in the liver, enabling them to bind calcium and initiate the clotting cascade. The coagulation process is like a row of dominoes — the last one won't fall if the others haven't fallen in sequence. Vitamin K activating clotting factors allows the next reaction in the cascade to occur where the clotting factors convert prothrombin to thrombin. Thrombin then

catalyzes the conversion of fibrinogen (water-soluble protein) to fibrin (water-insoluble protein). Fibrin forms a web-like clot to stop bleeding. Without vitamin K, the body would not be able to produce enough activated clotting factors, leading to impaired blood clotting and increased risk of bleeding.

## Consequences of Deficiency or Toxicity

Vitamin K deficiency is rare in adults, though can occur in individuals with fat malabsorption disorders, those on long-term antibiotics, or people taking medications that interfere with vitamin K activity. Long-term use of antibiotics can kill bacteria in the large intestine that produce vitamin K, while anticoagulants such as warfarin that are prescribed to prevent blood clots in individuals with cardiovascular disease, decrease the activity of vitamin K. Symptoms of vitamin K deficiency typically include easy bruising, excessive bleeding, or hemorrhage.

Vitamin K deficiency does occur in some infants and can be life-threatening with uncontrolled internal bleeding (vitamin K deficiency bleeding, VKDB). Furthermore, infants are born with low stores of vitamin K, lack vitamin K-producing bacteria at birth, and human milk contains low levels of vitamin K. For these reasons, the American Academy of Pediatrics recommends a vitamin K injection be routinely given at birth to avoid VKDB.

## Health Note

Vitamin K is essential for blood clotting and bone health.

## Fun Fact

Newborns get a vitamin K shot because they don't have enough gut bacteria to make it yet.

## Water-Soluble Vitamins

There are nine essential water-soluble vitamins - eight B vitamins and vitamin C. These water-soluble vitamins all share similar biological features (Table 8.2). As with the fat-soluble vitamins, the water-soluble vitamins are micronutrients and are required in small amounts daily for optimal health. They tend to be bound to proteins in food and have to be cleaved (separated) in order to be absorbed and available for use by the body. Absorption primarily occurs in the small intestine, though some can occur in the stomach as well (to a lesser extent). Once absorbed, the water-soluble vitamins are circulated directly to the liver in the blood. The body does not store these vitamins, therefore, they are typically not toxic when consumed in large amounts — the body excretes what it does not need. The bioavailability of the water-soluble vitamins can be impacted by nutritional status, meaning that the body will increase absorption of a vitamin if intake has been low, or alternatively, decrease absorption of a vitamin if intake has been high. Furthermore, bioavailability can be impacted by other nutrients and substances in foods, medications, age, and illness status.

**Table 8.2 Characteristics of the Water-Soluble Vitamins**

Similar properties
<ul style="list-style-type: none"><li>● Dissolve in H<sub>2</sub>O</li><li>● Tend to be bound to proteins in food</li><li>● Absorbed primarily in the small intestine, some in stomach (to lesser extent)</li><li>● Circulated directly to the liver</li><li>● Bioavailability can be influenced</li><li>● No toxicity</li></ul>
Functions are diverse
<ul style="list-style-type: none"><li>● Coenzymes in energy metabolism pathways</li><li>● Carriers of methyl units</li><li>● Free radical damage</li></ul>

The water-soluble vitamins have a diverse range of functions. Most are involved in energy metabolism pathways in some way, often acting as coenzymes. Others are important carriers of methyl units, while others are important in acting as antioxidants to protect the body from free radical damage.

## Vitamin B1 –Thiamin

Thiamin is a water-soluble vitamin that needs to be activated to be used by the body. This is done through phosphorylation, whereby two phosphate groups are added to thiamin to form thiamin pyrophosphate (TPP).

### Important Roles

Active TPP is a crucial coenzyme that plays an important role in various metabolic pathways, primarily in carbohydrate metabolism. TPP is essential for the reactions that convert glucose into energy, acting as a cofactor for several enzymes involved in this process. TPP is also involved in metabolism of some amino acids used for energy production, as well as the synthesis of neurotransmitters in the nervous system. Overall, by facilitating the breakdown of carbohydrates and amino acids and their entry into energy-producing pathways, TPP is critical for generating cellular energy in the form of ATP.

### Dietary Sources

The RDA for thiamin is 1.1 mg/day for women and 1.2 mg/day for men. Thiamin is found abundantly in foods such as whole grains, pork, legumes, seeds, and fortified cereals (Figure 8.10).

In terms of bioavailability, absorption of thiamin will increase when intake is chronically low, and decrease when intake is chronically high. There are anti-



Figure 8.10 Foods such as black eyed peas are rich sources of vitamin B1 (thiamin). Image by [Jud McCranie](#) is licensed under [CC BY-SA 4.0](#).

thiamin factors in some food sources that can interfere with the bioavailability of thiamin, interfering with the absorption, utilization, or activation of thiamin. Anti-thiamin factors can include enzymes that break thiamin down directly or chemical compounds such as polyphenols that can inhibit thiamin's activity. Foods such as raw fish, tea, berries, and certain vegetables like cabbage or Brussels sprouts, often contain anti-thiamin factors. Consuming foods with these anti-thiamin factors could lead to thiamin deficiency.

## Consequences of Deficiency

Vitamin B1 deficiency often presents initially with symptoms such as headache, fatigue, nausea, and abdominal discomfort. However, it can lead to beriberi, which presents in two main types, with distinct symptoms and affecting different physiological systems.

- Dry beriberi typically results from chronic low thiamin intake, especially in adults with poor diets or malabsorption disorders. It impacts the nervous system, leading to nerve damage, muscle weakness, difficulty walking, numbness or tingling in the hands and feet, and eventual loss of coordination and reflexes.
- Wet beriberi tends to occur more rapidly and is often seen in areas where high carbohydrate, low thiamin diets are common (such as in areas where there is consumption of polished or milled rice as a primary staple food). Wet beriberi impacts the cardiovascular system, leading to swelling (edema) in the legs, rapid heartbeat, enlargement of the heart, difficulty breathing, and congestive heart failure. This form can be life threatening if not treated promptly.
- Wernicke-Korsakoff Syndrome (sometimes referred to as cerebral beriberi) is typically associated with alcoholism. An acute phase known as Wernicke's encephalopathy occurs with confusion, poor coordination, and eye movement abnormalities. This may be followed by a chronic condition known as Korsakoff's psychosis with short-term memory loss and confusion. This is most commonly seen in situations of chronic alcoholism, where both intake and absorption of thiamin are impaired.

## Vitamin B2 –Riboflavin

Riboflavin is a multi-ring structure attached to a ribose (5-carbon sugar, lending to its name). It is a vital water-soluble vitamin that plays a crucial role in various bodily functions such as energy production, cellular growth, and the metabolism of fats, drugs, and steroids.

### Important Roles

Riboflavin is a precursor to the coenzymes flavin adenine dinucleotide (FAD) and flavin mono nucleotide (FMN), which are important for cellular respiration and energy metabolism, resulting in the formation of ATP. Riboflavin is also involved in the metabolism of other vitamins: it aids in converting vitamin A and folate to their active forms, converting tryptophan to niacin, and forming vitamin B6 and vitamin K. It also aids in the function of cytochrome P-450, a family of enzymes that metabolize drugs and toxins.



Figure 8.11 Yogurt, eggs, and mushrooms are good examples of food sources of vitamin B2 (riboflavin). Photo by Andres Felipe Rengifo on Pexels.

## Dietary Sources

The RDA for riboflavin is 1.1 mg/day for women and 1.3 mg/day for men. It is abundant in meat and dairy products, found in sources such as milk, yogurt, eggs, beef liver, mushrooms, almonds, and fortified cereals (Figure 8.11). When intake of riboflavin is chronically low, the body will increase active transport mechanisms for absorption; conversely, when intake is chronically high, simple diffusion is used for absorption.

The bioavailability of riboflavin can be significantly decreased by exposure to light. Fun fact: this is why milk is packaged in opaque or cardboard containers!

## Consequences of Deficiency

Riboflavin deficiencies are typically associated with broader nutrient deficiencies and overall malnutrition. Riboflavin deficiency may result in ariboflavinosis with symptoms such as cheilosis (swelling and fissuring of the lips), glossitis (swollen and inflamed tongue), and stomatitis (swollen, inflamed, sore mouth). Muscle weakness and confusion can also be seen with ariboflavinosis.

## Vitamin B3 – Niacin

Niacin is found in various foods in two primary forms —nicotinic acid and nicotinamide. Additionally, the body can convert the essential amino acid tryptophan into niacin (nicotinamide). This conversion requires riboflavin (vitamin B2) due to the need for the coenzyme FAD.

## Important Roles

Niacin is another essential water-soluble vitamin important in supporting energy metabolism. It is a key component of the coenzymes nicotinamide adenine dinucleotide (NAD) and nicotinamide adenine dinucleotide phosphate (NADP), which extract energy from carbohydrates, fatty acids, and proteins during cellular respiration. Niacin is also often used as a dietary supplement to help manage cholesterol levels, as it has been shown to increase levels of high-density lipoprotein cholesterol and lower triglyceride levels.

## Dietary Sources

The RDA for niacin is 14 mg/day for women and 16 mg/day for men. The tolerable upper limit is established at 35 mg/day with concern that chronic large doses of nicotinic acid can increase plasma glucose levels and damage the liver (primarily from high dose supplementation). Niacin is found in both plant- and animal-based foods, with animal sources providing higher bioavailability. It is also synthesized from tryptophan, which is abundant in animal proteins. Niacin can be found in food sources such as poultry, beef, fish, tomatoes, mushrooms, and fortified cereals (Figure 8.12). Niacin is measured in terms of a Niacin Equivalent (NE), which refers to the combined amounts of niacin and tryptophan in foods.



Figure 8.12 Citrus foods and avocados are good examples of sources of vitamin B3 (niacin). Modified from [photo](#) by [Bernadette Wurzinger](#) courtesy of and copyright [Free Range Stock](#).

## Consequences of Deficiency

Niacin deficiency is typically seen in conjunction with general malnutrition or chronic alcoholism. Deficiency causes pellagra, which is characterized by the “3 D” symptoms — dermatitis, dementia, and diarrhea. The skin irritation experienced with pellagra is typically made worse by sunlight. Niacin deficiency can also be caused by a condition called Hartnup disorder. This is a genetic abnormality that impairs the absorption of tryptophan, thereby removing a source of niacin.

## Vitamin B5 — Pantothenic Acid

Pantothenic acid is a nitrogen-containing compound, a combination of pantoic acid and beta-alanine. Interestingly, its name comes from the Greek *pantothern*, meaning “from everywhere,” because it is in almost all foods at least in small amounts.

## Important Roles

Pantothenic acid is involved in the synthesis of coenzyme A (CoA), a molecule essential for the breakdown of macronutrients and production of energy. CoA is also crucial for fatty acid synthesis and breakdown and synthesis of cholesterol and bile acids.

## Dietary Sources



Figure 8.13 Examples of food sources of vitamin B5 (pantothenic acid). [Image](#) from [pxhere](#) is in the [CC0 1.0 Public Domain](#).

The adequate intake level of pantothenic acid has been established to be 5 mg/day for both men and women. It is found in almost every plant and animal food consumed in the diet (Figure 8.13), and is abundant in fortified cereal as well.

## Consequences of Deficiency

Pantothenic acid deficiency is extremely rare, especially in developed countries, because it is so widely available in food. However, severe deficiency can result in numbness and burning sensations in the hands and feet, fatigue, headache,

weakness, nausea, and vomiting.

## Vitamin B6 —Pyridoxine

The term vitamin B6 refers to six common forms, namely pyridoxal, pyridoxine, pyridoxamine, and their phosphorylated forms. All forms are made of a modified nitrogen-containing ring structure and have similar biological activity.

## Important Roles

Vitamin B6 is converted to pyridoxal phosphate (PLP), the active form of vitamin B6 in the body. PLP acts as a coenzyme in more than 100 chemical reactions. It is important in the metabolism of proteins and amino acids, and helps to prepare amino acids to enter the citric acid cycle. Significantly, vitamin B6 is necessary for making nonessential amino acids. This means that without vitamin B6, all 20 amino acids would be essential!

## Dietary Sources

The RDA for vitamin B6 is established to be 1.3 mg/day for both men and women. Vitamin B6 is found in dietary sources including chickpeas, tuna, salmon, bananas, sweet potatoes, and fortified cereal (Figure 8.14). Vitamin B6 is fairly unstable, so is not added to enriched foods.

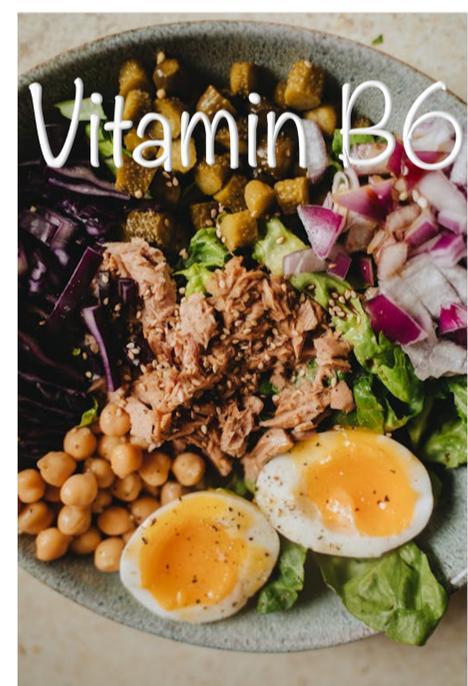


Figure 8.14 Tuna and chickpeas are great examples of food sources of vitamin B6 (pyridoxine). Modified from [Image](#) by [Alesia Kozic](#) from [Pexels](#)

## Consequences of Deficiency

Symptoms of a vitamin B6 deficiency are similar to those of a riboflavin deficiency, including cheilosis, glossitis, stomatitis, and fatigue. One of the differentiators is the presence of microcytic hypochromic anemia, where red blood cells are small and pale. This results in inadequate heme production, so there are lower concentrations of hemoglobin in the red blood cells. Overall, the anemia interferes with the ability of the red blood cells to deliver oxygen to tissues.

Though there are typically no concerns about toxicity with water-soluble vitamins, vitamin B6 can be toxic if it is supplemented excessively. This can result in severe neurological problems, including difficulty walking and numbness in the feet and hands. For this reason, the tolerable upper limit has been established as 100 mg/day.

## Vitamin B7 –Biotin

Biotin, like many of the other water-soluble vitamins, supports the metabolism of carbohydrates, fats, and proteins. It is typically attached to the proteins in food and is cleaved by small intestine enzymes to release the free biotin form for absorption.

### Important Roles

Biotin is necessary for the formation of glucose and fatty acids, which are used as fuel by the body. It plays a role in gene expression and cell growth, supporting the health of hair, nails, and skin.

### Dietary Sources

The adequate intake level of biotin is established as 30 µg/day for both men and women. It is found abundantly in foods such as eggs, nuts, seeds, salmon, sweet potatoes, and avocados (Figure 8.15). Biotin is also produced by the bacteria in the large intestine, though this is not a significant source.

The bioavailability of biotin is decreased with chronic alcohol consumption. It is also reduced when biotin is consumed with foods containing the protein avidin.

Avidin attaches to biotin and makes the vitamin difficult to absorb.

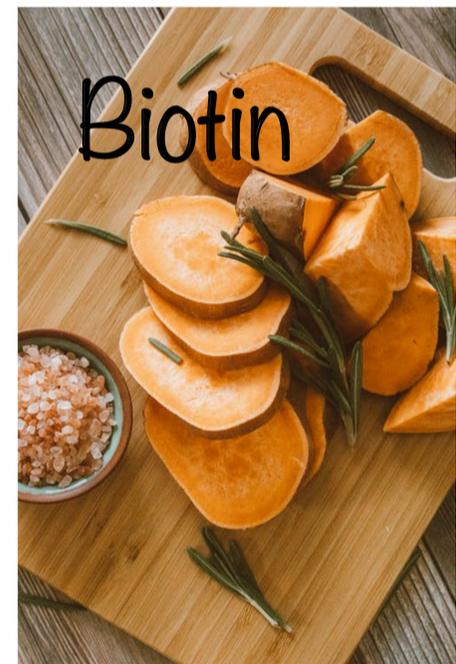


Figure 8.15 Sweet potatoes are one of many rich sources of vitamin B7 (biotin). Modified from [Image](#) by [Jess Loiterton](#) from [Pexels](#).

## Consequences of Deficiency

Biotin deficiency is rare, though can occur particularly in people who consume raw egg whites. This is because egg whites contain avidin, which binds biotin and makes it unavailable (cooking eggs denatures avidin so biotin can be released and absorbed!). Deficiency of biotin may cause thinning hair, rash around the eyes, nose, and mouth, and lethargy and fatigue.

## Vitamin B9 – Folate

Folate, also known as vitamin B9, exists in several forms. Folate is naturally occurring and found in foods and the body. Folic acid is the most oxidized and stable form, used in supplements and fortified foods. The most active form, 5-methylfolate (5-MTHF), is readily used by the body.

### Important Roles

Folate is required for the normal growth and development of nerve tissue in the fetus, therefore making maternal intake of folate crucial. It is believed this may have to do with the folate-containing enzymes needed for DNA synthesis. Folate is required for the closure of the neural tube, the tissue that becomes the brain and spinal cord during development.

### Dietary Sources

Dietary folate equivalents (DFE) is a measurement that estimates the amount of folate absorbed by the body since absorption is variable. Specifically, bioavailability varies depending on the form of folate in food, where folic acid is more readily absorbed than the folate naturally occurring in food.



Figure 8.16 Cereals and grains are great sources of vitamin B9 (folate). Photo by [Ovidiu Creanga](#) on [Pexels](#).

The RDA for folate is 400  $\mu\text{g}/\text{day}$  DFE for both men and women. However, the RDA increases to 600  $\mu\text{g}/\text{day}$  for pregnant women or those capable of becoming pregnant. The tolerable upper limit is set at 1000  $\mu\text{g}/\text{day}$ , though there is no evidence for toxicity. Folate is commonly found in food sources such as leafy green vegetables, legumes, beans, oranges, and fortified cereals or grains (Figure 8.16).

### Consequences of Deficiency

Folate is exceptionally important during pregnancy, and a maternal deficiency during pregnancy increases the risk of neural tube defects (NTDs) in the fetus.

NTDs are a group of birth defects that affect the brain and spinal cord, occurring when the neural tube doesn't close completely. Spina bifida is the most common type of NTD (Figure 8.17), typically involving the protrusion of the spinal cord and fluid and resulting in a range of disabilities. This can result in conditions such as mental impairment, partial paralysis, or poor bowel and bladder control. Folic acid supplementation before and during early pregnancy can significantly reduce the risk of NTDs. Furthermore, folic acid has been added to foods labeled as enriched, such as breads, pastas, rice, and cereals. This initiative has led to a decrease in the number of babies born with NTDs each year.

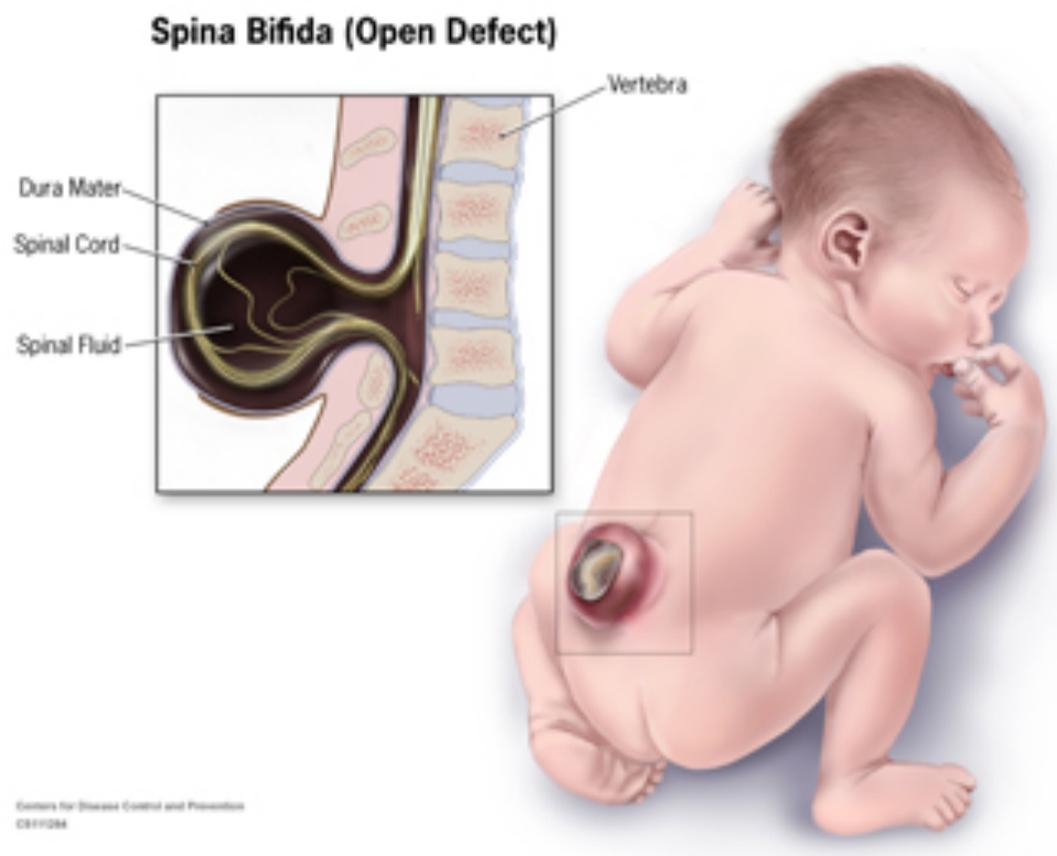


Figure 8.17 Spina bifida is the most common type of neural tube defect. [Image](#) from the [Centers for Disease Control and Prevention](#) is licensed under [Creative Commons CC0 1.0 Universal Public Domain Dedication](#).

Outside of pregnancy, folate deficiency (in a mild form) can lead to fatigue, weakness, and headaches. In a more severe deficiency, megaloblastic microcytic anemia can occur where red blood cells remain immature as megaloblasts. Megaloblasts are large and have organelles not normally found in red blood cells. As with any anemia, this impacts the oxygen-carrying capacity of the cells.

## Vitamin B12 —Cobalamin

Cobalamin is a structure that contains the trace element cobalt and nitrogen atoms. It can only be made by microorganisms, meaning that the presence of cobalamin in food is the result of it being made in the microorganisms living in the food source's environment or GI tract. Cobalamin is bound to proteins in food, and these are removed in the stomach by acids and the protease pepsin.

The free form of cobalamin is bound to R protein and intrinsic factor (both made in the stomach). R protein is released in the small intestine, and the vitamin B12-intrinsic factor complex is absorbed in the small intestine. After absorption, vitamin B12 is released from intrinsic factor and bound to transcobalamin for transport through the blood.



Figure 8.18 Examples of food sources of vitamin B12 (cobalamin). [Image](#) by [Marco Verch](#) from [CCNull](#) is licensed under [CC BY 2.0 DE Attribution 2.0 Germany](#).

## Important Roles

Vitamin B12 is vital for red blood cell formation and DNA synthesis. Vitamin B12 acts as a cofactor for enzymes involved in DNA synthesis, which is essential for cell division and maturation. Red blood cells are constantly being produced and replaced, and vitamin B12 is essential for this. Vitamin B12 also allows the body to use amino acids and fatty acids for ATP production, and is a coenzyme in the conversion of homocysteine to methionine.

During the conversion of homocysteine to methionine, the inactive form of folate (5-methyltetrahydrofolate) is converted to its active form of tetrahydrofolate (THF) through the transfer of a methyl group to vitamin B12. The methylated vitamin B12 then transfers a methyl group to homocysteine to form methionine. Without adequate vitamin B12, homocysteine levels build up in the blood and traps folate in its inactive form (in this way, vitamin B12 deficiency can lead to secondary folate deficiency).

## Dietary Sources

The RDA for cobalamin is 2.4  $\mu\text{g}/\text{day}$  for both men and women. Cobalamin is primarily found in animal-based foods. Excellent sources include shellfish, beef, liver, tuna, salmon, eggs, and dairy products like milk, yogurt and cheese (Figure 8.18).

Many breakfast cereals are also fortified with vitamin B12. This is especially important for vegans who typically need fortified foods or supplements.

## Consequences of Deficiency

Cobalamin deficiency is typically due to inadequate dietary intake or poor absorption. Megaloblastic macrocytic anemia can result, in addition to neurological issues like numbness, tingling, memory loss, difficulty sleeping, and balance issues.

Pernicious anemia is an autoimmune disease where antibodies destroy the parietal cells in the stomach that produce intrinsic factor. Intrinsic factor is required for the absorption of vitamin B12. Pernicious anemia can occur even when large amounts of vitamin B12 are consumed, and is treated with injections instead of orally.

## Ascorbic Acid –Vitamin C

Vitamin C is a water-soluble vitamin made from glucose by all plants and most animals, but not humans. Absorption of vitamin C occurs via the use of glucose transport proteins in the small intestine. If there is chronically high intake of vitamin C, it will also be absorbed in the stomach to a lesser extent.

### Important Roles

Vitamin C plays a vital role in many functions of the body. It acts as a powerful antioxidant, protecting cells from damage by free radicals. Exposure to smog, cigarette smoke, ozone, or intense sunlight can increase free radical production. Vitamin C, acting as an antioxidant system, is able to help stabilize free radicals before they oxidize other compounds and repair damage they cause. Vitamin C can easily accept and donate electrons, so is involved in a variety of redox reactions. It is also essential for the synthesis of collagen, a protein that helps maintain the structure of the skin, blood vessels, bones, and connective tissues.

Specifically, the formation of collagen requires a copper-containing enzyme to be oxidized. Vitamin C is needed to reduce the copper-containing enzyme between reactions so it can continue to form collagen.

Minerals such as iron and copper are better absorbed in their reduced states. Vitamin C can chemically reduce them in the GI tract. For example, vitamin C in orange juice reduces cereal's ferric iron to ferrous iron, making it readily bioavailable. This means that drinking orange juice, for example, along with iron-fortified cereal increases the amount of iron absorbed from the cereal.



Figure 8.19 Citrus foods are rich sources of vitamin C (ascorbic acid). Image by [PublicDomainPictures](#) from [Pixabay](#).

### Dietary Sources

The RDA for vitamin C is 75 mg/day for women and 90 mg/day for men. Vitamin C is found primarily in

fruits and vegetables, particularly in citrus fruits (such as oranges, grapefruits, lemons), strawberries, kiwi, bell peppers, broccoli, and tomatoes (Figure 8.19).

### Consequences of Deficiency

Vitamin C deficiency is rare, though can still be seen in developing countries, children, elderly on restricted diets, and alcoholics. A deficiency in vitamin C can lead to scurvy, a condition marked by fatigue, bleeding gums, joint pressure, and poor wound healing, all symptoms due to impaired collagen production.

## Health Note

B vitamins help convert food into energy and support brain function. Vitamin C boosts immune function and helps the body make collagen.

## Fun Fact

B12 is only naturally found in animal products — vegans need to supplement!

Sailors used to eat citrus fruits (with vitamin C) to prevent scurvy on long voyages!

## Food Fortification and Enrichment

Food fortification and enrichment are public health strategies used to improve the nutritional quality of the food supply and help prevent deficiencies in the population. **Fortification** involves adding nutrients to foods that may not naturally contain them, such as adding vitamin D to milk or orange juice, thiamin to milled rice and flour, or iodine to salt. **Enrichment**, on the other hand, refers to replacing nutrients that are lost during food processing — like adding B vitamins and iron back into refined grains. Particular attention is paid to enriching food with thiamin, niacin, riboflavin, folate, and the mineral iron. These practices have played a significant role in reducing the prevalence of nutrient deficiencies, such as goiter (iodine deficiency), rickets (vitamin D deficiency), and neural tube defects (folate deficiency), especially in vulnerable populations. Fortified and enriched foods make it easier for individuals to meet their daily nutrient needs, even when dietary variety is limited (Figure 8.20).

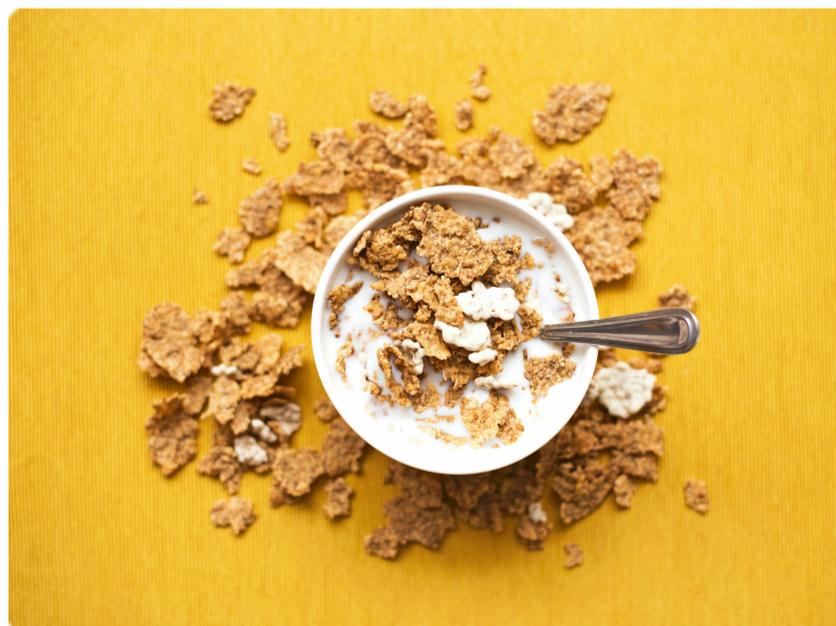


Figure 8.20 Breakfast cereal is a great example of a fortified food. Photo by [Nyana Stoica](#) on [Unsplash](#).

# Chapter 9: Minerals

Minerals are essential micronutrients that play critical roles in maintaining health and supporting life. Unlike vitamins, which are organic compounds, minerals are inorganic elements that originate in the earth and cannot be created or destroyed. They are required in varying amounts, with some—known as **major minerals**—needed in larger quantities, while others—called **trace minerals**—are required in much smaller amounts. Despite their size classifications, all minerals are equally important for functions such as building strong bones and teeth, transmitting nerve impulses, maintaining fluid balance, and supporting cellular processes (Table 9.1). Many of the minerals work together in interrelated tasks. They are abundant in both plant- and animal-based foods, though animal-based foods are more rich sources of the minerals. This chapter explores the different types of minerals, their dietary sources, physiological roles, and the consequences of both deficiencies and toxicities.

## Major Minerals

Major minerals, also known as macrominerals, are essential nutrients that the body requires in amounts greater than 100 mg/day to carry out vital physiological functions. These minerals play critical roles in building and maintaining strong bones and teeth, regulating fluid and electrolyte balance, supporting nerve transmission and muscle contraction, and enabling key metabolic processes. The major minerals include calcium, phosphorus, magnesium, sodium, potassium, chloride, and sulfur, each contributing uniquely to overall health.

### Calcium

Calcium is the most abundant mineral in the body, accounting for 2.2 pounds of the average adult's body weight. The majority (>99%) of calcium in the body is stored in the bones and teeth to provide structural strength, while the rest is found in the blood and other tissues.

### Dietary Sources

The RDA for calcium (people ages 19-50) is 1,000 mg/day for both men and women. Calcium is abundantly found in dairy products such as milk, yogurt, and cheese, fortified plant-based milks, leafy greens like kale and bok choy, and almonds (Figure 9.1). Overall, animal-based foods are much richer sources of calcium.

The bioavailability of calcium is increased by vitamin D, which aids in its absorption. However, bioavailability is decreased by age, as absorption of calcium tends to decrease after the age of 50 (the RDA raises to 1,200 mg/day for individuals aged 51+). The presence of oxalate and phytate compounds in foods also inhibits absorption of calcium. These compounds chelate (bind) calcium and make it unavailable for absorption. For example, spinach is a great source of calcium, but has a lot of oxalates in it that prohibit that calcium from being absorbed. Oxalates tend to be found in many vegetables, teas, and cocoa, while phytates are found in many whole grains and nuts.



*Dairy Food Sources of Calcium*

*Non Dairy Food Sources of Calcium*

Figure 9.1 Examples of dairy and non-dairy food sources of calcium. [Image](#) by [Brookepinsent](#) is licensed under [Creative Commons Attribution Share-Alike 4.0 International license](#).

## Important Roles

Calcium is a main component of hydroxyapatite, the mineral matrix of bones and teeth (and storage depot for calcium). Calcium aids to maintain the structure of the skeleton and strength of the bones and teeth. Calcium also has a number of regulatory functions. For example, it works with vitamin K for blood clot formation, activating clotting factors in the coagulation cascade. Calcium is important for nerve impulse transmission is essential for all types of muscle contraction.

Due to calcium's significant role in structure, nerve signaling and muscle contraction, it is crucial that calcium levels in the blood are maintained at a homeostasis (Figure 9.2). If calcium levels are low in the blood, the parathyroid gland releases parathyroid hormone (PTH). PTH stimulates the conversion of 25-

hydroxyvitamin D3 to active vitamin D (calcitriol) in the kidneys. Calcitriol and PTH then work together to stimulate: increased calcium absorption in the small intestine, decreased calcium excretion in the urine, and increased bone breakdown (resorption) by osteoclasts and release of calcium into the blood. Conversely, if blood calcium is high, the thyroid gland releases the hormone calcitonin. Increased calcitonin then leads to decreased calcium absorption in the small intestine, decreased bone breakdown, and increased calcium excretion through the urine.

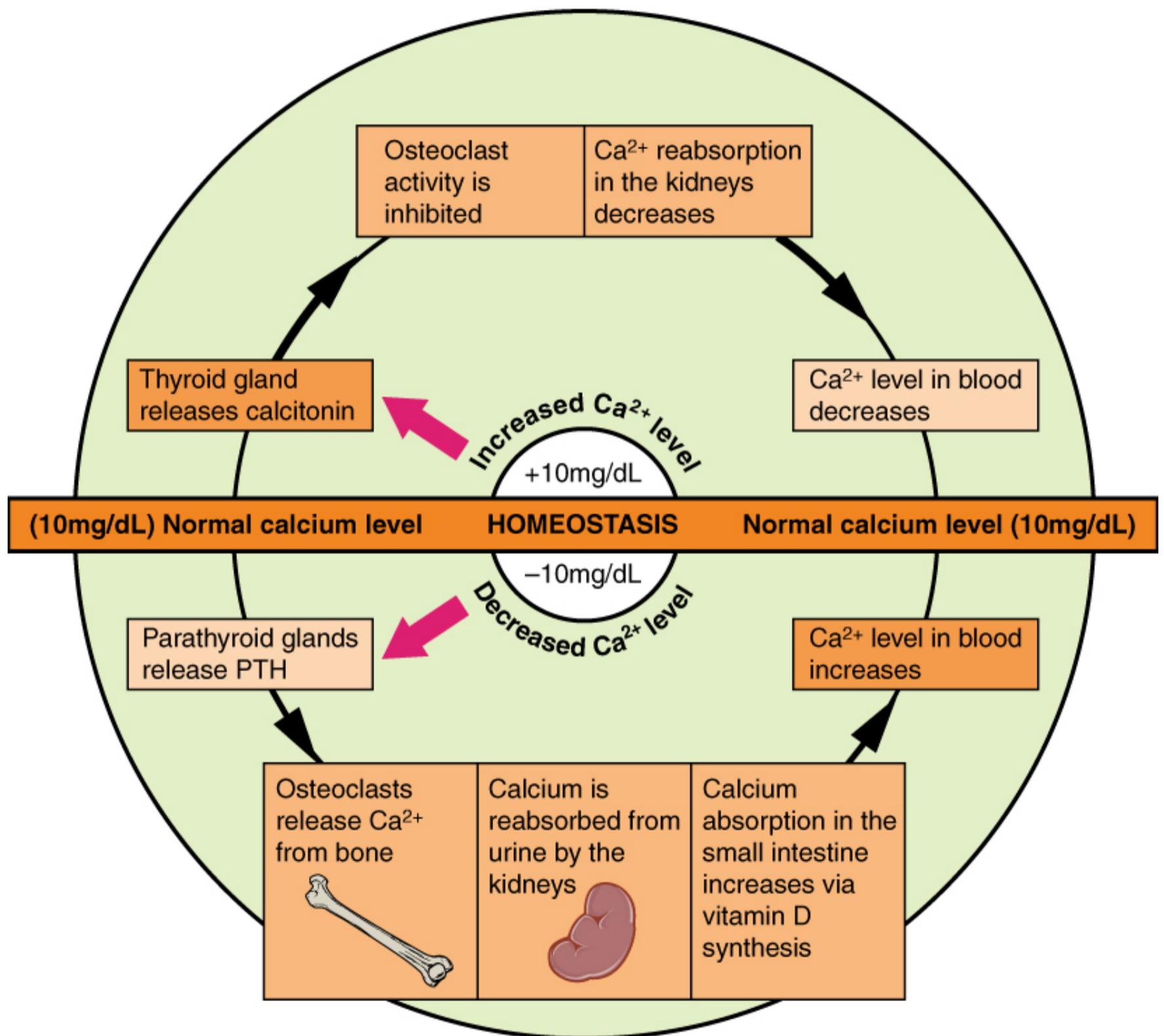


Figure 9.2 Calcium homeostasis is primarily regulated by parathyroid hormone (PTH). [Figure 6.24](#) by J. Gordon Betts, Kelly A. Young, James A. Wise, Eddie Johnson, Brandon Poe, Dean H. Kruse, Oksana Korol, Jody E. Johnson, Mark Womble, Peter DeSaix, OpenStax from *Anatomy and Physiology 2e* (2022) is licensed under the [Creative Commons Attribution 3.0 Unported license](#) [Read image transcript](#).

## Consequences of Deficiency and Toxicity

Calcium deficiency manifests in similar ways as discussed for vitamin D. In children, calcium deficiency can lead to poor bone development and increase the risk of rickets. In adults, it may contribute to osteopenia (moderate loss of bone mass) or osteoporosis, progressive bone loss that causes bones to become weak, fragile, and at risk for fractures. Calcium deficiency can also result in muscle pain, muscle spasms, abnormal heart rhythms, and tingling sensations.

Toxicity typically results from excess calcium consumption through supplementation. This may lead to constipation, development of kidney stones, and impaired absorption of other minerals such as iron and zinc.

### Health Note

Calcium is key for strong bones and teeth, and muscle contraction too.

### Fun Fact

99% of the calcium in your body is stored in your bones!

## Phosphorus

Phosphorus is a major mineral that is a component of phospholipids and associated with nearly all body structures. It is sometimes added to foods to promote moisture retention, smoothness, and taste.

### Important Roles

In addition to its importance in the structure of phospholipids, phosphorus works alongside calcium to build bones and teeth. It also plays key roles in energy metabolism as part of DNA and RNA synthesis, and maintaining acid-base balance.

Phosphorus levels are regulated in a similar manner as calcium with PTH, calcitriol, and calcitonin. If blood levels of phosphorus are low, PTH and calcitriol increase absorption in the small intestine and resorption from bones. If levels are high in the blood, calcitonin stimulates the bone building activity of osteoblasts which take up phosphorus from the blood.

### Dietary Sources

The RDA is established as 700 mg/day for both women and men. It is abundant in food sources such as meat, poultry, fish, dairy, nuts, legumes (Figure 9.3), and processed foods (which often contain phosphate additives). For example, a typical cola drink has 50 mg phosphorus (labeled as phosphoric acid), though it's

certainly not a good idea to rely on soft drinks for phosphorus intake!

The bioavailability of phosphorus is high in most foods, though it is more difficult to absorb from seeds and grains due to the presence of phytates.

### Consequences of Deficiency and Toxicity

Deficiency of phosphorus is quite rare, but can occur with certain genetic conditions, medical conditions, or malnutrition. Symptoms may include bone pain, muscle weakness, and irregular breathing. In terms of toxicity, the chronic intake of excess phosphorus, usually from supplements or processed foods, can disrupt calcium balance and lead to bone loss.



Figure 9.3 Animal products are rich sources of phosphorus. Image modified from photo by [FERMOSERGIO](#) from [Pixabay](#).

### Health Note

Phosphorus works with calcium to build bones and plays a role in energy metabolism.

### Fun Fact

Phosphorus is found in every cell in your body—mostly as part of ATP, your energy currency.

## Magnesium

Magnesium is a vital mineral involved in over 300 biochemical reactions in the body. Magnesium is widely promoted as a supplement, mainly for its calming effects on the nervous system. It is often marketed as a natural remedy for stress, anxiety and insomnia. During stressful periods, the body uses more magnesium, and some research suggests that low magnesium levels may worsen stress responses and disrupt sleep. Supplements like magnesium glycinate or magnesium citrate are frequently used to support relaxation and better sleep.

### Important Roles

Magnesium is involved in a variety of processes. It contributes to the structural development of bone, plays a central role in energy production, protein synthesis, and nerve transmission. It is especially important in muscle function in heart tissue, keeping the heartbeat steady. In muscle, calcium binds to proteins such as troponin C and myosin. This changes the shape of these proteins, which

generates a muscle contraction. Magnesium acts as a natural calcium blocker and competes with calcium for these same binding spots to help relax your muscles. If your body doesn't have enough magnesium to compete with calcium, your muscles may contract too much, causing cramps or spasms.

## Dietary Sources

The RDA for magnesium is established as 320 mg/day for women and 420 mg/day for men. It is found in food sources such as fish like halibut, whole grains, nuts, seeds, leafy green vegetables, and dark chocolate (Figure 9.4).

## Consequences of Deficiency and Toxicity

Magnesium deficiency can cause muscle cramps and irregular heartbeat, fatigue, migraines, and in severe cases, seizures. Toxicity is typically rare from food sources, though is possible with supplements or medications (such as antacids like milk of magnesia). Associated symptoms are typically GI related, including diarrhea and nausea.



Figure 9.4 Nuts, seeds, cocoa, and vegetables are rich sources of magnesium. Photo by FotoshopTofs from Pixabay

## Health Note

Magnesium supports muscle and nerve function and over 300 enzyme systems. It may help improve sleep and reduce muscle cramps.

## Fun Fact

About 60% of the body's magnesium is stored in the bones, highlighting its role in bone structure alongside calcium and phosphorus.

## Sodium

Sodium, like many other minerals, is important for nerve transmission and muscle contraction. It also plays a crucial role in fluid balance. Sodium comprises approximately 40% of table salt, the other 60% being chloride. Perhaps unique to sodium — this is not a nutrient you typically need to look for in foods, it will find you!

The majority of sodium absorption occurs in the small intestine, though the colon does actively absorb sodium as well. Because water follows sodium in the body —

without colonic absorption, large amounts of water would be lost in the feces resulting in diarrhea and dehydration.

## Important Roles

Sodium plays a crucial role in nerve impulse transmission. When a nerve cell is stimulated, sodium channels in the cell membrane open, allowing sodium ions to rush into the cell. This influx of sodium causes a change in the electrical charge across the membrane, a process called depolarization, which propagates as a nerve impulse or action potential. Similarly, sodium plays a vital role in muscle

contraction by initiating the action potential that triggers the process. When a nerve impulse arrives at the neuromuscular junction, the neurotransmitter acetylcholine is released and binds to receptors on the muscle fiber membrane. This causes sodium channels to open, sodium to flood into the cell, and this influx depolarizes the membrane and sends an action potential along the muscle fiber for eventual muscle contraction.

Sodium is also crucial for maintaining fluid balance in the body, maintaining both blood volume and blood pressure. It is the primary electrolyte in the extracellular fluid and helps regulate the distribution of water between the outside and inside of cells.

The kidneys play a key role in sodium (and water) balance, working with hormones to adjust sodium and water excretion to maintain homeostasis. If sodium levels in the blood are low (hyponatremia), the adrenal glands will increase secretion of the hormone aldosterone. Aldosterone then stimulates the kidneys to decrease sodium excretion in the urine, and

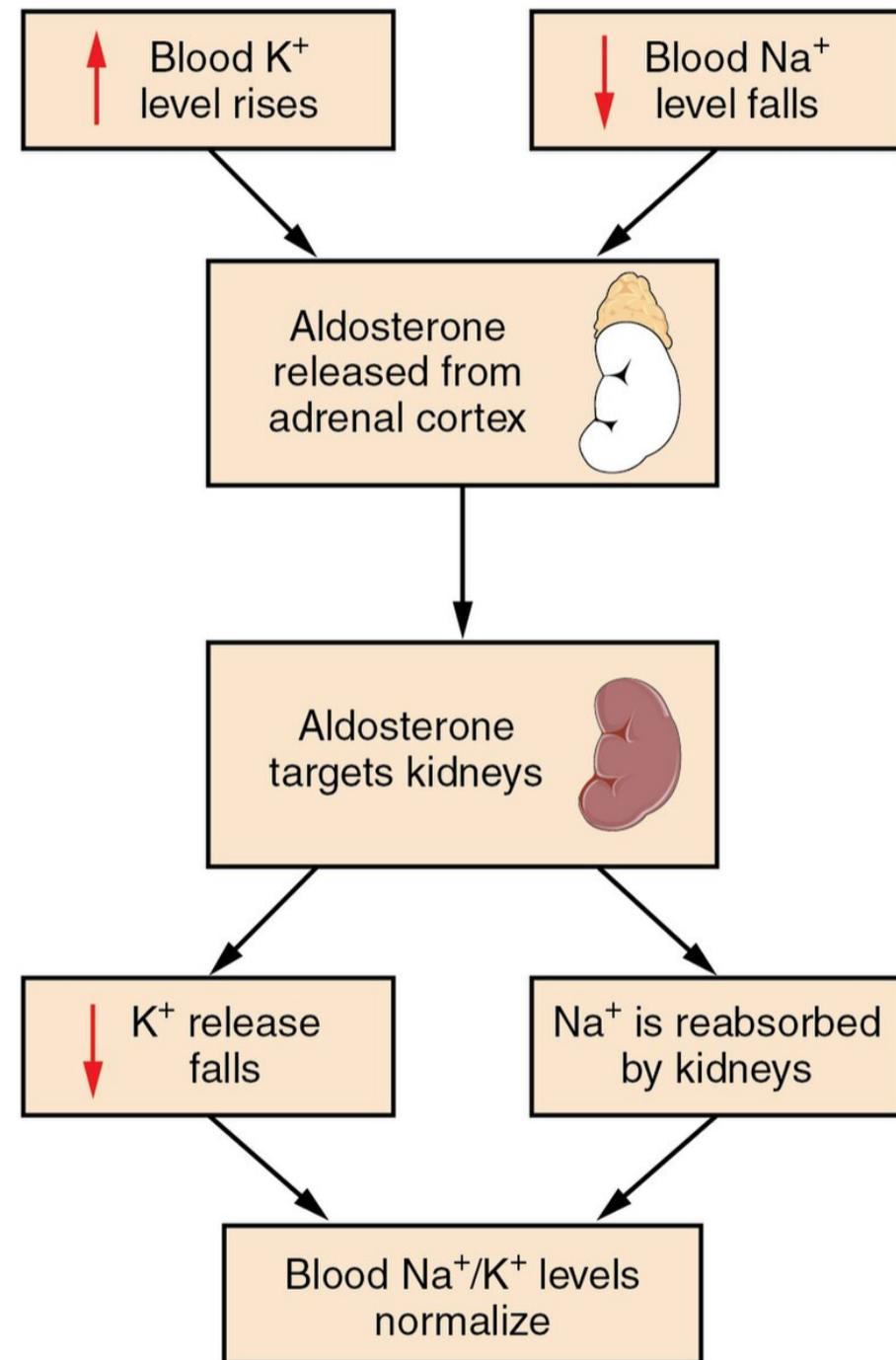


Figure 9.5 Regulation of sodium levels by the hormone aldosterone targeting the kidneys to impact sodium excretion. Image by J. Gordon Betts, Kelly A. Young, James A. Wise, Eddie Johnson, Brandon Poe, Dean H. Kruse, Oksana Korol, Jody E. Johnson, Mark Womble, Peter DeSaix, [OpenStax](https://openstax.org) (2013) is licensed under the [Creative Commons Attribution 3.0 Unported license](https://creativecommons.org/licenses/by/3.0/).

therefore increase sodium reabsorption, to bring blood sodium levels to homeostasis (Figure 9.5). Alternatively, if blood sodium levels are high

(hypernatremia), the adrenal glands will decrease their release of aldosterone. Low aldosterone levels then favor increased sodium excretion in the urine to bring blood sodium levels down.

## Dietary Sources

Although there is great interest in the effects of salt in the diet, data are insufficient to establish RDAs for sodium. The adequate intake levels are 1,500 mg/day for both men and women. Processed foods provide the majority of sodium to the diet (this is also true of chloride, as foods that contribute sodium to the diet are also good sources of chloride). Table salt is also a rich source of sodium, with one teaspoon of salt containing more than 2,000 mg (Figure 9.6). Other sources include canned soups, ham, many condiments, and snack foods like potato chips. The average individual consumes approximately 3,400 mg of sodium per day.



Figure 9.6 Table salt is a rich source of sodium (and chloride). [Image from Pixabay.](#)

## Consequences of Deficiency and Toxicity

Sodium deficiencies due to inadequate food intake are fairly uncommon, though can be caused by inadequate salt intake. It is much more common as a result of the loss of sodium from extreme sweating or excessive water consumption not accompanied by adequate sodium intake. Deficiency can also occur in situations of vomiting and diarrhea. Symptoms include headache, dizziness, nausea, muscle cramps, and confusion.

High sodium intake is associated with increased blood pressure (hypertension). With a higher sodium concentration in the blood, there will be a higher blood volume, and increased blood pressure. This increases the risk for cardiovascular disease and stroke.

### Health Note

Sodium is important for fluid balance, nerve impulses and muscle contractions.

### Fun Fact

While essential, most Americans consume double the recommended sodium intake!

## Chloride

Chloride is a mineral that is typically found in foods with sodium, including table salt (sodium chloride).

**Table 9.1 Examples of functions of major and trace minerals**

Category	Mineral	Key Functions
<b>Major Minerals</b>	Calcium	Bone and teeth formation Muscle contraction Nerve function Blood clotting
	Phosphorus	Bone and teeth structure Energy metabolism
	Magnesium	Muscle and nerve function Bone health
	Sodium	Fluid balance Nerve transmission Muscle function
	Chloride	Fluid balance Stomach acid production
	Potassium	Fluid balance Muscle contraction Heart function
	Sulfur	Component of some amino acids and vitamins
	<b>Trace Minerals</b>	Iron
Zinc		Immune function Wound healing
Copper		Iron metabolism Antioxidant activity
Iodine		Thyroid hormone production
Selenium		Antioxidant activity Thyroid function
Fluoride		Tooth enamel formation and protection
Chromium		Enhances insulin action
Manganese		Metabolism Antioxidant function
Molybdenum		Enzyme function in metabolism

## Important Roles

Chloride helps maintain fluid and electrolyte balance, working with sodium to regulate the proper amount of fluid inside and outside of the cells, and maintain blood volume and pressure. Chloride is a key component of hydrochloric acid (HCl) in the stomach, thereby playing a major role in digestion as HCl is important in maintaining the acidity of the stomach, digesting proteins, and killing ingested pathogens.

## Dietary Sources

The RDA for chloride is 2,300 mg/day. Chloride is found in table salt and other food sources such as seaweed, rye, tomatoes, celery, and many processed foods.

## Consequences of Deficiency and Toxicity

Chloride deficiency is uncommon, though may occur in situations of vomiting or diarrhea. Symptoms include muscle cramps, loss of appetite, and lethargy. Toxicity from high levels of chloride is most commonly seen with excessive salt intake. Like sodium, this would contribute to hypertension and fluid retention.

### Health Note

Chloride helps maintain fluid balance and is part of stomach acid.

### Fun Fact

Chloride makes up half of table salt (sodium chloride)!

## Potassium

Potassium is the most abundant cation in intracellular fluids. It is crucial for maintaining fluid and electrolyte balance, and works closely as a partner with sodium and chloride to maintain that fluid balance.

## Important Roles

The main role of potassium in the body is to help maintain normal levels of fluid inside the cells while sodium maintains normal fluid levels outside of cells. Potassium is also important in muscle contraction, particularly the heart and supporting normal blood pressure. It is important for nerve function and energy metabolism as well.

Potassium levels are regulated with the action of aldosterone (Figure 9.5). In response to elevated blood potassium levels (hyperkalemia), aldosterone is released from the adrenal glands. Aldosterone targets the kidneys to excrete

potassium in the urine, thus normalizing blood potassium levels. Conversely, low blood potassium levels (hypokalemia) results in the decrease of aldosterone and reabsorption of potassium by the kidneys.

### **Dietary Sources**

The adequate intake level for potassium has been determined to be 4,700 mg/day for both women and men. It is abundant in fruits such as bananas, oranges, and cantaloupe, as well as vegetables like potatoes, spinach, and tomatoes. Potassium can also be obtained from dairy sources, legumes, and nuts (Figure 9.7).



Figure 9.7 Examples of food sources of potassium (K). Image by [Arcturus525](#) from [Pixabay](#).

### **Consequences of Deficiency and Toxicity**

Potassium deficiency most commonly occurs with prolonged diarrhea and/or vomiting, or in individuals using diuretics. Diuretics are drugs that help the body eliminate water by increasing urine formation and are often taken to help lower blood pressure. Symptoms of potassium deficiency may include weakness, fatigue, muscle cramps, and abnormal heart rhythms. Toxicity from potassium is rare from food intake, but can occur with high dosage supplementation or conditions of kidney dysfunction. This typically impacts the heart, potentially causing a slowed heart rate and heart arrhythmias.

### **Health Note**

A potassium-rich diet is associated with lower blood pressure and a reduced risk of stroke. For this reason, potassium is considered a "nutrient of public health concern" in populations where intake is commonly below recommended levels.

### **Fun Fact**

Bananas are famous for potassium—but potatoes and beans have more!

## Sulfur

Sulfur is among the most biologically abundant elements in the human body. It plays a role in functions including cellular signaling, detoxification of free radicals, structural support, and energy production.

### Important Roles

Sulfur is a component of amino acids like methionine and cysteine, which are building blocks of protein. It is also a component of vitamins like thiamin and biotin. Sulfur is important for the synthesis of glutathione, a powerful antioxidant that protects cells from free radical damage. It also aids in the overall detoxification process of the liver to rid of the body of harmful substances and waste products.

### Dietary Sources

While there is no RDA established for sulfur in the diet, it can be found in protein-rich foods like meat, fish, poultry, eggs, legumes, and dairy. It can also be found in vegetables such as onions, garlic, kale, and broccoli.

### Consequences of Deficiency and Toxicity

Sulfur deficiency is not typically seen, as average protein intake will meet an individual's sulfur needs. There have been no well-documented deficiency symptoms in humans. There are also no known toxic effects from dietary intake, though excessive supplementation may cause diarrhea and foul-smelling gas.

#### Health Note

Sulfur is needed for certain amino acids and detoxification pathways.

#### Fun Fact

The smell of rotten eggs? That's sulfur at work!

## Trace Minerals

Trace minerals, also called microminerals, are essential nutrients required by the body in much smaller amounts than major minerals, but their impact on health is just as significant. Despite being needed in tiny quantities, trace minerals play critical roles in a wide range of biological processes, including oxygen transport, immune function, hormone production, antioxidant defense, and enzyme activity. There are eight essential trace minerals, including iron, copper, iodine, selenium,

chromium, manganese, molybdenum, and zinc. Other trace minerals, such as fluoride, are not technically essential nutrients, but may influence health.

## Iron

Iron exists in two forms in food - heme and nonheme iron. Heme iron is iron bound to a heme group. Heme is an iron-containing prosthetic (nonprotein) group that is a component of complex proteins such as hemoglobin and myoglobin (in red blood cells). Nonheme iron is iron that is not a component of a heme molecule. Whether iron is heme vs. nonheme impacts its bioavailability.

### Important Roles

Iron is essential for the formation of hemoglobin in red blood cells, which transports oxygen throughout the body. In the hemoglobin molecule, iron is the site of oxygen binding; therefore, required for oxygen to be transported. Iron is also a cofactor for nonheme containing enzymes in the electron transport chain, citric acid cycle, and gluconeogenesis. Iron is a cofactor for cytochrome P450 enzymes as well, which help to metabolize drugs and toxins.

### Dietary Sources

The RDA for iron is 18 mg/day for women (27 mg/day if pregnant) and 8 mg/day for men. Women have an increased requirement for iron intake due to the loss of blood, and therefore iron, through monthly menstruation. Pregnancy significantly increases a woman's iron needs, as there is an increase in the woman's blood volume as the body produces more blood to support the growing fetus and placenta.



9.8 Meat has an abundance of iron, though non-animal foods like spinach and broccoli are also iron-rich. [Image from pxhere](#) is in the [CC0 Public Domain](#).

Heme iron is most abundantly found in shellfish, beef, poultry, and organ meats, while nonheme iron is typically found in plant sources such as green leafy vegetables, mushrooms, and legumes, as well as fortified cereals (Figure 9.8). Nonheme iron accounts for approximately 85% of the iron consumed by an average individual.

Heme iron is 2-3 times more bioavailable than nonheme iron, with absorption of heme iron typically being high, depending on

how much iron the body needs (iron status of the individual). One of the most important factors for nonheme iron is its ionic state — ferric iron ( $\text{Fe}^{3+}$ ) is a

more oxidized state and ferrous iron ( $\text{Fe}^{2+}$ ) is a more reduced state — and ferrous iron is more bioavailable.

The amount of iron in the body is regulated by absorption at the small intestine. Heme iron can be transported across the brush border and basolateral membrane of the intestinal enterocytes without being modified. However, nonheme iron needs to be reduced to its ferrous form prior to transport. Reducing agents like vitamin C increase the bioavailability of nonheme iron — one of the benefits of eating a diverse diet.

## Consequences of Deficiency and Toxicity

Hepcidin is a liver-derived hormone that regulates (decreases) synthesis of transport proteins (for iron homeostasis). High levels of hepcidin lead to decreased transport protein production and low levels of hepcidin lead to increased transport protein production. If an individual is iron deficient, the liver releases less hepcidin to increase the production of iron transport proteins, so transport of iron into and across the enterocytes increases to get more iron into circulation. In an individual has excess iron, hepcidin levels will increase, decreasing transport protein production, and retaining more iron in the cells.

Despite it being the most studied mineral, iron is the most common micronutrient deficiency worldwide. Iron deficiency causes anemia (lack of healthy red blood cells) and is especially common in women in general, but also those of childbearing age, infants, and adolescents. Symptoms include reduced energy, fatigue, inability to heal, chronic recurrent infection, weakness, pale skin, and impaired cognitive function (Figure 9.9). If an individual has iron deficiency anemia, it is typically suggested to supplement with ferrous iron, as it is readily available for absorption.

Iron overload is often from supplemental overdose or genetic abnormalities like hemochromatosis. Hereditary hemochromatosis is a condition in which there is a defect in one of a number of genes that code for hepcidin or an intestinal iron

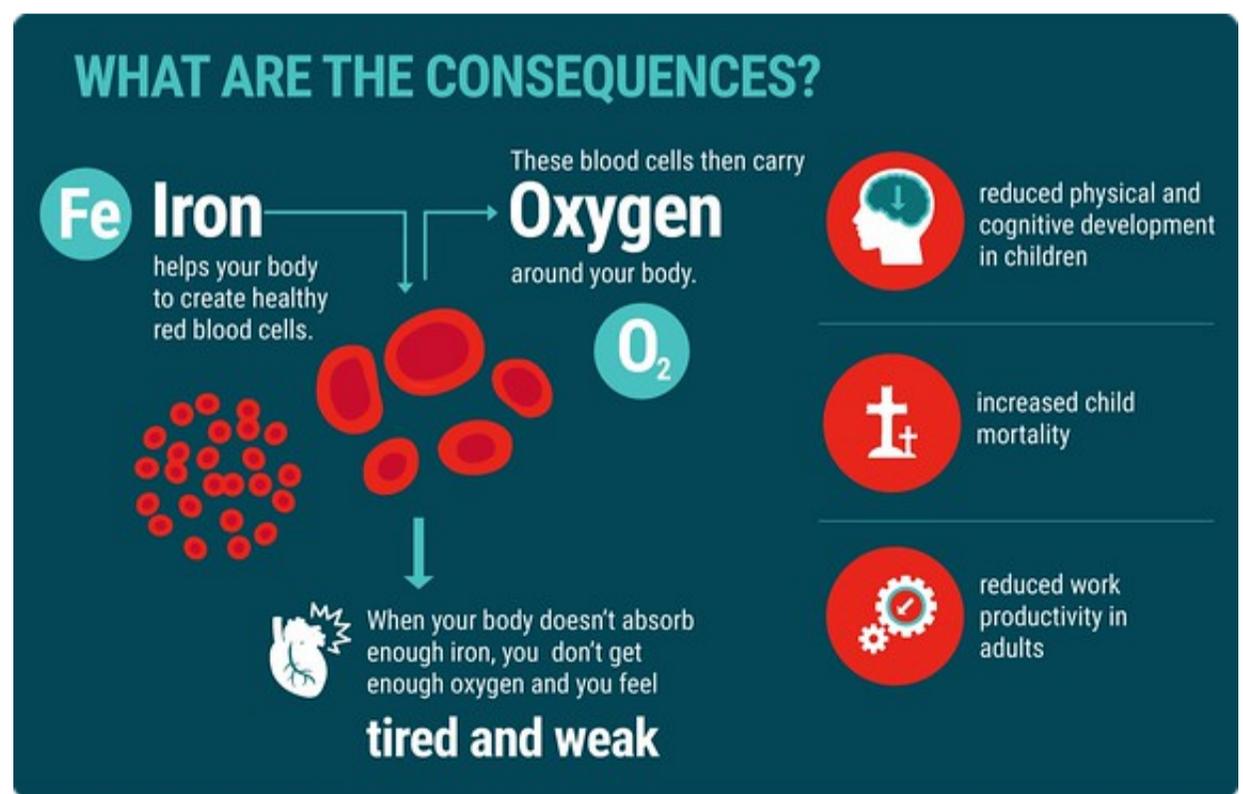


Figure 9.9 Consequences of anemia. Cropped from [Iron-infographic-FINAL 011015-page-001](#) by Nestlé is licensed under [CC BY-NC-SA 2.0](#).

transport protein — either way, this leads to large amounts of iron being absorbed into the blood. Iron toxicity symptoms typically include vomiting, diarrhea, black stools, and can cause organ damage due to iron deposits in the liver and heart.

### **Health Note**

Iron is crucial for oxygen transport in the blood.

### **Fun Fact**

Iron-rich foods paired with vitamin C (like in oranges) help your body absorb more iron!

## **Zinc**

Zinc is an essential trace mineral needed for growth, reproduction, immunity, and protein synthesis. Absorption of zinc in the small intestine requires two proteins — the first, a zinc transport protein for transport across the brush border into the enterocyte. Metallothioneine then binds zinc once inside the cell, regulating how much zinc gets transported across the basolateral membrane depending on the zinc status of the individual and physiological needs. Metallothioneine synthesis decreases during periods of low zinc (allowing more zinc to be released into the blood) and increases if zinc is in excess (holding it in the cell). Any excess zinc bound to metallothioneine is excreted in the feces when enterocytes get sloughed off every few days.

### **Important Roles**

Zinc supports immune function, helping the body fight invading pathogens by supporting the growth and normal functioning of immune cells. Zinc is also involved in the repair and growth of tissues, making it essential for wound healing. It is important for cell division, cell growth, DNA synthesis, and particularly during pregnancy and periods of development. Zinc is also a cofactor for hundreds of enzymes involved in various metabolic processes, and is a component of an enzyme needed for the proper sense of taste and smell.

### **Dietary Sources**

Zinc has an RDA of 8 mg/day for women and 11 mg/day for men. It is abundant in shellfish such as oysters, but can also be found in meat, dairy, legumes, whole grains, seeds, and fortified cereals (Figure 9.10).

Bioavailability of zinc is generally influenced by dietary factors similar to iron. Animal foods are greater sources of zinc than plant sources, which often have

phytates that interfere with absorption. Excessive intake of other minerals, such as iron or copper, can decrease absorption of zinc. Though, acidic substances tend to increase absorption. Absorption in the small intestine requires two proteins — the first, a zinc transport protein for transport across the brush border into the enterocyte. Metallothionein then binds zinc once inside the cell, regulating how much zinc gets transported across the basolateral membrane depending on the zinc status of the individual and physiological needs. Metallothionein synthesis decreases during periods of low zinc (allowing more zinc to be released into the blood) and increases if zinc is in excess (holding it in the cell). Any excess zinc bound to metallothionein is excreted in the feces when enterocytes get sloughed off every few days.



Figure 9.10 Foods rich in zinc include items like seafood, meats, and seeds. [Image](#) by the [US Department of Agriculture](#) is in the [public domain](#).

## Consequences of Deficiency and Toxicity

Most individuals eating a balanced diet are able to intake sufficient zinc, though medical conditions or restrictive diets may impact zinc status. Mild zinc deficiency decreases the ability to taste and smell, impairs immune function, delays wound healing, and leads to hair loss. A more severe deficiency can lead to developmental delays in children and delayed sexual maturation.

### Health Note

Zinc supports wound healing and immune function.

### Fun Fact

Zinc lozenges are popular during cold season, but oysters are the top zinc food!

## Copper

There are two oxidation states of copper — cupric ( $\text{Cu}^{2+}$ ) and cuprous ( $\text{Cu}^{1+}$ ), with cupric compounds being generally more readily bioavailable than cuprous. Like other minerals, copper is majorly absorbed in the small intestine; however, it is able to be absorbed in the stomach to a lesser extent depending on the overall copper status of the individual. Excess copper in the body is typically incorporated into bile and eliminated in the feces.

## Important Roles

Copper aids in iron metabolism, supports antioxidant activity, and is important for nerve function and collagen synthesis. Copper is intricately linked with iron absorption, metabolism and utilization in the body. Copper is essential for the functioning of several enzymes, including those involved in the absorption and mobilization of iron. Furthermore, ceruloplasmin, a copper-containing protein, acts as a ferroxidase (enzyme) to oxidize ferrous iron ( $\text{Fe}^{2+}$ ) to ferric iron ( $\text{Fe}^{3+}$ ). This conversion is necessary for iron to bind to transferrin, the protein that transports iron in the blood. Copper acts as a cofactor in many redox reactions, needed for the proper functioning of many enzymes, including those that help convert food into energy and those that help form neurotransmitters for nerve signal transmission, for example.



Figure 9.11 Examples of food sources of copper (Cu). [Image](#) from the [U.S. Department of Agriculture](#) is licensed under the [Creative Commons Attribution 2.0 Generic license](#).

## Dietary Sources

The RDA established for copper intake is 900  $\mu\text{g}/\text{day}$  for both women and men. It is found abundantly in organ meats such as beef liver, as well as shellfish, nuts, seeds, whole grains, and legumes (Figure 9.11).

## Consequences of Deficiency and Toxicity

Deficiency and toxicity for copper are rare. Deficiency can cause weakened immune function. Importantly, due to the role of copper in the absorption, transport, and utilization of iron in the body, a copper deficiency can lead to a secondary iron deficiency. Excess copper can cause nausea, cramping, and diarrhea.

### Health Note

Copper helps form red blood cells and supports the immune and nervous systems.

### Fun Fact

You only need 900  $\mu\text{g}$  per day, but too much zinc can block its absorption.

## Iodine

Iodine is an essential component of thyroid hormones, which regulate metabolism, growth, development, and reproduction, to name a few. Iodine is essential in the biosynthesis of thyroid hormones. It combines with the protein thyroglobulin in the follicle of the thyroid to produce thyroxine (T4), which then gets converted into triiodothyronine (T3).

In the normal regulatory axis of thyroid hormone production, thyrotropin-releasing hormone (TRH) is released from the hypothalamus when thyroid hormone levels are low in the blood (or iodine is low in the blood). This stimulates the anterior pituitary gland to release thyroid-stimulating hormone (TSH). TSH then stimulates the thyroid gland to take up iodine and produce the thyroid hormones T3 and T4 (Figure 9.12).

### Important Roles

The thyroid hormones T3 (triiodothyronine) and T4 (thyroxine) affect virtually every cell and organ of the body. They influence our basal metabolic rate, stimulate metabolism of carbohydrates, proteins, and fats, and are essential for proper development of the brain, spinal cord, and skeleton during fetal growth and in periods of growth in children. Thyroid hormones help maintain body temperature, raising or lowering body temperature in response to the body's needs. Thyroid hormones impact female menstrual cycles and fertility, playing a role in reproductive health.

### Dietary Sources

The RDA established for iodine is 150 µg/day for both women and men. Perhaps the richest source of iodine is iodized table salt. It can also be found in foods such as seafood, dairy like yogurt, cheese, and milk, some beans, and seaweed.

### Consequences of Deficiency and Toxicity

Cases of iodine deficiency are most prevalent in countries without iodized salt and not near an ocean for access to seafood rich in iodine. Deficiency can cause goiter, where the thyroid gland becomes enlarged; this can occur in children and

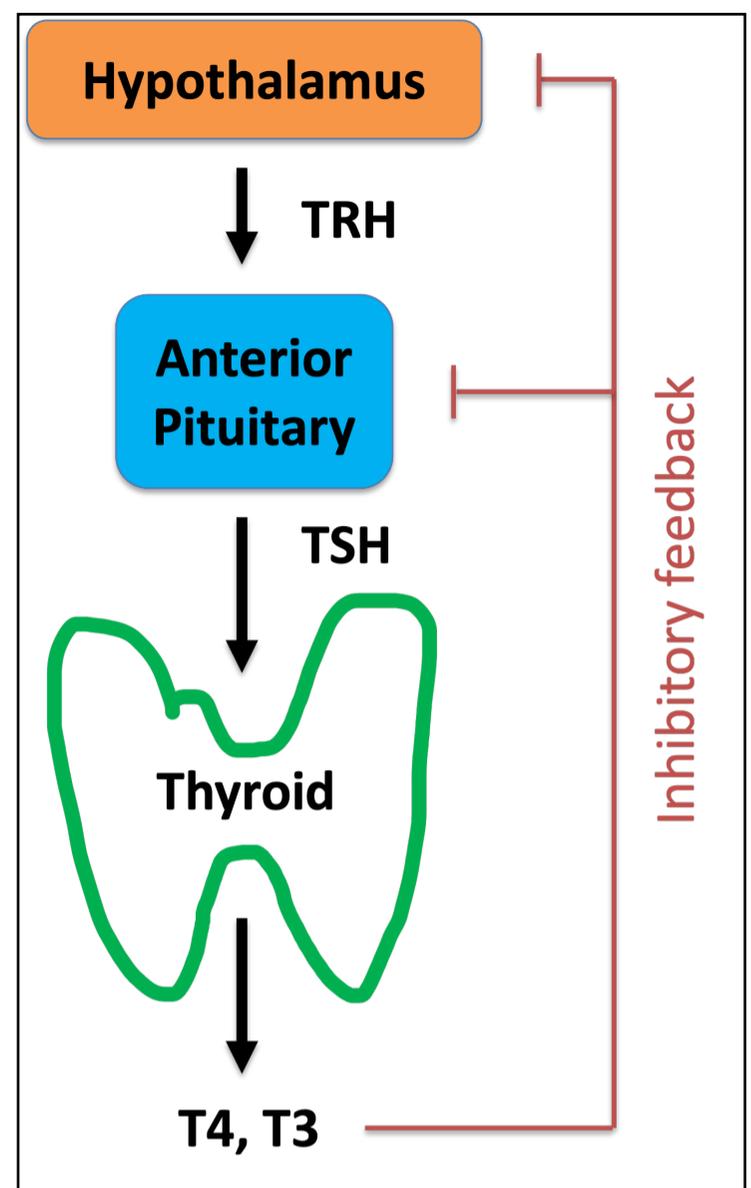


Figure 9.12. Thyroid hormone (T4, T3) production is regulated by the release of TRH from the hypothalamus and TSH from the anterior pituitary gland. Low iodine levels in the blood can stimulate this pathway. Image by Author.

adults. This results from low levels of iodine leading to low levels of thyroid hormone production. This then signals the anterior pituitary gland to release TSH and increase production of T3 and T4 hormones. However, because there is no iodine, thyroglobulin is produced and enlarges the thyroid, but with no thyroid hormone production. If a mother is iodine deficient during pregnancy, this may lead to cretinism in the baby. Cretinism typically results in severe physical and mental developmental delays in infants. Excessive iodine can also impair thyroid function, and can cause iodine poisoning with symptoms of nausea, vomiting, and diarrhea.

## Health Note

Iodine is essential for thyroid hormone production and metabolism.

## Fun Fact

The United States added iodine to salt in the 1920s to fight goiter!

## Selenium

Selenium is a trace mineral that is crucial for antioxidant activity, thyroid function, and reproductive health. Selenium acts as a component of various enzymes, including those involved in supporting the immune system. It is found abundantly in the soil.

### Important Roles

Selenium is a key component of selenoproteins, which act as antioxidant enzymes by neutralizing free radicals and protecting cells from oxidative damage. It is also essential for the production and metabolism of thyroid hormones. Selenium plays a role in reproductive health, including sperm motility.

### Dietary Sources

The RDA for selenium is established as 55  $\mu\text{g}$ /day for both women and men. It is found in very high levels in Brazil nuts (over 500  $\mu\text{g}$  for 1 oz. nuts). Selenium can also be found in seafood, meats, and whole grains (Figure 9.13).



Figure 9.13 Brazil nuts are very rich in selenium. Image from [Quadell](#) is licensed under the [Creative Commons Attribution-Share Alike 2.0 Generic](#) license.

## Consequences of Deficiency and Toxicity

Selenium deficiency may contribute to Keshan disease, a type of cardiomyopathy found particularly in regions with low selenium in the soil. It is characterized by heart muscle damage and enlargement that can lead to heart failure. Selenosis results from selenium toxicity, with symptoms like garlic breath odor, hair loss, and nausea.

### Health Note

Selenium acts as an antioxidant and supports thyroid function.

### Fun Fact

Just one Brazil nut can provide your daily selenium needs.

## Fluoride

Fluoride is a nonessential trace mineral, though is considered important due to evidence showing it positively impacts health (Figure 9.14).

### Important Roles

Fluoride is incorporated into the matrix of the bone and teeth, adding strength to tooth enamel as well as bone structure. It has been demonstrated that teeth that contain extra fluoride are more resistant to bacterial breakdown and the development of dental cavities. The topical application of

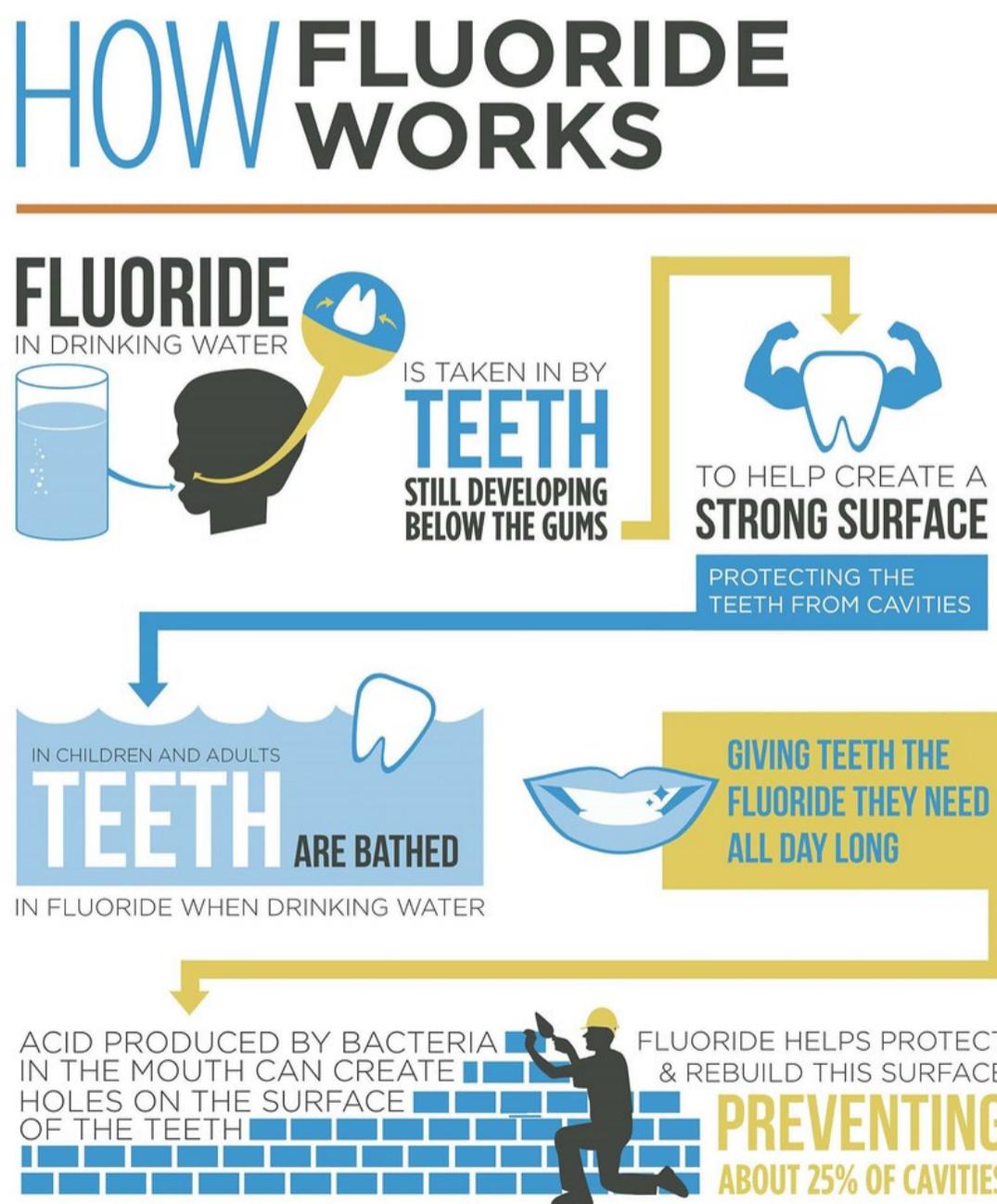


Figure 9.14 Fluoride positively benefits teeth. Image by Harlan Tennant on Flickr licensed under CC BY 2.0.

fluoride-containing toothpaste works on bacteria to decrease acid production, resulting in fewer cavities.

### **Dietary Sources**

Foods provide very little fluoride, so it is often added to water. It can be found in tea, fish with bones, and some dental products such as toothpaste and mouth rinses.

### **Consequences of Deficiency and Toxicity**

Deficiency of fluoride increases the risk of dental cavities, particularly in children. Conversely, excess fluoride can cause dental fluorosis, which leads to spotting of the teeth. Toxicity is generally only a concern if there is chronic swallowing of fluoridated toothpaste.

#### **Health Note**

Fluoride strengthens tooth enamel and helps prevent cavities.

#### **Fun Fact**

Many communities add fluoride to water supplies to reduce dental decay.

## **Chromium**

Chromium was designated as an essential nutrient because scientists found that deficiency in animals caused a diabetic-like state. Chromium enhances the action of insulin, helping regulate blood glucose levels.

### **Important Roles**

Studies suggest that chromium is needed for insulin to function properly. It is also required for growth and development in children. Interestingly, it has been suggested that chromium helps increase lean mass and decrease fat mass. All this considered, chromium supplements have been promoted as an ergogenic aid for athletes or to help regulate blood glucose.

### **Dietary Sources**

The adequate intake level established for chromium is 25 µg/day for women and 35 µg/day for men. It can be found in whole grain products, fruits, and vegetables. Chromium content in foods tends to vary greatly by the content in the soil of the food source.

The majority of chromium that is consumed is excreted. However, the bioavailability of chromium is significantly increased in the presence of vitamin C.

### **Consequences of Deficiency and Toxicity**

Chromium deficiency is rare, though if present, may impair glucose tolerance. There is no known toxicity from food, though there has been evidence of toxicity from environmental exposure in those who weld steel.

#### **Health Note**

Chromium enhances insulin action and helps regulate blood sugar.

#### **Fun Fact**

Chromium is found in broccoli, whole grains, and even grape juice!

## **Manganese**

Manganese is an essential mineral with diverse functions and found in various plant and animal foods. Most individuals can obtain sufficient manganese through a balanced diet.

### **Important Roles**

Manganese is crucial for the metabolism of carbohydrates, amino acids, and cholesterol, as it is a cofactor for enzymes involved in gluconeogenesis. Manganese is also involved in the synthesis of cartilage and bone. It is important for energy metabolism, as well as working with vitamin K in the blood clotting cascade.

### **Dietary Sources**

The RDA for manganese is established as 1.8 mg/day for women and 2.3 mg/day for men. It can be found in dietary sources including whole grain products, pineapples, spinach and other leafy vegetables, nuts, and legumes. Any excess manganese in the body is typically delivered to the liver, incorporated into bile, and excreted.

### **Consequences of Deficiency and Toxicity**

Manganese deficiency is extremely rare, but could cause scaly skin, poor bone growth, and altered carbohydrate and fat metabolism. Toxicity associated with manganese is typically related to excessive environmental exposure (mainly from inhalation in occupational settings); this may cause neurological symptoms.

## Health Note

Manganese supports bone formation and antioxidant defenses.

## Fun Fact

Tea is one of the richest sources of manganese in the diet.

## Molybdenum

Molybdenum is an essential trace mineral that plays a crucial role in various bodily functions due to its action as a cofactor for several important enzymes.

### Important Roles

Molybdenum is a cofactor for four enzymes in the body (aldehyde oxidase, sulfite oxidase, xanthine oxidase, and mitochondrial amidoxime-reducing component). These enzymes are involved in the metabolism of sulfur-containing amino acids, the breakdown of certain drugs and toxins, the breakdown of purines (components of DNA and RNA), and the production of uric acid.

### Dietary Sources

The RDA of molybdenum for both adult men and women is 45  $\mu\text{g}/\text{day}$ . It is primarily found in legumes, grains, and nuts (Figure 9.15).



Figure 9.15 Examples of food sources of molybdenum. Image by [Vanessa Loring](#) from [Pexels](#).

### Consequences of Deficiency and Toxicity

Deficiency of molybdenum is extremely rare; likely only possible in individuals with genetic mutations that lead to molybdenum cofactor deficiency. High intakes of molybdenum may cause gout-like symptoms due to increased uric acid production.

Minerals, both major and trace, are vital to the structure and function of the human body. Though needed in different amounts, each mineral plays a unique and irreplaceable role in processes such as building strong bones, maintaining fluid balance, supporting nerve and muscle function, and enabling enzyme activity and hormone production. A balanced, varied diet that includes fruits, vegetables, whole grains, lean proteins, and dairy products is the best way to meet mineral needs and support overall health.

## **Health Note**

Molybdenum acts as a cofactor for enzymes involved in detoxifying sulfites.

## **Fun Fact**

You need only micrograms a day —molybdenum is truly “small but mighty!”

# Chapter 10: Making Healthy Choices

There is no shortage of information when it comes to nutrition — so much that it can be overwhelming to figure out what to focus on and how to use the information. While the Dietary Reference Intakes (DRIs) provide important scientific benchmarks for nutrient needs, they aren't very practical for everyday meal planning. DRIs are detailed numbers based on age, sex, and life stage, which makes them useful for researchers and health professionals but overwhelming and confusing for most people. That's why tools like the **Dietary Guidelines for Americans**, the **MyPlate** graphic, and the concept of **food groups** were developed — to translate complex nutritional science into simple, actionable advice. These tools help individuals make balanced food choices by focusing on variety, portion sizes, and overall patterns rather than memorizing nutrient amounts. Instead of calculating milligrams of calcium or grams of fiber, people can aim to “make half your plate fruits and vegetables,” choose whole grains, and include a variety of protein sources — practical strategies rooted in the DRIs but much easier to apply in daily life.

## The Food Groups

### Fruits

Fruits are a vital part of a healthy diet, offering a wide range of vitamins, minerals, antioxidants, and dietary fiber (Figure 10.1). They are naturally sweet and can be consumed fresh, frozen, dried, canned, or as 100% fruit juice. Fruits like apples, oranges, berries, bananas, and melons are rich in vitamin C, potassium, and other nutrients that support immune function and overall health. Choosing whole fruits over fruit juices helps increase fiber intake and reduce added sugar consumption.



Figure 10.1 Variety of fruits. [Image by szjeno09190 from Pixabay.](#)

### Vegetables

Vegetables provide essential nutrients such as vitamin A, vitamin C, potassium, fiber, and folate, and they are typically low in calories and fat (Figure 10.2). This group includes a diverse array of plant foods, from leafy greens and root vegetables to legumes (which can also be counted in the protein category) and starchy options like potatoes and corn. Eating a variety of colorful vegetables — such as spinach, carrots, broccoli, and bell peppers — ensures a wide intake of



Figure 10.2 Variety of vegetables. Image from Flickr by joannapoe is licensed under the [CC BY-SA 2.0 license](#).

beneficial plant compounds and nutrients that promote heart health, digestion, and disease prevention.

## Grains

Grains are a major source of energy, primarily in the form of carbohydrates (Figure 10.3). They are divided into whole grains and



Figure 10.3 Variety of grains. Image by [PublicDomainImages](#) on [Pixabay](#).

refined grains. Whole grains like brown rice, oats, and whole wheat bread retain the bran, germ, and endosperm, making them higher in fiber, B vitamins, and other nutrients. Refined grains, such as white bread and white rice, have been milled to improve shelf life but lose many beneficial nutrients in the process. Including more whole grains in the diet supports digestive health and helps regulate blood sugar levels.

## Protein

Protein foods supply the building blocks the body needs to build and repair



tissues, produce enzymes and hormones, and maintain muscle mass (Figure 10.4). This group includes both animal-based sources

Figure 10.4 Animal- and plant-based foods are rich sources of protein. [Left image](#) by [Smastronardo](#) is licensed under the [Creative Commons Attribution-Share Alike 4.0 International](#) license. [Right image](#) by [Messofo](#) is licensed under the [Creative Commons Attribution-Share Alike 4.0 International](#) license.

like meat, poultry, fish, eggs, and dairy, as well as plant-based sources such as beans, lentils, tofu, nuts, and seeds. Lean protein options and plant-based

proteins are encouraged to help reduce saturated fat intake while still providing iron, zinc, and essential amino acids.

## Dairy

Dairy products are important sources of calcium, vitamin D, protein, and potassium, all of which are essential for maintaining strong bones and teeth, especially during growth and aging (Figure 10.5). This group includes milk, cheese, and yogurt, as well as fortified plant-based alternatives like soy milk. Choosing low-fat or fat-free dairy options can help reduce saturated fat intake while still delivering key nutrients. Lactose-free products are available for individuals with lactose intolerance.

## Oils and Fats

Though not always classified as a traditional food group, oils and healthy fats are essential for proper body function (Figure 10.6). They help absorb fat-soluble vitamins (A, D, E, and K) and provide essential fatty acids that the body cannot make on its own. Healthy fat sources include olive oil, avocados, nuts, seeds, and fatty fish. While fats are calorie-



Figure 10.6 Oils and healthy fats. Image from [rawpixel](#) is licensed under the [CC0 1.0 Universal](#).



Figure 10.5 Dairy foods. Image by [Alexschneider250](#) is licensed through [Creative Commons CC0 1.0 Universal Public Domain Dedication](#).

dense, choosing unsaturated fats over saturated and trans fats can promote heart health and support brain function.

## Dietary Guidelines

The Dietary Guidelines for Americans are science-based recommendations designed to help people make healthier food and beverage choices throughout every stage of life. Updated every five years by the U.S. Departments of Agriculture (USDA) and Health and Human Services (HHS), these guidelines aim to promote overall health, reduce the risk of chronic diseases, and help people maintain a healthy weight. Rather than focusing on single nutrients or strict diets, the guidelines emphasize healthy eating patterns — eating plenty of fruits and vegetables, choosing whole grains, including lean protein, and limiting added sugars, saturated fat, and sodium. They serve as the foundation for federal nutrition programs and resources, including school meals, food labels, and public health campaigns. Ultimately, the Dietary Guidelines help

Americans take practical steps toward lifelong health through the food choices they make each day.

## Key Recommendations of the Dietary Guidelines

The Dietary Guidelines for Americans get updated every five years, though typically have consistent themes of recommendations within them (Table 10.1).

**Table 10.1 Some key recommendations of the Dietary Guidelines for Americans**

Recommendation	What It Means	Quick Tips
<b>Follow a healthy dietary pattern at every life stage</b>	Nutrition matters from infancy through older adulthood	Start healthy habits early
<b>Customize food and beverage choices</b>	Personalize based on culture, preferences, and budget	Choose familiar, affordable healthy foods
<b>Focus on nutrient dense options</b>	Choose foods rich in nutrients, low in added sugars, saturated fat, and sodium	Think whole fruits, veggies, whole grains, lean proteins, low-fat dairy
<b>Limit added sugars</b>	Keep added sugars to <10% of total daily calories	Watch for sugar in drinks, desserts, snacks
<b>Limit saturated fats</b>	Keep saturated fat to <10% of daily calories	Choose healthy oils over butter or lard
<b>Limit sodium</b>	Keep sodium under 2,300 mg/day (less for children)	Choose fresh over processed foods; check labels
<b>If you drink alcohol, do so in moderation</b>	Up to 1 drink/day for women, 2 for men	Not recommended for children, pregnant individuals, or those with health risks

## MyPlate

MyPlate is a visual guide developed by the USDA in 2011 to help people make healthier food choices and build balanced meals. Shaped like a plate divided into five food groups — fruits, vegetables, grains, protein, and dairy — it shows how to proportion meals in a way that supports good nutrition and overall health (Figure 10.7). Half the plate should be filled with fruits and vegetables, one quarter with grains (preferably whole grains), and one quarter with protein-rich foods. A serving of dairy, like milk or yogurt, is shown on the side.

MyPlate is a practical, easy-to-understand tool that simplifies healthy eating without needing to count calories or nutrients. It encourages variety, portion control, and balance, making it useful for individuals and families of all ages.

## Using MyPlate

To use MyPlate, start by thinking about your plate as a guide for building balanced meals. Fill half your plate with fruits and vegetables, choosing a variety of colors and types to get a range of nutrients. Then, divide the remaining half between grains and protein foods — aim for at least half of your grains to be whole grains like brown rice, whole wheat bread, or oats, and choose lean protein sources like chicken, beans, or tofu.

Include a serving of dairy on the side, such as a glass of milk or a cup of yogurt, or a fortified plant-based alternative like soy, oat, or almond milk.

MyPlate can be used at every meal, whether you're cooking at home, packing a lunch, or eating out. It's a flexible tool that helps you focus on portion balance, food variety, nutritional adequacy, and moderation without needing to track specific nutrients. Options are endless when combining the food groups to have balanced and nutritious meals (Table 10.2).

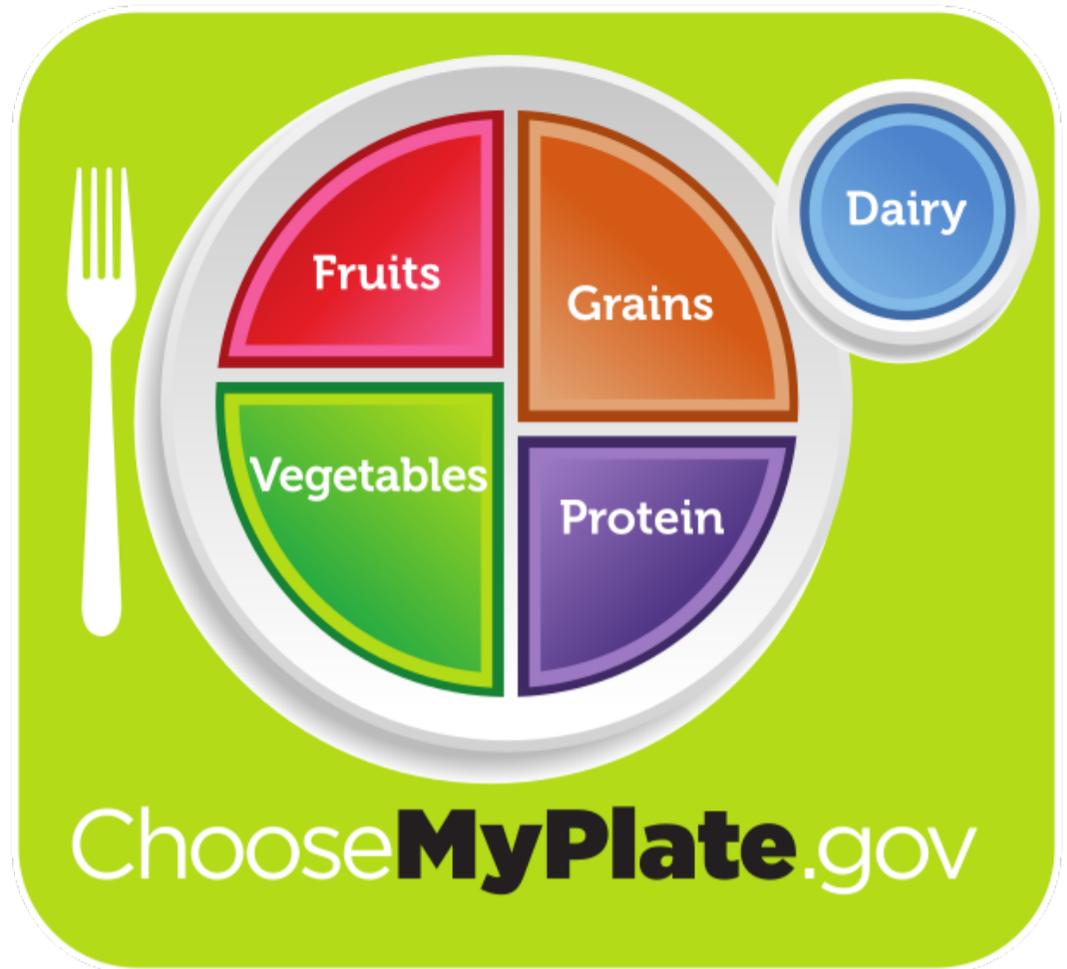


Figure 10.7 MyPlate is an interactive dietary and menu planning guide, focusing on 5 different food groups established by the United States Department of Agriculture. As a work of the US federal government, image is in the public domain.

**Table 10.2 Example Meals and Snacks**

### **BREAKFAST**

- **Grains:** whole grain toast or oatmeal
- **Protein:** scrambled eggs or peanut butter
- **Fruit:** sliced strawberries or banana
- **Dairy:** low-fat milk or yogurt

♦ *Tip: Add some spinach or tomatoes to the eggs for a veggie boost!*

### **LUNCH**

- **Vegetables:** mixed greens with cucumbers and cherry tomatoes
- **Protein:** grilled chicken or chickpeas
- **Grains:** brown rice or whole wheat pasta
- **Fruit:** apple slices or orange segments
- **Dairy:** string cheese or yogurt cup

### **DINNER**

- **Vegetables:** steamed broccoli and carrots
- **Protein:** baked salmon or tofu
- **Grains:** quinoa or whole wheat pasta
- **Fruit:** fresh berries for dessert
- **Dairy:** glass of milk or sprinkle of parmesan cheese

♦ *Tip: Aim to make half your plate veggies and fruit*

### **SNACK (kid-friendly)**

- **Fruit:** apple slices
- **Protein/Dairy:** hard boiled egg, peanut butter, or cheese stick

♦ *Tip: A great mini-MyPlate snack that hits 2 food groups!*

## 2025-2030 Dietary Guidelines for Americans

In the 2025–2030 Dietary Guidelines for Americans, the long-standing MyPlate visual (used since 2011) was replaced with a redesigned food pyramid graphic (often described as an *inverted pyramid*) that reflects the updated federal guidance for healthy eating. The new pyramid (Figure 10.8) places emphasis on whole, nutrient-dense foods, encourages high-quality proteins, healthy fats, vegetables, fruits, and whole grains, and continues to discourage highly processed foods, added sugars, and refined carbohydrates. This shift highlights protein sources (including a variety of animal and plant proteins) and full-fat dairy alongside fruits and vegetables near the top of the pyramid, with whole grains featured at the base, while reinforcing core messages to limit added sugars, saturated fat, and sodium consistent with previous editions' health objectives. The updated graphics and guidance are intended to continue prioritizing patterns associated with improved long-term health outcomes.



Figure 10.8 The Dietary Guidelines for Americans 2025-2026 included a new food pyramid graphic. [Image from the Department of Health and Human Services](#) is licensed under [CC0 1.0 Universal Public Domain Dedication](#).

# Chapter 11: Physical Activity

Physical activity is a cornerstone of a healthy lifestyle and plays a vital role in maintaining and promoting optimal nutritional health. It impacts body composition, metabolism, cardiovascular health, and mental well-being. Understanding the relationship between physical activity and nutrition is essential for individuals aiming to improve their overall health, manage chronic diseases, or enhance athletic performance.

## Categories of Physical Activity

Physical activity is defined as any bodily movement produced by skeletal muscles that results in energy expenditure. It includes a range of activities such as walking, running, cycling, strength training, and even routine tasks like gardening or cleaning.

There are various categories of physical activity, including:

- **Aerobic (Endurance) Exercise:** Sustained movement that increases heart rate and breathing (e.g., jogging, swimming).
- **Resistance (Strength) Training:** Exercises that improve muscular strength and endurance (e.g., weightlifting, resistance bands).
- **Flexibility Exercises:** Activities that enhance the range of motion (e.g., stretching, yoga).
- **Neuromotor Training:** Incorporates balance, agility, and coordination (e.g., tai chi).

## Physical Activity Guidelines

Physical inactivity is a widespread problem, for adults as well as children. In consideration of this, the Physical Activity Guidelines for Americans are published by the U.S. Department of Health and Human Services (HHS) and make recommendations for physical activity.

### Adults

Adults (18-64 years) should aim for at least 150 minutes of moderate intensity aerobic activity per week. Alternatively, they can engage in 75 minutes of vigorous-intensity aerobic activity. An equivalent combination of both moderate and vigorous activity is also acceptable. Adults should also include muscle-strengthening activities on at least two days of the week.

Moderate intensity aerobic activity includes activities such as brisk walking, water aerobics, or dancing, where you can talk but not sing comfortably. Vigorous-

intensity aerobic activity includes jogging, running, or swimming, where you can only say a few words without pausing for breath. Muscle-strengthening activities would include lifting weights, working with resistance bands, or activities like rock climbing and yoga.

## Older Adults

Older adults (aged 65+ years) should try to meet the adult recommendations. It is recommended to be as physically active as abilities allow.

## Children and Adolescents

Children and adolescents (6-17 years) should aim for 60 minutes or more of moderate-to-vigorous intensity physical activity daily, vigorous-intensity aerobic activity at least three days a week, and muscle- and bone-strengthening activities at least three days a week.



Figure 11.1 Physical activity is important for children. [Photo by Lars Bo Nielsen on Unsplash.](#)

## Preschool-Aged Children

Preschool-aged children (3-5 years) should have active play encouraged each day.

## General Recommendations

- Any physical activity is better than none. Even small increases in physical activity can provide health benefits, especially for those who may be currently inactive.

- Spread activity throughout the week. It is beneficial to distribute physical activity across several days rather than cramming it all into one or two days.
- Consult a healthcare provider. Individuals with chronic conditions or symptoms should seek guidance from a healthcare professional about appropriate types and amounts of physical activity.

## **Benefits of Physical Activity**

Physical activity has far-reaching benefits for both the body and mind. Whether it's a structured exercise regimen or daily activities like walking or gardening, staying active can improve overall health, boost quality of life, and prevent or manage chronic diseases.

### **Cardiovascular Health**

One of the most well-documented benefits of regular physical activity is its positive impact on heart health. Engaging in aerobic exercises such as walking, running, cycling, and swimming can improve heart function and reduce the risk of cardiovascular diseases (CVD), including heart attack, stroke, and high blood pressure.

- **Improved blood circulation:** Physical activity helps improve blood circulation by enhancing the elasticity of blood vessels and lowering cholesterol levels.
- **Reduced risk of hypertension:** Regular exercise helps to lower resting blood pressure by improving the function of the heart and blood vessels.
- **Lower LDL cholesterol:** Exercise increases the breakdown of low-density lipoprotein (LDL) cholesterol (the "bad" cholesterol) and enhances the production of high-density lipoprotein (HDL), the "good" cholesterol.
- **Increased heart efficiency:** Consistent exercise strengthens the heart muscle, enabling it to pump blood more efficiently.

### **Weight Management**

Physical activity is crucial for managing body weight. By increasing energy expenditure, it helps create the energy deficit necessary for weight loss or weight maintenance.

- **Calorie burn:** Exercises like cardio, strength training, and high-intensity interval training (HIIT) burn calories, helping to maintain a healthy weight.
- **Fat loss:** Aerobic exercises, in particular, help reduce visceral fat (fat stored around organs), which is associated with various health conditions, including type 2 diabetes and metabolic syndrome.

- Muscle preservation: Resistance training not only promotes fat loss but also helps preserve or increase muscle mass, which is critical for maintaining a higher resting metabolic rate.

## **Bone and Muscle Health**

Regular physical activity, especially weight-bearing exercises, significantly benefits bone density and muscle function. This is particularly important for preventing osteoporosis and sarcopenia (age-related muscle loss).

- Bone health: Weight-bearing activities such as walking, jogging, or resistance training increase bone mineral density and help reduce the risk of osteoporosis and fractures.
- Muscle strength: Resistance exercises like weightlifting and bodyweight exercises (e.g., squats, push-ups) stimulate muscle growth, improve strength, and enhance balance.
- Joint health: Regular movement strengthens the muscles and ligaments around joints, reducing the risk of joint degeneration and stiffness. It can also help manage the symptoms of osteoarthritis by improving joint function and reducing pain.

## **Mental Health and Mood Enhancement**

Physical activity has a powerful effect on mental well-being, influencing mood, stress, and cognitive function. Exercise promotes the release of endorphins—chemicals in the brain that act as natural mood lifters—and helps reduce symptoms of anxiety, depression, and stress.

- Stress reduction: Physical activity reduces levels of cortisol, a stress hormone, while stimulating the production of endorphins and other mood-enhancing chemicals like serotonin.
- Reduced symptoms of depression: Research shows that exercise is an effective adjunct treatment for people experiencing mild to moderate depression. It can be as effective as some types of psychotherapy or medication.
- Improved cognitive function: Exercise has been linked to better cognitive performance, improved memory, and a reduced risk of cognitive decline and neurodegenerative diseases like Alzheimer's.

## **Enhanced Immune Function**

Moderate physical activity can strengthen the immune system by promoting better circulation, helping immune cells travel through the body more efficiently.

Regular physical activity can also reduce the likelihood of illness, shorten recovery time, and decrease the frequency of colds.

- Improved immunity: Exercise increases the circulation of immune cells, helping the body detect and fight infections more effectively.
- Inflammation reduction: Chronic inflammation is linked to several diseases, including heart disease and diabetes. Regular moderate activity reduces systemic inflammation over time, helping to prevent the development of these diseases.

## **Increased Lifespan**

Numerous studies show that physical activity is associated with a longer life. Engaging in regular exercise, especially as part of a healthy lifestyle, can reduce the risk of chronic diseases and lower premature death rates. Even moderate levels of physical activity have been shown to extend life expectancy by reducing the risk of conditions such as cardiovascular disease, diabetes, and cancer.

- Reduced mortality risk: Regular exercise, especially after the age of 40, has been linked to a significant reduction in the risk of dying prematurely from all causes.
- Prevention of chronic diseases: Active individuals have a lower risk of developing chronic diseases like type 2 diabetes, cancer, and obesity, all of which can contribute to shorter life expectancy.

## **Better Sleep Quality**

Physical activity plays a vital role in promoting quality sleep. Regular exercise helps regulate the body's internal clock, ensuring more consistent and restorative sleep patterns.

- Faster sleep onset: People who engage in regular physical activity tend to fall asleep more quickly.
- Deeper sleep: Physical activity helps increase the proportion of deep, restorative sleep, which is crucial for memory consolidation, cell repair, and immune function.
- Reduced insomnia: Moderate physical activity has been shown to improve sleep in individuals suffering from insomnia, reducing the need for sleep medications.

## **Social Benefits**

Physical activity can serve as a social outlet and enhance social connections, whether through group exercise classes, sports teams, or community fitness

programs. This social interaction contributes to a sense of belonging and emotional well-being.

- **Community building:** Joining exercise groups or recreational leagues fosters a sense of community and camaraderie, which is crucial for emotional and social health.
- **Motivation and accountability:** Exercising with friends or in a group setting provides motivation and accountability, making it easier to stick to a fitness routine.

## **Enhanced Flexibility and Balance**

Physical activity, particularly stretching exercises, yoga, and balance training, improves flexibility and coordination. This is particularly important as we age, as it can help prevent falls and injuries.

- **Improved mobility:** Activities like yoga, Pilates, and stretching increase joint flexibility, reduce muscle stiffness, and improve posture.
- **Fall prevention:** Balance training exercises are essential for older adults in preventing falls and maintaining independence, as they enhance proprioception (the body's sense of position in space).

## **Better Digestion and Gut Health**

Exercise also benefits gastrointestinal health by improving gut motility (the movement of food through the digestive tract) and reducing the risk of constipation. It has been shown to help manage conditions like irritable bowel syndrome (IBS) and promote a healthy gut microbiota.

- **Faster digestion:** Regular physical activity accelerates the movement of food through the digestive system, reducing bloating and discomfort.
- **Gut microbiome:** Exercise has a positive impact on the diversity and balance of gut bacteria, which plays a key role in overall health, including immune function and metabolism.

## **Get Active!**

The benefits of physical activity extend well beyond the physical body; they enhance mental, emotional, and social well-being, while also preventing or managing a variety of chronic diseases (Figure 11.2). Whether you're seeking to improve cardiovascular health, boost mood, manage weight, or simply live a longer, healthier life, incorporating regular physical activity into your routine is one of the most effective and accessible ways to enhance your overall quality of life.



Figure 11.2 Being active is a crucial component of overall wellbeing. Image by [Sketchplanations](#) is licensed under the [Creative Commons Attribution NonCommercial 4.0 International license](#).

# Appendix: Image Transcripts

## Diagram Title: Regulation of Blood Glucose Levels

### Central Label

- Normal Blood Glucose: **70–130 mg/dL**

### Left Side: High Blood Glucose Pathway

- Stimulus: Blood glucose increases.
- Pancreas  $\beta$ -cells → **Insulin** released.
- Insulin effects:
  - Liver stores glucose as glycogen.
  - Body cells absorb glucose.
- Outcome: Blood glucose decreases.

### Right Side: Low Blood Glucose Pathway

- Stimulus: Blood glucose decreases.
- Pancreas  $\alpha$ -cells → **Glucagon** released.
- Glucagon effects:
  - Liver breaks down glycogen to release glucose.
- Outcome: Blood glucose increases.

### Feedback Loop

This system maintains stable blood glucose levels through hormonal regulation.

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## Diagram Title: Regulation of Blood Calcium Levels

### Central Label

- Normal Calcium Level: **10 mg/dL**

### Left Side: High Calcium Pathway

- Stimulus: Calcium levels increase.
- Thyroid gland → **Calcitonin** released.

- Calcitonin effects:
  - Inhibits osteoclast activity.
  - Reduces calcium reabsorption in kidneys.
- Outcome: Blood calcium decreases.

### **Right Side: Low Calcium Pathway**

- Stimulus: Calcium levels decrease.
- Parathyroid glands → PTH released.
- PTH effects:
  - Osteoclasts release calcium from bone.
  - Kidneys reabsorb calcium from urine.
  - Small intestine absorbs more calcium via vitamin D.
- Outcome: Blood calcium increases.

### **Feedback Loop**

This system maintains calcium homeostasis through hormonal regulation by the thyroid and parathyroid glands.

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