Unit 10: Digestive & Excretory System

Ms. Randall

Essential Questions:

- How does the digestive system provide the body with vital nutrients?
- How does the urinary system filter blood?

Unit Objectives:

- List and describe the functional anatomy of the organs and accessory organs of the digestive system
- Discuss the processes and control of ingestion, propulsion, mechanical digestion, chemical digestion, absorption, and defecation
- Identify the organs of the alimentary canal from proximal to distal, and briefly state their function
- Identify the accessory digestive organs and briefly state their function
- Describe the four fundamental tissue layers of the alimentary canal
- Contrast the contributions of the enteric and autonomic nervous systems to digestive system functioning
- Describe the composition of urine
- Label structures of the urinary system
- Characterize the roles of each of the parts of the urinary system
- Illustrate the macroscopic and microscopic structures of the kidney
- Trace the flow of blood through the kidney
- Outline how blood is filtered in the kidney nephron
- Describe the regulation of major ions by the kidney
- Summarize the role of the kidneys in maintaining acid–base balance

Unit Vocabulary:

Alimentary canal
Reabsorption
Secretion
Mastication
Microvilli
Peristalsis
Metabolism
Renal
Nephron
Glomerulus
Absorption
Digestion
Excretion
Filtration
Urea

Lesson 1:

Objective:

- Describe the four fundamental tissue layers of the alimentary canal
- Explain the process of digestion
- Relate the nervous and endocrine systems to the regulation of digestion.

The function of the digestive system is to break down the foods you eat, release their nutrients, and absorb those nutrients into the body. Although the small intestine is the workhorse of the system, where most of the digestion occurs, and where most of the released nutrients are **absorbed** into the blood or lymph, each of the digestive system organs makes a vital contribution to this process. The digestive system uses **mechanical and chemical** activities to break food down into absorbable substances during its journey through the digestive system.

Table 1. Contribution of Other Body Systems to the Digestive System

Body system	Benefits received by the digestive system
Cardiovascular	Blood supplies digestive organs with oxygen and processed nutrients
Endocrine	Endocrine hormones help regulate secretion in digestive glands and accessory organs
Integumentary	Skin helps protect digestive organs and synthesizes vitamin D for calcium absorption
Lymphatic	Mucosa-associated lymphoid tissue and other lymphatic tissue defend against entry of pathogens; lacteals absorb lipids; and lymphatic vessels transport lipids to bloodstream
Muscular	Skeletal muscles support and protect abdominal organs
Nervous	Sensory and motor neurons help regulate secretions and muscle contractions in the digestive tract
Respiratory	Respiratory organs provide oxygen and remove carbon dioxide
Skeletal	Bones help protect and support digestive organs
Urinary	Kidneys convert vitamin D into its active form, allowing calcium absorption in the small intestine

As is the case with all body systems, the digestive system does not work in isolation; it functions cooperatively with the other systems of the body. Consider for example, the interrelationship between the digestive and cardiovascular systems. Arteries supply the digestive organs with oxygen and processed nutrients, and veins drain the digestive tract. These intestinal veins, constituting the hepatic portal system, are unique; they do not return blood directly to the heart. Rather, this blood is diverted to the liver where its nutrients are off-loaded for processing before blood completes its circuit back to the heart. At the same time, the digestive system provides nutrients to the heart muscle and vascular tissue to support their functioning. The interrelationship of the digestive and endocrine systems is also critical. Hormones secreted by several endocrine glands, as well as endocrine cells of the pancreas, the stomach, and the small intestine, contribute to the control of digestion and nutrient metabolism. In turn, the digestive system provides the nutrients to fuel endocrine function.

Digestive System Organs

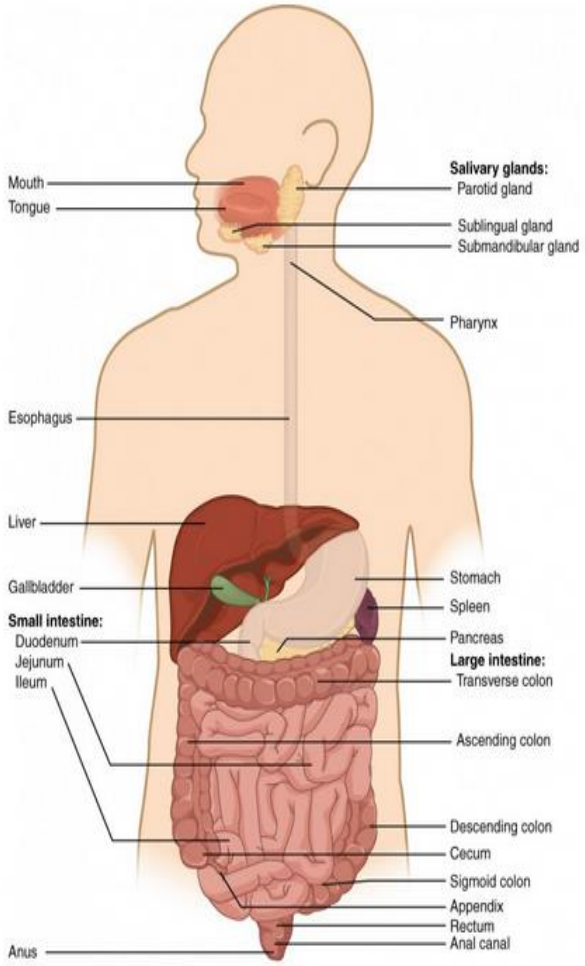
The easiest way to understand the digestive system is to divide its organs into two main categories. The first group is the organs that make up the **alimentary canal. Accessory digestive organs** comprise the second group and are critical for orchestrating the breakdown of food and the assimilation of its nutrients into the body. Accessory digestive organs, despite their name, are critical to the function of the digestive system.

Alimentary Canal Organs

Also called the **gastrointestinal (GI) tract** or gut, the **alimentary canal** is a one-way tube about 7.62 meters (25 feet) in length during life and closer to 10.67 meters (35 feet) in length when measured after death, once smooth muscle tone is lost. The main function of the organs of the alimentary canal is to nourish the body. This tube begins at the **mouth** and terminates at the **anus.** Between those two points, the canal is modified as the **pharynx, esophagus, stomach, and small and large intestines** to fit the functional needs of the body. Both the mouth and anus are open to the external environment; thus, food and wastes within the alimentary canal are technically considered to be outside the body. Only through the process of absorption do the nutrients in food enter and nourish the body's "inner space."

Accessory Structures

Each **accessory digestive organ** aids in the breakdown of food. Within the mouth, the **teeth** and **tongue** begin **mechanical digestion,** whereas the **salivary glands** begin **chemical digestion**. Once food products enter the **small intestine, the gallbladder, liver,** and **pancreas** release secretions—such as **bile** and **enzymes**—essential for digestion to continue. Together, these are called accessory organs because they sprout from the lining cells of the developing gut (mucosa) and augment its function; indeed, you could not live without their vital contributions, and many significant diseases result from their malfunction. Even after development is complete, they maintain a connection to the gut by way of ducts.



Histology of the Alimentary Canal

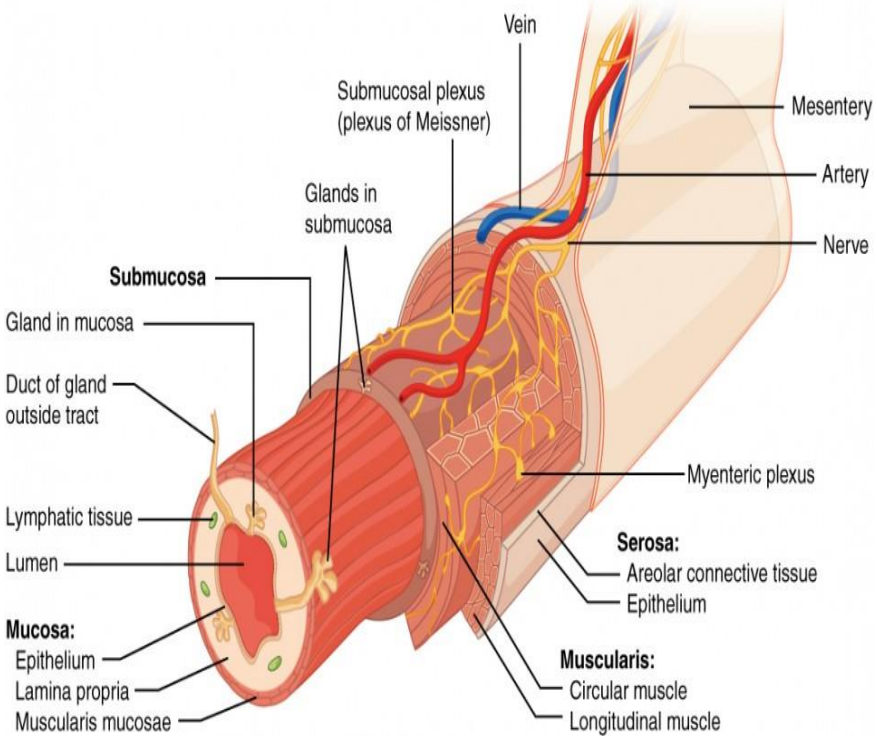
Throughout its length, the alimentary tract is composed of the same four tissue layers; the details of their structural arrangements vary to fit their specific functions. Starting from the lumen and moving outwards, these layers are the mucosa, submucosa, muscularis, and serosa, which is continuous with the mesentery.

The **mucosa** is referred to as a mucous membrane, because mucus production is a characteristic feature of gut epithelium. The membrane consists of **epithelium,** which is in direct contact with ingested food, and the **lamina propria**, a layer of connective tissue analogous to the dermis. In addition, the mucosa has a thin, smooth muscle layer, called the **muscularis mucosa** (not to be confused with the muscularis layer, described below).

- *Epithelium*—In the mouth, pharynx, esophagus, and anal canal, the epithelium is primarily a non-keratinized, stratified squamous epithelium. In the stomach and intestines, it is a simple columnar epithelium. Notice that the epithelium is in direct contact with the **lumen**, the space inside the alimentary canal. Interspersed among its epithelial cells are **goblet cells**, which secrete mucus and fluid into the lumen, and **enteroendocrine cells**, which secrete hormones into the interstitial spaces between cells. Epithelial cells have a very brief lifespan, averaging from only a couple of days (in the mouth) to about a week (in the gut). This process of rapid renewal helps preserve the health of the alimentary canal, despite the wear and tear resulting from continued contact with foodstuffs.

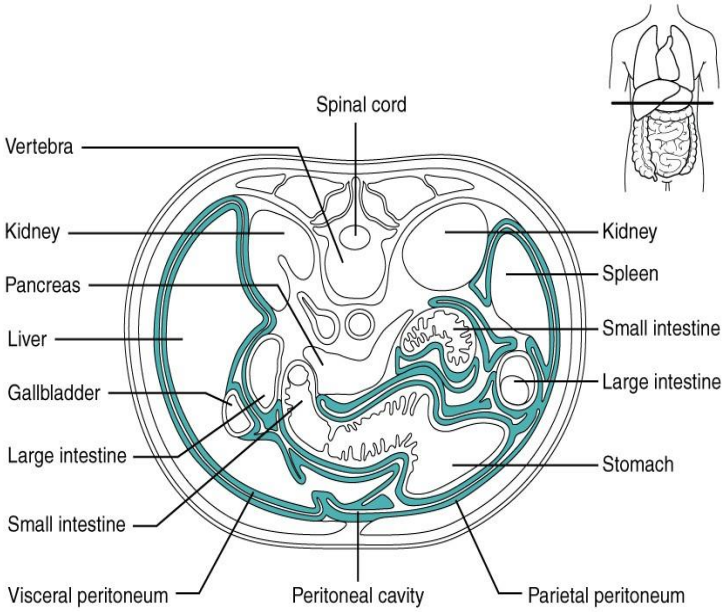
- *Lamina propria*—In addition to loose connective tissue, the lamina propria contains numerous blood and lymphatic vessels that transport nutrients absorbed through the alimentary canal to other parts of the body. The lamina propria also serves an immune function by housing clusters of lymphocytes, making up the **mucosa-associated lymphoid tissue (MALT**). These lymphocyte clusters are particularly substantial in the distal ileum where they are known as **Peyer's patches**. When you consider that the alimentary canal is exposed to foodborne bacteria and other foreign matter, it is not hard to appreciate why the immune system has evolved a means of defending against the pathogens encountered within it.
- *Muscularis mucosa*—This thin layer of smooth muscle is in a constant state of tension, pulling the mucosa of the stomach and small intestine into undulating folds. These folds dramatically increase the surface area available for digestion and absorption.

As its name implies, the **submucosa** lies immediately beneath the mucosa. A broad layer of dense connective tissue, it connects the overlying mucosa to the underlying muscularis. It includes blood and lymphatic vessels which transport absorbed nutrients, and a scattering of submucosal glands that release digestive secretions. Additionally, it serves as a conduit for a dense branching network of nerves, the **submucosal plexus,** which functions as described below.



The third layer of the alimentary canal is the **muscalaris** (also called the muscularis externa). The muscularis in the small intestine is made up of a double layer of smooth muscle: an inner circular layer and an outer longitudinal layer. The contractions of these layers promote mechanical digestion, expose more of the food to digestive chemicals, and move the food along the canal. In the most proximal and distal regions of the alimentary canal, including the mouth, pharynx, anterior part of the esophagus, and external anal sphincter, the muscularis is made up of skeletal muscle, which gives you voluntary control over swallowing and defecation. The basic two-layer structure found in the small intestine is modified in the organs proximal and distal to it. The stomach is equipped for its churning function by the addition of a third layer, the oblique muscle. While the colon has two layers like the small intestine, its longitudinal layer is segregated into three narrow parallel bands, the tenia coli, which make it look like a series of pouches rather than a simple tube.

The **serosa** is the portion of the alimentary canal superficial to the muscularis. Present only in the region of the alimentary canal within the abdominal cavity, it consists of a layer of visceral peritoneum overlying a layer of loose connective tissue. Instead of serosa, the mouth, pharynx, and esophagus have a dense sheath of collagen fibers called the **adventitia**. These tissues serve to hold the alimentary canal in place near the ventral surface of the vertebral column.



The Peritoneum

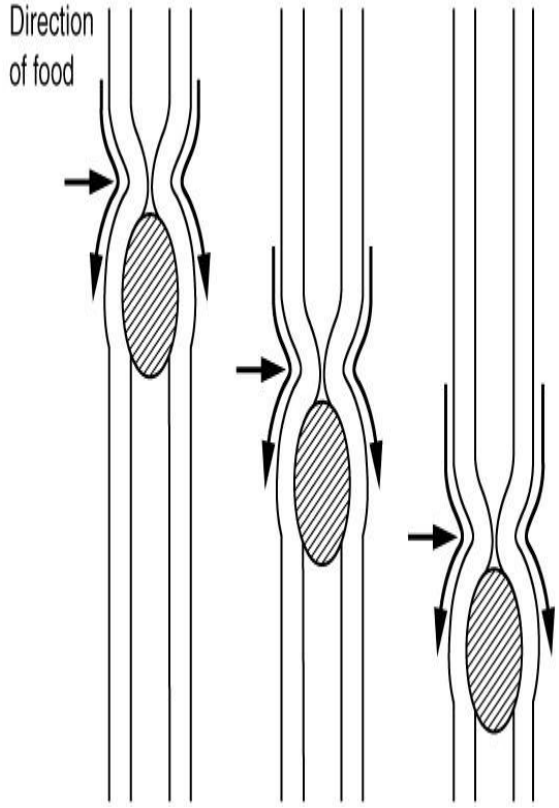
The digestive organs within the abdominal cavity are held in place by the **peritoneum**, a broad serous membranous sac made up of squamous epithelial tissue surrounded by connective tissue. It is composed of two different regions: the **parietal peritoneum,** which lines the abdominal wall, and the **visceral peritoneum**, which envelopes the abdominal organs. The peritoneal cavity is the space bounded by the visceral and parietal peritoneal surfaces. A few milliliters of watery fluid act as a lubricant to minimize friction between the serosal surfaces of the peritoneum.

Digestive Processes

The processes of digestion include six activities: ingestion, propulsion, mechanical or physical digestion, chemical digestion, absorption, and defecation.

The first of these processes, **ingestion**, refers to the entry of food into the alimentary canal through the mouth. There, the food is chewed and mixed with saliva, which contains enzymes that begin breaking down the carbohydrates in the food plus some lipid digestion via lingual lipase. Chewing increases the surface area of the food and allows an appropriately sized bolus to be produced.

Food leaves the mouth when the tongue and pharyngeal muscles propel it into the esophagus. This act of **swallowing**, the last voluntary act until defecation, is an example of **propulsion**, which refers to the movement of food through the digestive tract. It includes both the voluntary process of swallowing and the involuntary process of peristalsis. **Peristalsis** consists of sequential, alternating waves of contraction and relaxation of alimentary wall smooth muscles, which act to propel food along. These waves also play a role in mixing food with digestive juices. Peristalsis is so powerful that foods and liquids you swallow enter your stomach even if you are standing on your head.

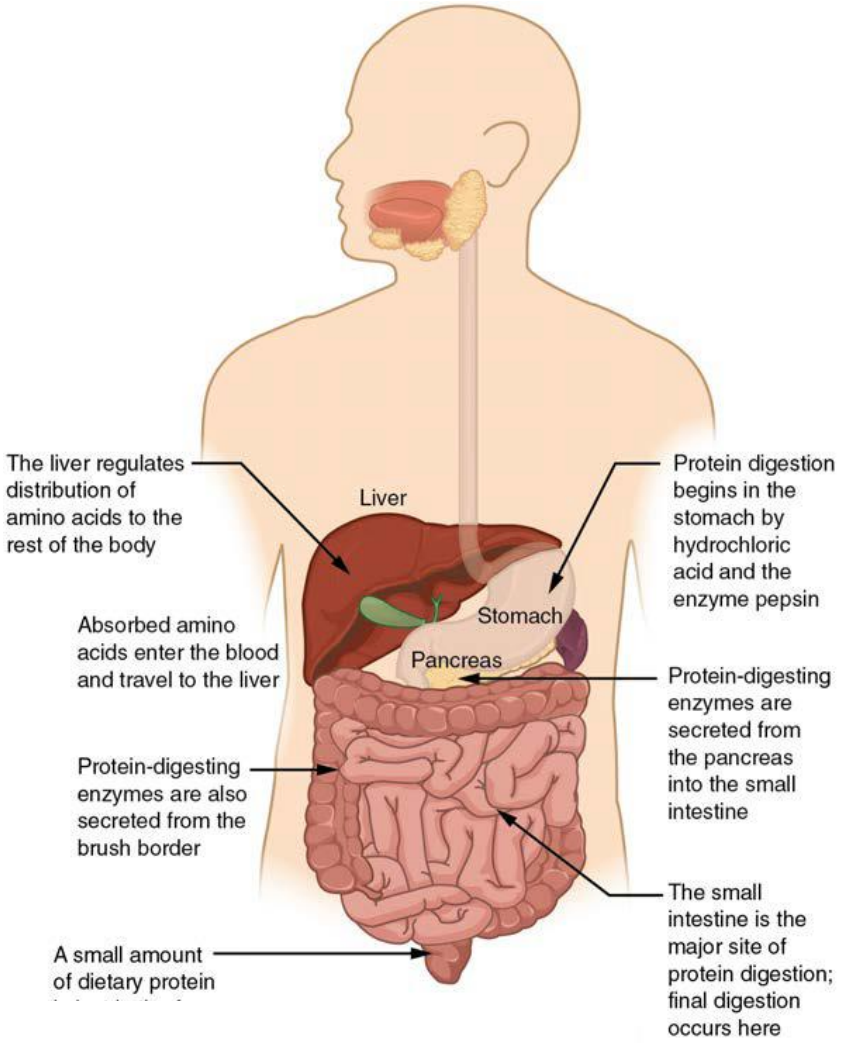


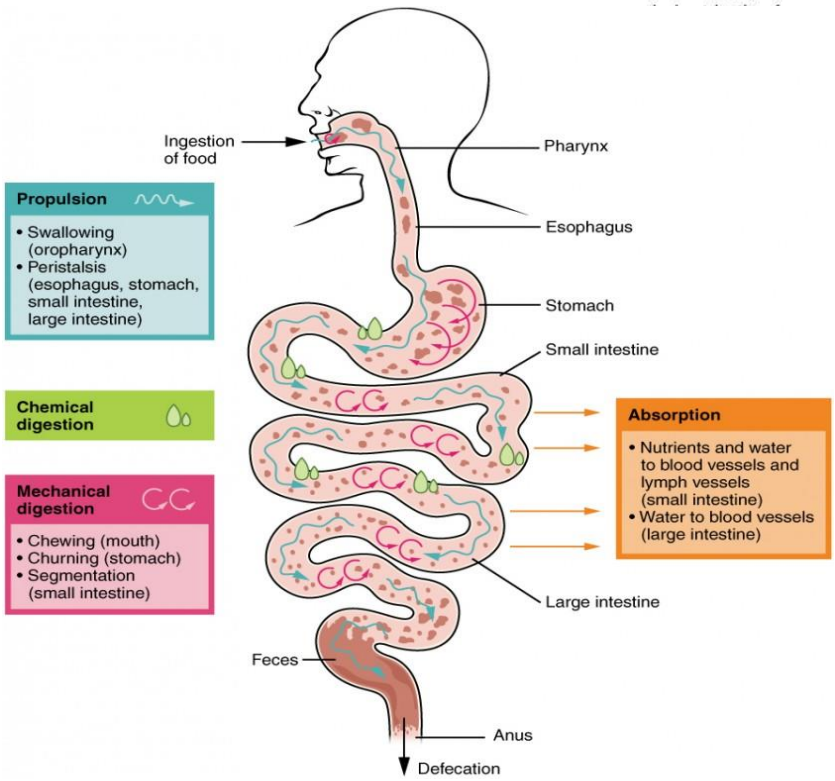
Digestion includes both mechanical and chemical processes. **Mechanical digestion** is a purely physical process that does not change the chemical nature of the food. Instead, it makes the food smaller to increase both surface area and mobility. It includes **mastication**, or chewing, as well as tongue movements that help break food into smaller bits and mix food with saliva. Although there may be a tendency to think that mechanical digestion is limited to the first steps of the digestive process, it occurs after the food leaves the mouth, as well. The mechanical churning of food in the stomach serves to further break it apart and expose more of its surface area to digestive juices, creating an acidic “soup” called **chyme**. **Segmentation**, which occurs mainly in the small intestine, consists of localized contractions of circular muscle of the muscularis layer of the alimentary canal. These contractions isolate small sections of the intestine, moving their contents back and forth while continuously subdividing, breaking up, and mixing the contents. By moving food back and forth in the intestinal lumen, segmentation mixes food with digestive juices and facilitates absorption.

In **chemical digestion**, starting in the mouth, digestive secretions break down complex food molecules into their chemical building blocks (for example, proteins into separate amino acids). These secretions vary in composition, but typically contain water, various enzymes, acids, and salts. The process is completed in the small intestine.

Food that has been broken down is of no value to the body unless it enters the bloodstream and its nutrients are put to work. This occurs through the process of **absorption**, which takes place primarily within the small intestine. There, most nutrients are absorbed from the lumen of the alimentary canal into the bloodstream through the epithelial cells that make up the mucosa. Lipids are absorbed into **lacteals** and are transported via the lymphatic vessels to the bloodstream (the subclavian veins near the heart).

In **defecation**, the final step in digestion, undigested materials are removed from the body as feces.





In some cases, a single organ oversees a digestive process. For example, ingestion occurs only in the mouth and defecation only in the anus. However, most digestive processes involve the interaction of several organs and occur gradually as food moves through the alimentary canal.

Neural Controls

The walls of the alimentary canal contain a variety of sensors that help regulate digestive functions. These include mechanoreceptors, chemoreceptors, and osmoreceptors, which can detect mechanical, chemical, and osmotic stimuli, respectively. For example, these receptors can sense when the presence of food has caused the stomach to expand, whether food particles have been sufficiently broken down, how much liquid is present, and the type of nutrients in the food (lipids, carbohydrates, and/or proteins). Stimulation of these receptors provokes an appropriate reflex that furthers the process of digestion. This may entail sending a message that activates the glands that secrete digestive juices into the lumen, or it

may mean the stimulation of muscles within the alimentary canal, thereby activating peristalsis and segmentation that move food along the intestinal tract.

The walls of the entire alimentary canal are embedded with nerve plexuses that interact with the central nervous system and other nerve plexuses—either within the same digestive organ or in different ones. These interactions prompt several types of reflexes. Extrinsic nerve plexuses orchestrate long reflexes, which involve the central and autonomic nervous systems and work in response to stimuli from outside the digestive system. Short reflexes, on the other hand, are orchestrated by intrinsic nerve plexuses within the alimentary canal wall. These two plexuses and their connections were introduced earlier as the enteric nervous system. Short reflexes regulate activities in one area of the digestive tract and may coordinate local peristaltic movements and stimulate digestive secretions. For example, the sight, smell, and taste of food initiate long reflexes that begin with a sensory neuron delivering a signal to the medulla oblongata. The response to the signal is to stimulate cells in the stomach to begin secreting digestive juices in preparation for incoming food. In contrast, food that distends the stomach initiates short reflexes that cause cells in the stomach wall to increase their secretion of digestive juices.

Hormonal Controls

A variety of hormones are involved in the digestive process. The main digestive hormone of the stomach is **gastrin,** which is secreted in response to the presence of food. Gastrin stimulates the secretion of gastric acid by the parietal cells of the stomach mucosa. Other GI hormones are produced and act upon the gut and its accessory organs. Hormones produced by the duodenum include **secretin**, which stimulates a watery secretion of bicarbonate by the pancreas; **cholecystokinin** (CCK), which stimulates the secretion of pancreatic enzymes and **bile** from the liver and release of bile from the gallbladder; and **gastric inhibitory peptide**, which inhibits gastric secretion and slows gastric emptying and motility. These GI hormones are secreted by specialized epithelial cells, called **endocrinocytes**, located in the mucosal epithelium of the stomach and small intestine. These hormones then enter the bloodstream, through which they can reach their target organs.

Blood Supply

The blood vessels serving the digestive system have two functions. They transport the protein and carbohydrate nutrients absorbed by mucosal cells after food is digested in the lumen. Lipids are absorbed via **lacteals**, tiny structures of the lymphatic system. The blood vessels' second function is to supply the organs of the alimentary canal with the nutrients and oxygen needed to drive their cellular processes.

Specifically, the more anterior parts of the alimentary canal are supplied with blood by arteries branching off the aortic arch and thoracic aorta. Below this point, the alimentary canal is supplied with blood by arteries branching from the abdominal aorta. The celiac trunk services the liver, stomach, and duodenum, whereas the superior and inferior mesenteric arteries supply blood to the remaining small and large intestines.

The veins that collect nutrient-rich blood from the small intestine (where most absorption occurs) empty into the hepatic portal system. This venous network takes the blood into the liver where the nutrients are either processed or stored for later use. Only then does the blood drained from the alimentary canal viscera circulate back to the heart. To appreciate just how demanding the digestive process is on the cardiovascular system, consider that while you are "resting and digesting," about one-fourth of the blood pumped with each heartbeat enters arteries serving the intestines.

Lesson 2: Anatomy of the Digestive System

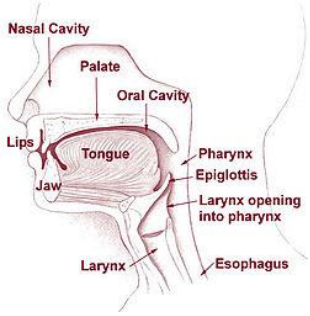
Objective:

- Identify the organs of the alimentary canal from proximal to distal, and briefly state their function
- Identify the accessory digestive organs and briefly state their function

The **mouth** is the first portion of the alimentary canal. It receives food and moistens the food with **saliva**, while the food is mechanically processed (**mastication**) by the teeth. The mouth is also known as the **oral cavity**, and within the oral cavity sits the tongue, the **soft** and **hard palate**, the **uvula**, and numerous **salivary glands**. The oral mucosa is the mucous membrane epithelial tissue that lines the inside of the mouth. This membrane maintains a moist and lubricated environment within the mouth to prepare the digestive system for the entry of food. In the digestive process, the mouth's purpose is to prepare food for further digestion in the stomach and the small intestine. This process begins with the mechanical breakdown of food by the teeth, which fit into the alveolar arches. The front teeth (incisors and canines) are used to cut and tear food, while the teeth further back (bicuspids and molars) crush and grind.

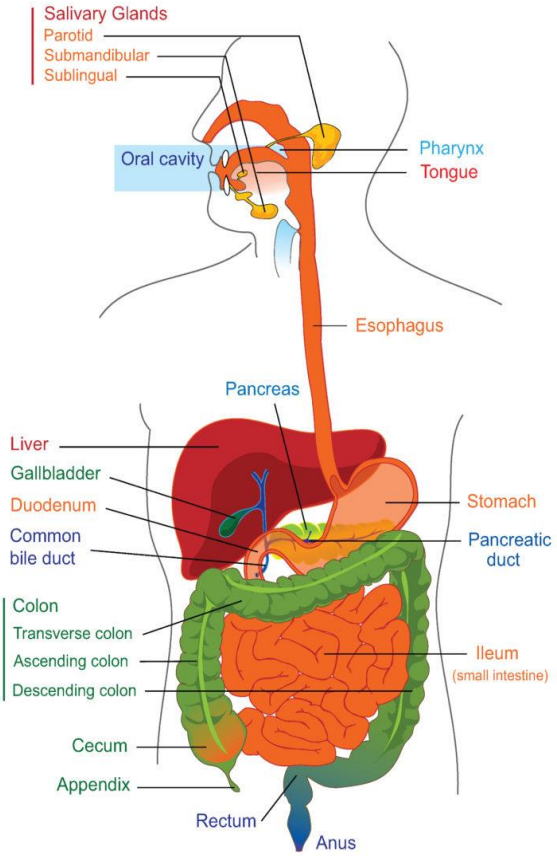
Saliva is projected from three main pairs of salivary glands: the large parotid glands near the cheeks, the submandibular glands beneath the mandible, and the sublingual glands beneath the tongue.

Saliva keeps the mouth moist and lubricates the food, helping the tongue form the food into a soft wad, called a bolus. The fluid of saliva also contains several enzymes, notably **lysozyme**—an antibacterial agent—and **amylase,** which catalyzes large starch molecules into simpler sugars via hydrolysis. Once properly chewed and lubricated, food and drink are swallowed into the esophagus, the tube that leads to the stomach.



Pharynx

The **pharynx** is part of the digestive and respiratory systems and consists of three main parts: the nasopharynx, oropharynx, and laryngopharynx. The human pharynx is the part of the throat situated immediately inferior to the mouth and nasal cavity, and superior to the esophagus and larynx. The human pharynx is conventionally divided into three sections: the nasopharynx (epipharynx), the oropharynx (mesopharynx), and the laryngopharynx (hypopharynx). The pharynx is part of the digestive system and the respiratory system, as well as an important part in vocalization.



Esophagus

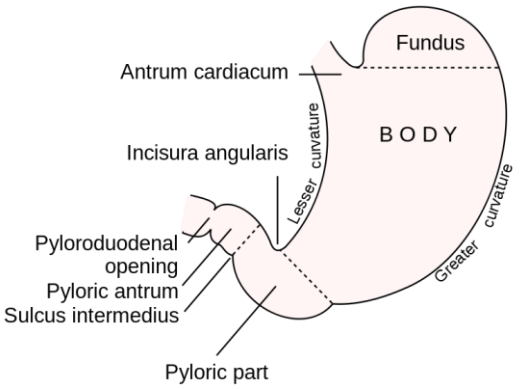
The **esophagus** is a muscular tube that moves food from the pharynx to the stomach via **peristalsis**. The esophagus is an organ in vertebrates that consists of a muscular tube through which food passes from the pharynx to the stomach. It is lined with mucus to aid in the passage of food.

In humans the esophagus is continuous with the laryngeal part of the pharynx within the neck, and it passes through the thorax diaphragm and into abdomen to reach the cardiac orifice of the stomach. It is usually about 10–50 cm long depending on an

individual's height. Due to the inferior pharyngeal constrictor muscle, the entry to the esophagus opens only when swallowing or vomiting.

The Gastroesophageal Junction

The junction between the esophagus and the stomach (the **gastroesophageal junction** or GE junction) is not actually considered a valve in the anatomical sense, although it is sometimes called the **cardiac sphincter.**



The Stomach

The **stomach** is a thick, walled organ that lies between the esophagus and the first part of the small intestine (the duodenum). It is on the left side of the abdominal cavity, the **fundus** of the stomach lying against the diaphragm. A mucous membrane lines the stomach that contains the glands (with chief cells) that secrete gastric juices. Up to three quarts of this digestive fluid is produced daily. The gastric glands begin secreting before food enters the stomach due to the parasympathetic impulses of the vagus nerve, that also make the stomach a storage vat for that acid. The stomach participates in virtually all the digestive activities except for ingestion and defecation. Although almost all absorption takes place in the small intestine, the stomach does absorb some nonpolar substances, such as alcohol and aspirin.

The stomach is divided into four sections, each of which has different cells and functions. The sections are:

1. The **cardiac region**, where the contents of the esophagus empty into the stomach.
2. The **fundus**, which is formed by the upper curvature of the organ.
3. The **body**, the main central region.
4. The **pylorus or atrium**, the lower section of the organ that facilitates the emptying of the contents into the small intestine.

Two smooth muscle valves, or **sphincters,** keep the contents of the stomach contained. They are the:

1. **Cardiac or esophageal sphincter** that divides the tract above.
2. **Pyloric sphincter or pyloric orifice** that divides the stomach from the small intestine.

The arteries that supply the stomach are the left gastric, the right gastric, and right gastroepiploic branches of the hepatic, and the left gastroepiploic and short gastric branches of the lineal. They supply the muscular coat, ramify in the submucous coat, and are finally distributed to the mucous membrane.

The layers of the stomach produce mucus to protect itself, enzymes to break down the food for digestion, and muscles to churn the food. Like the other parts of the gastrointestinal tract, the stomach walls are made of several layers. From the inside to the outside, the first main layer is the **mucosa**. This consists of an epithelium, the lamina propria underneath, and a thin bit of smooth muscle called the **muscularis mucosae.** The **submucosa** lies under this and consists of fibrous connective tissue that separate the mucosa from the next layer, the **muscularis externa.**

The epithelium of the stomach forms deep pits, called **fundic or oxyntic glands**. Different types of cells are at different locations down the pits. The cells at the base of these pits are **chief cells** that are responsible for the production of **pepsinogen**, an inactive precursor of pepsin, which degrades proteins. The secretion of pepsinogen prevents self-digestion of the stomach cells.

Further up the pits, **parietal cells** produce gastric acid and a vital substance, **intrinsic factor.** The function of gastric acid is twofold:

1. It kills most of the bacteria in food, stimulates hunger, and activates pepsinogen into pepsin.
2. It denatures the complex protein molecule as a precursor to protein digestion through enzyme action in the stomach and small intestines.

Near the top of the pits, closest to the contents of the stomach, there are mucus-producing cells called g**oblet cells** that help protect the stomach from self-digestion.

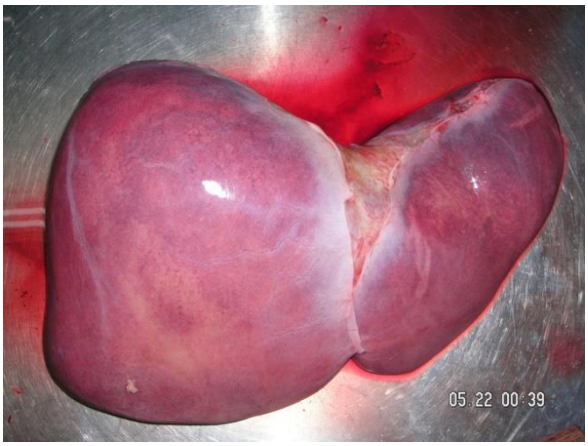
The muscularis externa is made up of three layers of smooth muscle.

- The innermost layer is obliquely-oriented: this is not seen in other parts of the digestive system. This layer is responsible for creating the motion that churns and physically breaks down the food.
- The next layers are the square and then the longitudinal, which are present as in other parts of the GI tract.
- The pyloric antrum has thicker skin cells in its walls and performs more forceful contractions than the fundus. The pylorus is surrounded by a thick circular muscular wall that is normally tonically constricted, forming a functional (if not anatomically discrete) pyloric sphincter that controls the movement of chyme.

The movement and flow of chemicals into the stomach is controlled by the autonomic nervous system and various digestive system hormones.

The Liver

The **liver** normally weighs between 1.3—3.0 kilograms and is a soft, pinkish-brown organ with four lobes. It is the second-largest organ in the body and is located on the right side of the abdomen resting just below the diaphragm. The liver lies to the right of the stomach and overlies the gall bladder.



The liver has a wide range of functions including detoxification, protein synthesis, and the production of the biochemicals necessary for digestion. The liver plays a major role in metabolism and has several functions in the body, including glycogen storage, plasma protein synthesis, and drug detoxification. It also produces bile, which is important for digestion.

A **hepatocyte** is the main tissue cell of the liver and makes up 70–80% of the liver's cytoplasmic mass. Hepatocytes contain large amounts of rough endoplasmic reticulum and free ribosomes.

Hepatocytes are involved in:

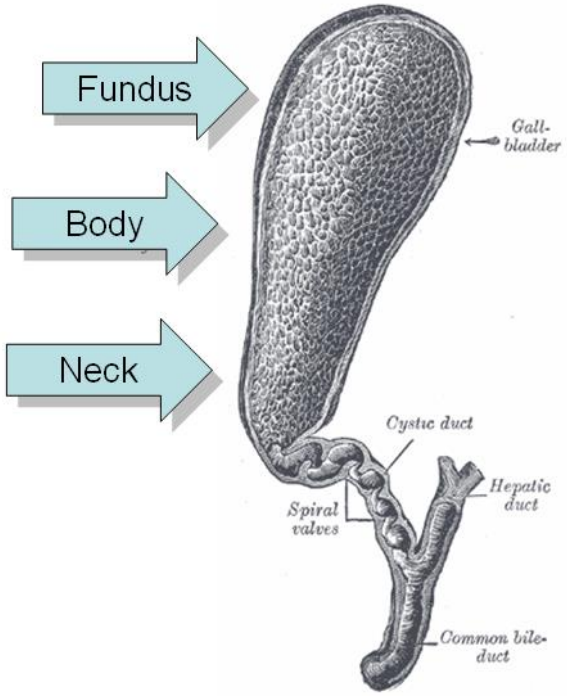
- Protein synthesis.
- Protein storage.
- The transformation of carbohydrates.
- The synthesis of cholesterol, bile salts, and phospholipids.
- The detoxification, modification, and excretion of exogenous and endogenous substances.

Hepatocytes also initiate the formation and secretion of **bile.** Hepatocytes are organized into plates separated by vascular channels (sinusoids) for blood vessels. The hepatocyte plates are one cell thick in mammals. Hepatocytes are unique in that they are one of the few types of cell in the human body that are capable of regeneration. Hepatocytes are derived from **hepatoblasts,** the precursor stem cell of the liver that divides to produce new hepatocytes. The liver is capable of complete regeneration from as little as 25% of the original organ.

The liver is supplied by two main blood vessels on its right lobe: the **hepatic artery** and **the portal vein.** The hepatic portal system connects the capillaries of the gastrointestinal tract with the capillaries in the liver. Nutrient-rich blood leaves the gastrointestinal tract and is first brought to the liver for processing before being sent to the heart. The portal vein brings venous blood from the spleen, pancreas, and small intestine so that the liver can process the nutrients and byproducts of food digestion. The liver also removes vitamins and cofactors from the blood for storage, as well as filters any toxins that may have been absorbed along with the food. When any of these stored substances are needed, the liver releases them back into circulation through the hepatic veins.

The Gallbladder

The gallbladder is a hollow organ that sits beneath the liver and stores bile made in the liver. In adults, the gallbladder measures approximately eight centimeters (3.1 in) in length and four centimeters (1.6 in) in diameter when fully distended.



The gallbladder is divided into three sections:

1. The fundus.
2. The body.
3. The neck.

The neck tapers and connects to the biliary tree via the cystic duct, which then joins the common hepatic duct to become the common bile duct. At the neck of the gallbladder is a mucosal fold where gallstones commonly get stuck.

Bile

The bile produced in the liver is essential for the digestion of fats. Bile is formed in the liver, and it is stored in the **gallbladder** or released directly into the small intestine. After being stored in the gallbladder, the bile becomes more concentrated than when it left the liver; this increases its potency and intensifies its effect in digesting fats. Bile acts as a **surfactant**, helping to emulsify the fats in the food, in the same way that soap emulsifies fat. The bile salts are ionically charged, with a **hydrophobic** end and a **hydrophillic** end. When exposed to water mixed with fat, such as in the small intestine, the bile salts congregate around a fat droplet with their hydrophobic side pointing towards the fat and their hydrophillic side pointing towards the water. This increases the surface area of the fat and allows greater access by the pancreatic enzymes that break down fats. **Bilirubin,** the main bile pigment, is a waste product produced when the spleen removes old or damaged red blood cells from the circulation. These breakdown products, including proteins, iron, and toxic bilirubin, are transported to the liver via the splenic vein of the hepatic portal system. In the liver, proteins and iron are recycled, whereas bilirubin is excreted in the bile. It accounts for the green color of bile. Bilirubin is eventually transformed by intestinal bacteria into a brown pigment that gives your stool its characteristic color!

The Pancreas

The **pancreas** is located posterior to the stomach and next to the duodenum. The pancreas functions as both an exocrine and endocrine gland. The exocrine function of the pancreas is essential for digestion as it produces many of the enzymes that break down the protein, carbohydrates, and fats in digestible foods.

The pancreas is composed of pancreatic **exocrine cells,** whose ducts are arranged in clusters called **acini.** The cells are filled with secretory granules containing the inactivated digestive enzymes, mainly **trypsinogen, chymotrypsinogen, pancreatic lipase,** and **amylase**, that are secreted into the lumen of the acini. The pancreas is a dual-function gland, having features of both endocrine and exocrine glands.

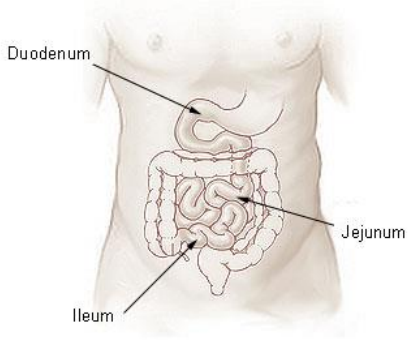
The pancreas synthesizes its enzymes in the inactive form, known as **zymogens**, to avoid digesting itself. The enzymes are activated once they reach the small intestine. The pancreas also secretes bicarbonate ions from the ductal cells to neutralize the acidic **chyme** that the stomach churns out. The exocrine function of the pancreas is controlled by the hormones **gastrin, cholecystokinin,** and **secretin**, which are hormones secreted by cells in the stomach and duodenum in response to food.

The part of the pancreas with endocrine function is made up of approximately a million cell clusters called the **islets of Langerhans**. Four main cell types exist in the islets. They are relatively difficult to distinguish using standard staining techniques, but they can be classified by their secretions:

1. α cells secrete glucagon (increase glucose in blood).
2. β cells secrete insulin (decrease glucose in blood).
3. Delta cells secrete somatostatin (regulates/stops α and β cells).
4. PP cells or gamma cells secrete pancreatic polypeptide.

The Small Intestine

The **small intestine** is the part of the gastrointestinal tract that follows the stomach, which is in turn followed by the large intestine. The small intestine is the site where almost all the digestion and absorption of nutrients and minerals from food takes place. The average length of the small intestine in an adult human male is 6.9 m (22 feet, 6 inches), and in the adult female 7.1 m (23 feet, 4 inches). It can vary greatly, from as short as 4.6 m (15 feet) to as long as 9.8 m (32 feet). The small intestine is approximately 2.5–3 cm in diameter, and is divided into three sections:

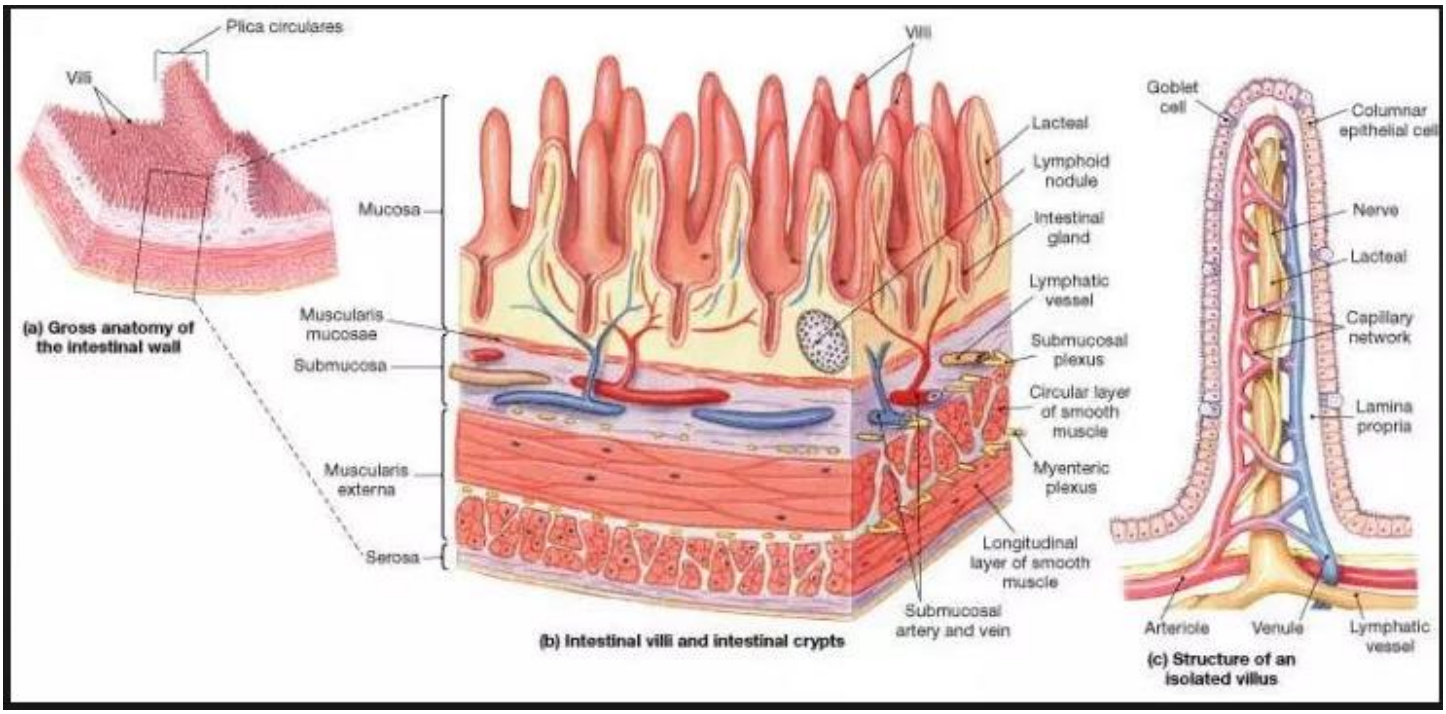


1. The **duodenum** is the first section of the small intestine and is the shortest part of the small intestine. It is where most chemical digestion using enzymes takes place.

2. The **jejunum** is the middle section of the small intestine. It has a lining which is designed to absorb carbohydrates and proteins. The inner surface of the jejunum, its mucous membrane, is covered in projections called **villi,** which increase the surface area of tissue available to absorb nutrients from the gut contents. The epithelial cells which line these villi possess even larger numbers of **microvilli**. The transport of nutrients across epithelial cells through the jejunum includes the passive transport of some carbohydrates and the active transport of amino acids, small peptides, vitamins, and most glucose. The villi in the jejunum are much longer than in the duodenum or ileum.

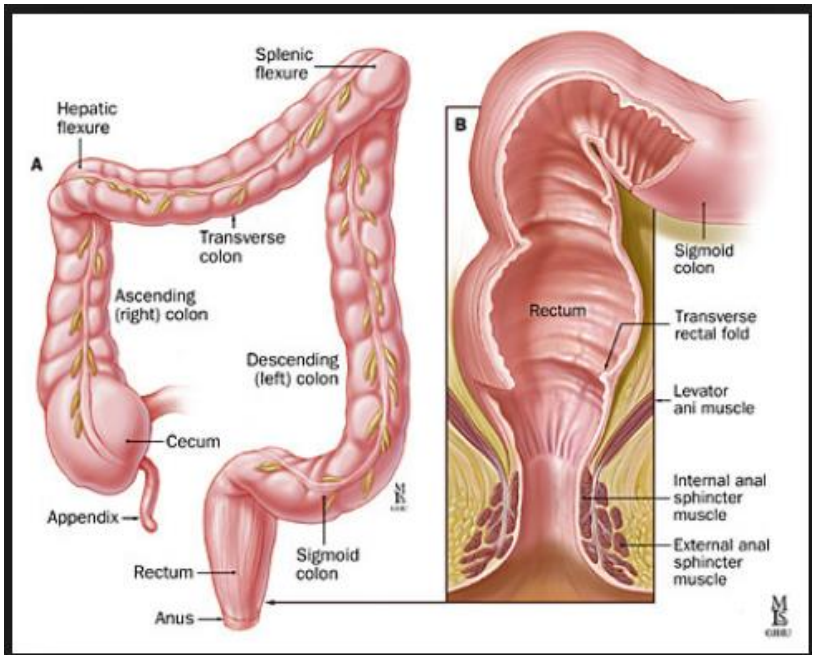
3. The **ileum** is the final section of the small intestine. The function of the ileum is mainly to absorb vitamin B12, bile salts, and any products of digestion that were not absorbed by the jejunum. The wall itself is made up of folds, each of which has many tiny finger-like projections known as **villi** on its surface. The ileum has an extremely large surface area both for the adsorption of enzyme molecules and for the absorption of products of

digestion. The villi contain large numbers of capillaries that take the **amino acids** and **glucose** produced by digestion to the hepatic portal vein and the liver. **Lacteals** are the small lymph vessels that are present in villi. They absorb fatty acids and glycerol, the products of fat digestion, into direct circulation. Layers of circular and longitudinal smooth muscle enable the digested food to be pushed along the ileum by waves of muscle contractions called **peristalsis.** The undigested food (waste and water) are sent to the **colon.**



The Large Intestine

The function of the **large intestine** (or colon) is to absorb water from the remaining indigestible food matter, and then to pass the useless waste material from the body. The large intestine consists of the cecum and colon.



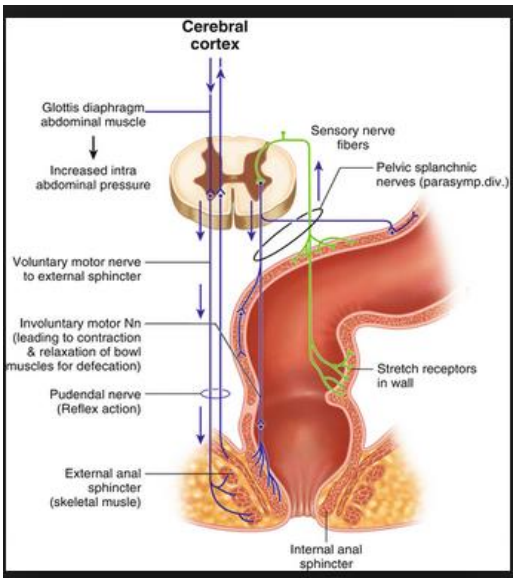
The large intestine is about 4.9 feet (1.5 m) long—about one-fifth of the whole length of the intestinal canal.

The large intestine, or large bowel, is the last part of the digestive system in vertebrate animals. Its function is to absorb water from the remaining indigestible food matter, and then to pass the useless waste material from the body. The large intestine consists of the **cecum, colon, rectum,** and **anal canal.**

It starts in the right iliac region of the pelvis, just at or below the right waist, where it is joined to the bottom end of the small intestine. From here it continues up the abdomen, across the width of the abdominal cavity, and then it turns downward, continuing to its endpoint at the anus.

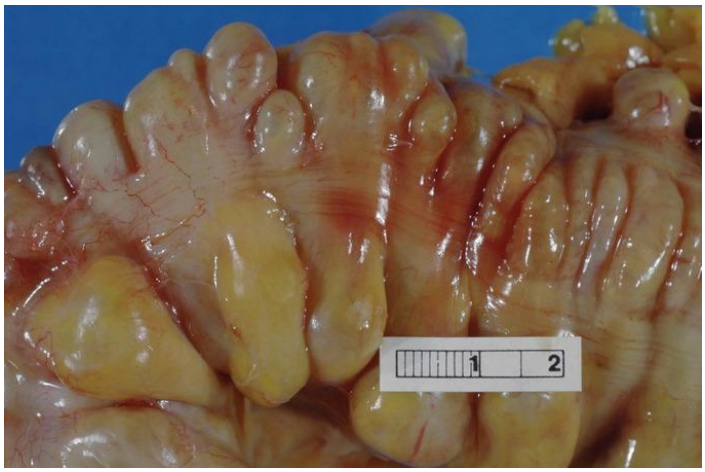
The large intestine differs in physical form from the small intestine in being much wider. The longitudinal layer of the muscularis is reduced to three strap-like structures known as the taeniae coli—bands of longitudinal

muscle fibers, each about 1/5 in wide. These three bands start at the base of the appendix and extend from the cecum to the rectum. Along the sides of the taeniae are tags of peritoneum filled with fat; these are called epiploic appendages, or appendices epiploicae. The wall of the large intestine is lined with simple columnar epithelium. Instead of having the evaginations of the small intestine (villi), the large intestine has invaginations (the intestinal glands). While both the small intestine and the large intestine have goblet cells that secrete mucin to form mucus in water, they are abundant in the large intestine.



Additional Structures

The **appendix** is attached to its inferior surface of the cecum. It contains the least lymphoid tissue, and it is a part of mucosa-associated lymphoid tissue, which gives it an important role in immunity. Appendicitis is the result of a blockage that traps infectious material in the lumen. The appendix can be removed with no apparent damage or consequence to the patient.



On the surface of the large intestine, bands of longitudinal muscle fibers called taeniae coli, each about 0.2 inches wide, can be identified. There are three bands, starting at the base of the appendix and extending from the cecum to the rectum. Along the sides of the taeniae, tags of peritoneum filled with fat, called epiploic appendages (or appendices epiploicae) are found. The sacculations, called haustra, are characteristic features of the large intestine, and distinguish it from the small intestine.

Intestinal Bacteria

The large intestine houses over 700 species of bacteria that perform a variety of functions. The large intestine absorbs some of the products formed by the bacteria that inhabit this region.

Undigested polysaccharides (fiber) are metabolized into short-chain fatty acids by bacteria in the large intestine and get absorbed by passive diffusion. The bicarbonate that the large intestine secretes helps to neutralize the increased acidity from the formation of fatty acids.

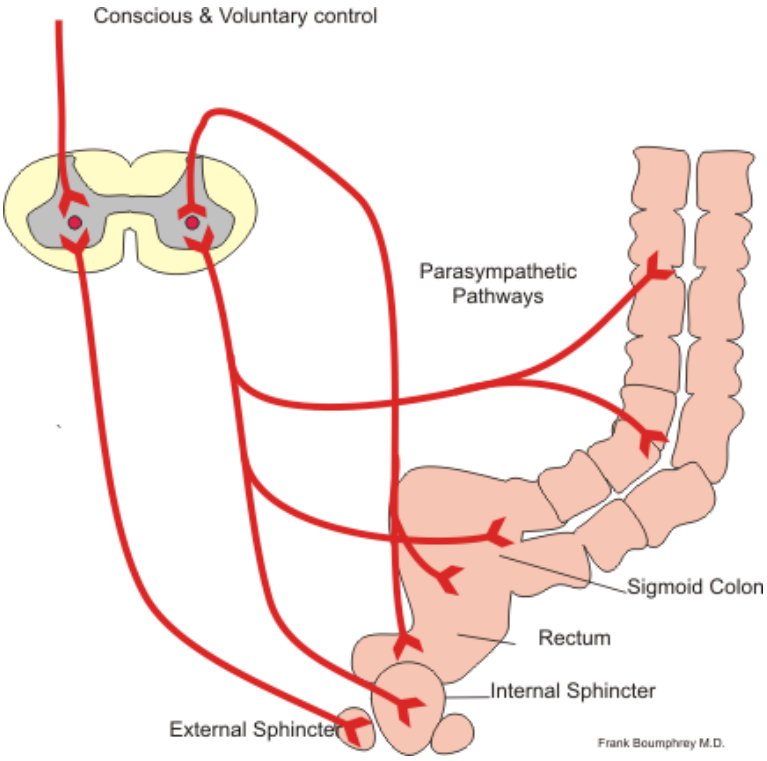
Intestinal bacteria also produce large amounts of vitamins, especially vitamin K and biotin (a B vitamin), which are absorbed into the blood. Although this source of vitamins provides only a small part of the daily requirement, it makes a significant contribution when dietary vitamin intake is low. An individual that depends on absorption of vitamins formed by bacteria in the large intestine may become vitamin-deficient if treated with antibiotics that inhibit other species of bacteria while targeting the disease-causing bacteria.

Other bacterial products include gas (flatus)—a mixture of nitrogen and carbon dioxide, with small amounts of the gas hydrogen, methane, and hydrogen sulfide. The bacterial fermentation of undigested polysaccharides produces these gases. Intestinal flora are also essential for the development of certain tissues, including the cecum and lymphatics.

The large intestine absorbs water from the chyme and stores feces until it can be defecated. Food products that cannot go through the villi, such as cellulose (dietary fiber), are mixed with other waste products from the body and become hard and concentrated feces. The feces is stored in the rectum for a certain period and then the

stored feces is eliminated from the body due to the contraction and relaxation of the **anus.** The exit of this waste material is regulated by the **anal sphincter.** Defecation is a combination of voluntary and involuntary processes that create enough force to remove waste material from the digestive system.

The rectal ampulla acts as a temporary storage facility for the unneeded material. As additional fecal material enters the rectum, the rectal walls expand. Enough increase in fecal material in the rectum causes the stretch receptors from the nervous system, located in the rectal walls, to trigger the contraction of rectal muscles, the relaxation of the internal anal sphincter, and an initial contraction of the skeletal muscle of the external sphincter. The relaxation of the internal anal sphincter causes a signal to be sent to the brain indicating an urge to defecate.



If this urge is not acted upon, the material in the rectum is often returned to the colon by reverse peristalsis where more water is absorbed, thus temporarily reducing pressure and stretching within the rectum. The additional fecal material is stored in the colon until the next mass peristaltic movement of the transverse and descending colon. If defecation is delayed for a prolonged period, the fecal matter may harden and autolyze, resulting in **constipation**.

Once the voluntary signal to defecate is sent back from the brain, the final phase begins. The abdominal muscles contract (straining), causing the intra-abdominal pressure to increase. The perineal wall is lowered and causes the anorectal angle to decrease from 90 degrees to less than 15 degrees (almost straight), and the external anal sphincter relaxes.

The rectum now contracts and shortens in peristaltic waves, thus forcing fecal material out of the rectum and down through the anal canal. The internal and external anal sphincters, along with the puborectalis muscle, allow the feces to be passed by pulling the anus up and over the exiting feces in shortening and contracting motions.

Table 1. Functions of the Digestive Organs

Organ	Major functions	Other functions
Mouth	• Ingests food • Chews and mixes food • Begins chemical breakdown of carbohydrates • Moves food into the pharynx • Begins breakdown of lipids via lingual lipase	• Moistens and dissolves food, allowing you to taste it • Cleans and lubricates the teeth and oral cavity • Has some antimicrobial activity
Pharynx	• Propels food from the oral cavity to the esophagus	• Lubricates food and passageways
Esophagus	• Propels food to the stomach	• Lubricates food and passageways
Stomach	• Mixes and churns food with gastric juices to form chyme • Begins chemical breakdown of proteins • Releases food into the duodenum as chyme • Absorbs some fat-soluble substances (for example, alcohol, aspirin) • Possesses antimicrobial functions	• Stimulates protein-digesting enzymes • Secretes intrinsic factor required for vitamin B_{12} absorption in small intestine
Small intestine	• Mixes chyme with digestive juices • Propels food at a rate slow enough for digestion and absorption • Absorbs breakdown products of carbohydrates, proteins, lipids, and nucleic acids, along with vitamins, minerals, and water • Performs physical digestion via segmentation	• Provides optimal medium for enzymatic activity
Accessory organs	• Liver: produces bile salts, which emulsify lipids, aiding their digestion and absorption • Gallbladder: stores, concentrates, and releases bile • Pancreas: produces digestive enzymes and bicarbonate	• Bicarbonate-rich pancreatic juices help neutralize acidic chyme and provide optimal environment for enzymatic activity
Large intestine	• Further breaks down food residues • Absorbs most residual water, electrolytes, and vitamins produced by enteric bacteria • Propels feces toward rectum • Eliminates feces	• Food residue is concentrated and temporarily stored prior to defecation • Mucus eases passage of feces through colon

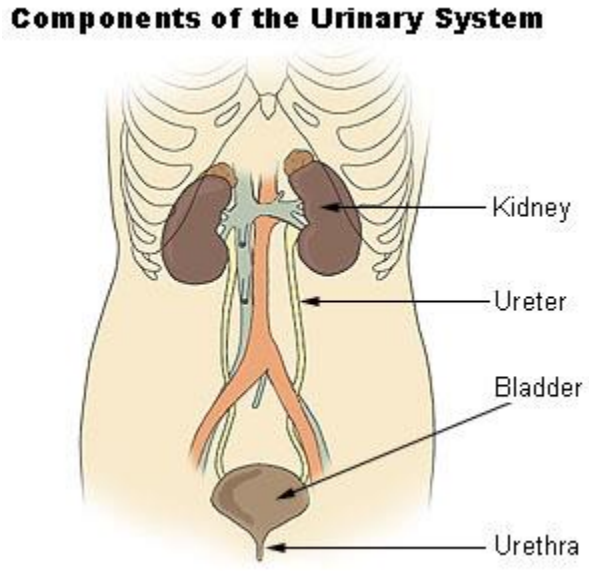
Lesson 3: Anatomy of the Excretory System

Objective:

- Describe the anatomy and function of the urinary tract and kidneys

The **renal** (excretory system), which is also called the urinary system, is a group of organs in the body that filters out excess fluid and other substances from the bloodstream. The purpose of the renal system is to eliminate wastes from the body, regulate blood volume and pressure, control levels of electrolytes and metabolites, and regulate blood pH. The renal system organs include the kidneys, ureters, bladder, and urethra.

Many of the functions of this system are interrelated with the physiological mechanisms in the cardiovascular and respiratory systems. Many of these functions are related to one another as well. For example, water follows ions via an osmotic gradient, so mechanisms that alter sodium levels or sodium retention in the renal system will alter water retention levels as well.



1. Removal of metabolic waste products from the body (mainly urea and uric acid).
2. Regulation of electrolyte balance (e.g., sodium, potassium, and calcium).
3. Osmoregulation controls the blood volume and body water contents.
4. Blood pressure homeostasis: The renal system alters water retention and thirst to slowly change blood volume and keep blood pressure in a normal range.
5. Regulation of acid-base homeostasis and blood pH, a function shared with the respiratory system.

Organs of the Renal System

Ureter

Urine passes from the renal tube through tubes called **ureters** and into the **bladder.** The ureters are retroperitoneal and lead from the renal pelvis of the kidney to the trigone area at the base of the bladder. A thick muscular wall consisting of longitudinal and circular smooth muscle helps move urine toward the bladder by way of **peristaltic** contractions.

Bladder

The **bladder** is flexible and is used as storage until the urine can pass through the urethra and out of the body. The bladder is largely retroperitoneal and can hold up to 500–600 mL urine**. Micturition** is the process of voiding the urine and involves both involuntary and voluntary actions. Voluntary control of voiding urine requires a mature and intact sacral micturition center. It also requires an intact spinal cord. Loss of control of being able to urinate is called incontinence and results in voiding when the bladder contains about 250 mL urine.

Urethra

The **urethra** is the only urinary structure that differs significantly between males and females. This is due to the dual role of the male urethra in transporting both urine and semen. The urethra arises from the trigone area at the base of the bladder. **Urination** is controlled by an involuntary internal sphincter of smooth muscle and a voluntary external sphincter of skeletal muscle. The shorter female urethra contributes to the higher incidence of bladder infections in females. The male urethra receives secretions from the prostate gland, Cowper's gland, and seminal vesicles as well as sperm.

The Kidneys

The **kidneys** are a pair of bean-shaped, brown organs about the size of your fist. They are covered by the renal capsule, which is a tough capsule of fibrous connective tissue. Adhering to the surface of each kidney are two layers of fat to help cushion them. The asymmetry within the abdominal cavity caused by the liver typically results in the right kidney being slightly lower than the left, and left kidney being located slightly more medial than the right. The right kidney sits just below the diaphragm and posterior to the liver, the left below the diaphragm and posterior to the spleen. Resting on top of each kidney is an **adrenal gland** (adrenal meaning on top of renal), which are involved in some renal system processes despite being a primarily endocrine organ. The upper parts of the kidneys are partially protected by lower ribs, and each whole kidney and adrenal gland are surrounded by two layers of fat (the perirenal and pararenal fat) and the renal fascia. The kidneys are located at the rear wall of the abdominal cavity just above the waistline and are protected by the ribcage. They are considered retroperitoneal, which means that they lie behind the peritoneum, the membrane lining of the abdominal cavity.

The kidneys are essential in homeostatic functions such as the regulation of electrolytes, maintenance of acid–base balance, and the regulation of blood pressure (by maintaining salt and water balance). They serve the body as a natural filter of the blood and remove wastes that are excreted through the urine. They are also responsible for the reabsorption of water, glucose, and amino acids, and will maintain the balance of these molecules in the body. In addition, the kidneys produce hormones including **calcitriol, erythropoietin**, and the **enzyme renin**, which are involved in renal and hematological physiological processes.

There are several important external structures connecting the kidneys to the rest of the body. The renal artery branches off from the lower part of the aorta and provides the blood supply to the kidneys. Renal veins take blood away from the kidneys into the inferior vena cava. The ureters are structures that come out of the kidneys, bringing urine downward into the bladder.

Internal Anatomy of the Kidneys

The cortex and medulla make up two of the internal layers of a kidney and are composed of individual filtering units known as nephrons.

There are three major regions of the kidney:

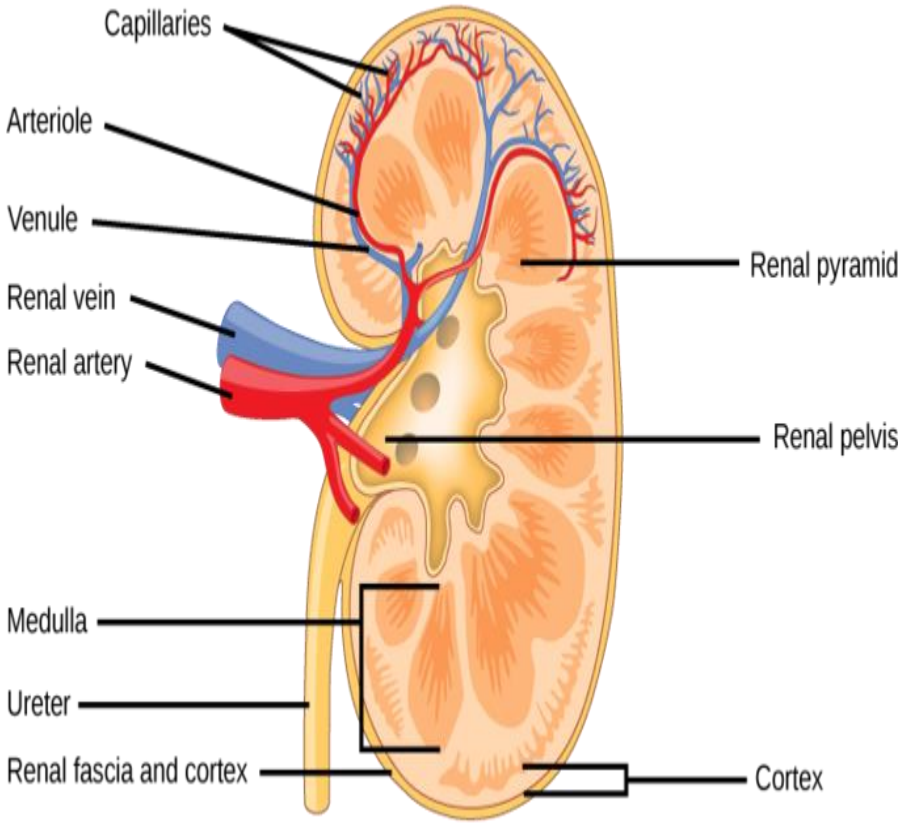
1. Renal cortex
2. Renal medulla
3. Renal pelvis

The renal cortex is a space between the medulla and the outer capsule. The renal medulla contains most of the length of nephrons, the main functional component of the kidney that filters fluid from blood. The renal pelvis connects the kidney with the circulatory and nervous systems from the rest of the body.

Renal Cortex

The kidneys are surrounded by a **renal cortex**, a layer of tissue that is also covered by **renal fascia** (connective tissue) and the renal capsule. The renal cortex is granular tissue due to the presence of nephrons—the functional unit of the kidney—that are located deeper within the kidney, within the renal pyramids of the medulla.

The cortex provides a space for arterioles and venules from the renal artery and vein, as well as the glomerular capillaries, to perfuse the nephrons of the kidney. Erythropoietin, a hormone necessary for the synthesis of new red blood cells, is also produced in the renal cortex.



Renal Medulla

The **medulla** is the inner region of the parenchyma of the kidney. The medulla consists of multiple pyramidal tissue masses, called the renal pyramids, which are triangle structures that contain a dense network of nephrons.

At one end of each nephron, in the cortex of the kidney, is a cup-shaped structure called the **Bowman's capsule**. It surrounds a tuft of capillaries called **the glomerulus** that carries blood from the renal arteries into the nephron, where plasma is filtered through the capsule.

After entering the capsule, the filtered fluid flows along the proximal convoluted tubule to the **loop of Henle** and then to the **distal convoluted tubule** and **the collecting ducts**, which flow into the ureter. Each of the different components of the nephrons are selectively permeable to different molecules and enable the complex regulation of water and ion concentrations in the body.

Renal Pelvis

The **renal pelvis** contains the **hilum**. The hilum is the concave part of the bean-shape where blood vessels and nerves enter and exit the kidney; it is also the point of exit for the ureters—the urine-bearing tubes that exit the kidney and empty into the urinary bladder. The renal pelvis connects the kidney to the rest of the body.

Supply of Blood and Nerves to the Kidneys

The renal veins drain the kidney and the renal arteries supply blood to the kidney. The **renal arteries** branch off the abdominal aorta and supply the kidneys with blood. The arterial supply of the kidneys is variable from person to person, and there may be one or more renal arteries supplying each kidney.

Due to the position of the **aorta**, the **inferior vena cava**, and the **kidneys** in the body, the right renal artery is normally longer than the left renal artery. The renal arteries carry a large portion of the total blood flow to the kidneys—up to a third of the total cardiac output can pass through the renal arteries to be filtered by the kidneys.

Renal blood supply starts with the branching of the **aorta** into the **renal arteries** (which are each named based on the region of the kidney they pass through) and ends with the exiting of the **renal veins** to join the **inferior vena cava.** The renal arteries split into several segmental arteries upon entering the kidneys, which then split into several **arterioles.**

These **afferent arterioles** branch into the **glomerular capillaries**, which facilitate fluid transfer to the nephrons inside the *Bowman's capsule*, while **efferent arterioles** take blood away from the **glomerulus**, and into the **interlobular capillaries**, which provide tissue oxygenation to the parenchyma of the kidney.

Renal Plexus

The renal plexus are the source of nervous tissue innervation within the kidney, which surround and primarily alter the size of the arterioles within the renal cortex. Input from the sympathetic nervous system triggers vasoconstriction of the arterioles in the kidney, thereby reducing renal blood flow into the glomerulus.

The kidney also receives input from the **parasympathetic nervous system**, by way of the renal branches of the vagus nerve (cranial nerve X), which causes vasodilation and increased blood flow of the afferent arterioles. Due to this mechanism, sympathetic nervous stimulation will decrease urine production, while parasympathetic nervous stimulation will increase urine production

Kidney diseases are conditions which incapacitate the kidney's ability to filter waste products from the blood

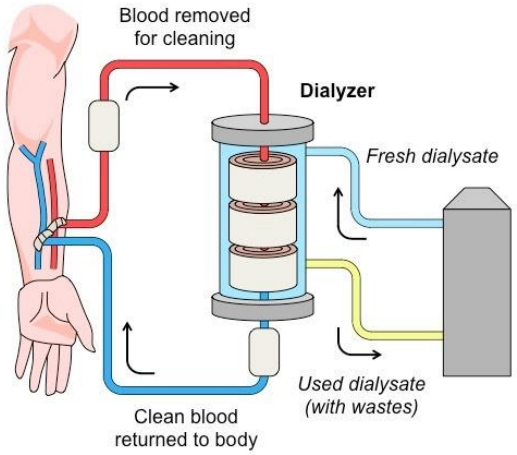
- Individuals with kidney diseases will demonstrate a reduced glomerular filtration rate (GFR)
- If untreated, kidney diseases can lead to kidney failure – which is life threatening

Hemodialysis

Kidney dialysis involves the external filtering of blood in order to remove metabolic wastes in patients with kidney failure. Blood is removed and pumped through a dialyzer, which has two key functions that are common to biological membranes:

- It contains a porous membrane that is *semi-permeable* (restricts passage of certain materials)
- It introduces fresh dialysis fluid and removes wastes to maintain an appropriate *concentration gradient*

Kidney dialysis treatments typically last about 4 hours and occur 3 times a week – these treatments can be effective for years.



Kidney Transplant

Hemodialysis ensures continued blood filtering, but does not address the underlying issue affecting kidney function

The best long-term treatment for kidney failure is a kidney transplant:

- The transplanted kidney is grafted into the abdomen, with arteries, veins and ureter connected to the recipient's vessels
- Donors must typically be a close genetic match in order to minimize the potential for graft rejection
- Donors can survive with one kidney and so may commonly donate the second to relative suffering kidney failure

Human Osmoregulation

The kidneys play a very large role in human **osmoregulation** by regulating the amount of water reabsorbed from the glomerular filtrate in kidney tubules, which is controlled by hormones such as antidiuretic hormone (ADH), renin, aldosterone, and angiotensin I and II.

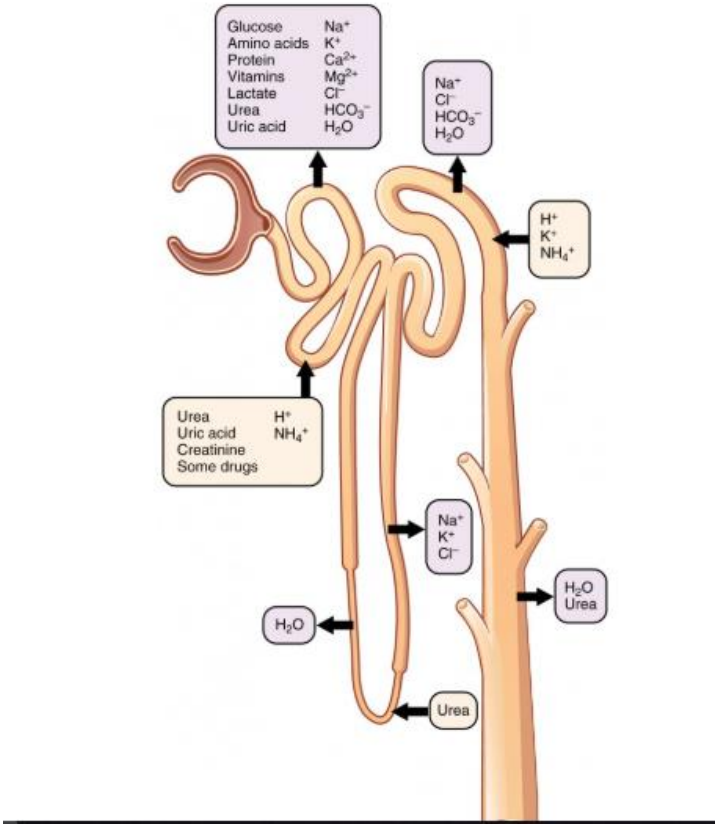
A basic example is that a decrease in water concentration of blood is detected by osmoreceptors in the hypothalamus, which stimulates ADH release from the pituitary gland to increase the permeability of the wall of the collecting ducts and tubules in the nephrons. Therefore, a large proportion of water is reabsorbed from fluid to prevent a fair proportion of water from being excreted.

The extent of blood volume and blood pressure regulation facilitated by the kidneys is a complex process. Besides ADH secretion, the renin-angiotensin feedback system is critically important to maintain blood volume and blood pressure homeostasis.

Lesson 4: Anatomy of the Nephron

Objective:

- Describe the anatomy and function of the nephron
- Explain ion concent5ration in the formation of urine



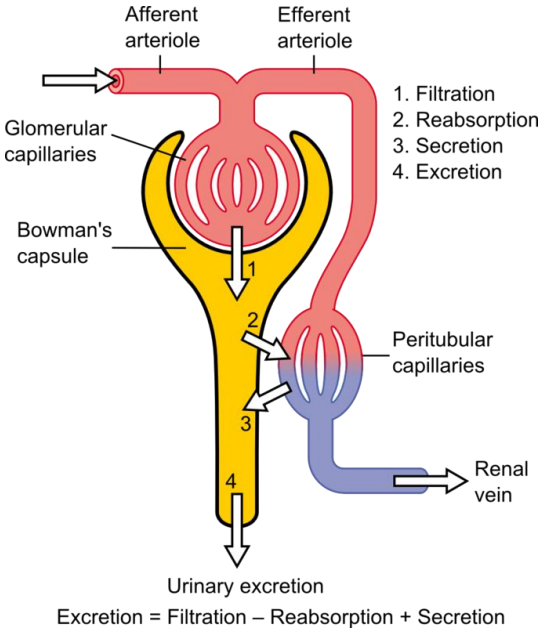
Nephron

A **nephron** is the basic structural and functional unit of the kidneys that regulates water and soluble substances in the blood by filtering the blood, reabsorbing what is needed, and excreting the rest as urine. Its function is vital for homeostasis of blood volume, blood pressure, and plasma osmolarity. It is regulated by the neuroendocrine system by hormones such as **antidiuretic hormone, aldosterone, and parathyroid hormone**.

Filtrate

The fluid filtered from blood, called **filtrate,** passes through the nephron and much of the filtrate and its contents are reabsorbed into the body. **Reabsorption** is a finely tuned process that is altered to maintain homeostasis of blood volume, blood pressure, plasma osmolarity, and blood pH. Reabsorbed fluids, ions, and molecules are returned to the bloodstream through the peri-tubular capillaries and are not excreted as urine.

Mechanisms of Reabsorption

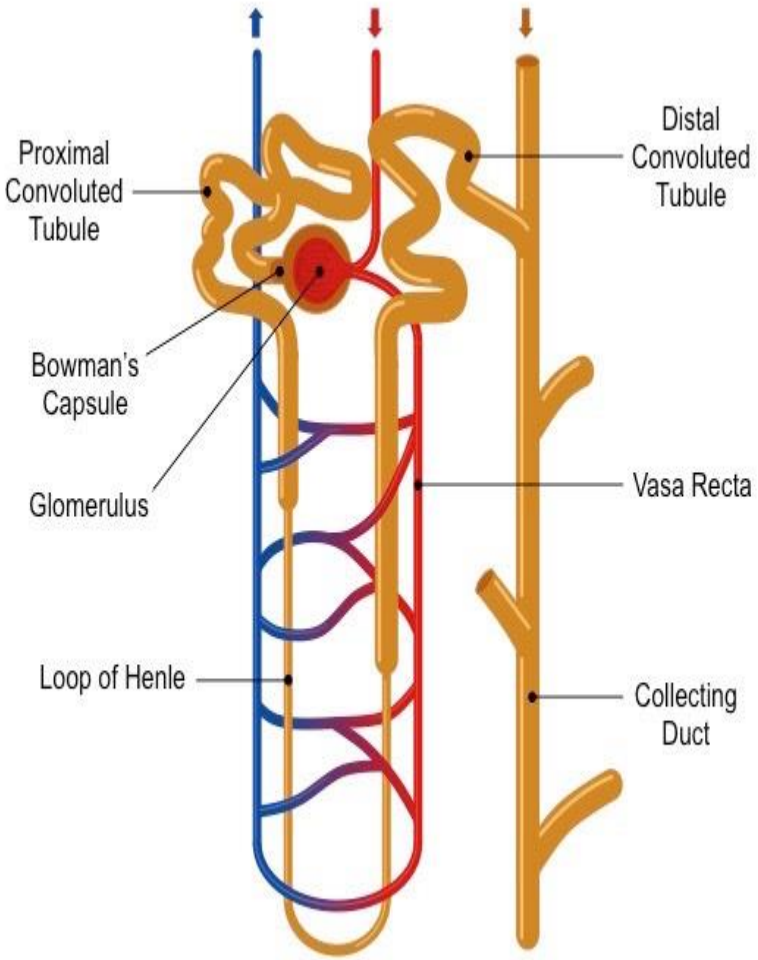


Reabsorption in the nephron may be either a passive or active process, and the specific permeability of each part of the nephron varies considerably in terms of the amount and type of substance reabsorbed. The mechanisms of reabsorption into the peri-tubular capillaries include:

- Passive diffusion—passing through plasma membranes of the kidney epithelial cells by concentration gradients.
- Active transport—membrane-bound ATPase pumps (such as NA^+/K^+ ATPase pumps) with carrier proteins that carry substances across the plasma membranes of the kidney epithelial cells by consuming ATP.
- Cotransport—this process is particularly important for the reabsorption of water. Water can follow other molecules that are actively transported, particularly glucose and sodium ions in the nephron.

These processes involve the substance passing though the luminal barrier and the basolateral membrane, two plasma membranes of the kidney epithelial cells, and into the peri-tubular capillaries on the other side. Some substances can also pass through tiny spaces in between the renal epithelial cells, called tight junctions.

The **nephron is the functional unit of the kidney**, with each nephron being comprised of the following components:



Bowman's capsule – first part of the nephron where blood is initially filtered (to form filtrate)

Proximal convoluted tubule – folded structure connected to the Bowman's capsule where selective reabsorption occurs

Loop of Henle – a selectively permeable loop that descends into the medulla and establishes a salt gradient

Distal convoluted tubule – a folded structure connected to the loop of Henle where further selective reabsorption occurs

The blood to be filtered enters the Bowman's capsule via an **afferent arteriole** and leaves the capsule via an **efferent arteriole**. Within the **Bowman's capsule**, the blood is filtered at a capillary tuft called the **glomerulus.** The efferent arteriole forms a blood network called the **vasa recta** that reabsorbs components of the filtrate from the nephron. Each nephron connects to a **collecting duct** (via the distal convoluted tubule), which feed into the **renal pelvis**. The collecting ducts are shared by nephrons and hence are not technically considered to be part of a single nephron.

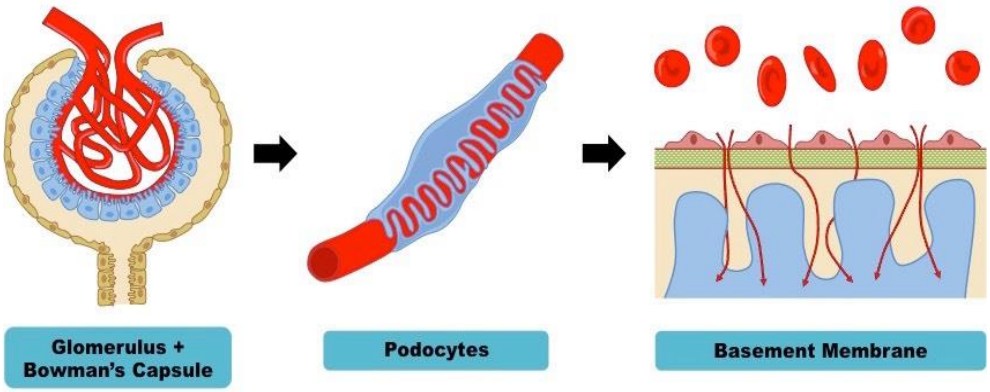
Nephron Function

Nephrons filter blood and then reabsorb useful materials from the filtrate before eliminating the remainder as urine

This process occurs over three key stages:

1. **Ultrafiltration** – Blood is filtered out of the glomerulus at the *Bowman's capsule* to form filtrate
2. **Selective reabsorption** – Usable materials are reabsorbed in *convoluted tubules* (both proximal and distal)
3. **Osmoregulation** – The *loop of Henle* establishes a salt gradient, which draws water out of the *collecting duct*

Ultrafiltration is the first of three processes by which metabolic wastes are separated from the blood and urine is formed. It is the non-specific filtration of the blood under high pressure and occurs in the Bowman's capsule of the nephron. As the blood moves into the kidney via afferent arterioles it enters a knot-like capillary tuft called a glomerulus. This glomerulus is encapsulated by the Bowman's capsule, which is comprised of an inner surface of cells called **podocytes.** Podocytes have cellular extensions called **pedicels** that wrap around the blood vessels of the glomerulus. Between the podocytes and the glomerulus is a glycoprotein matrix called the **basement membrane** that filters the blood.

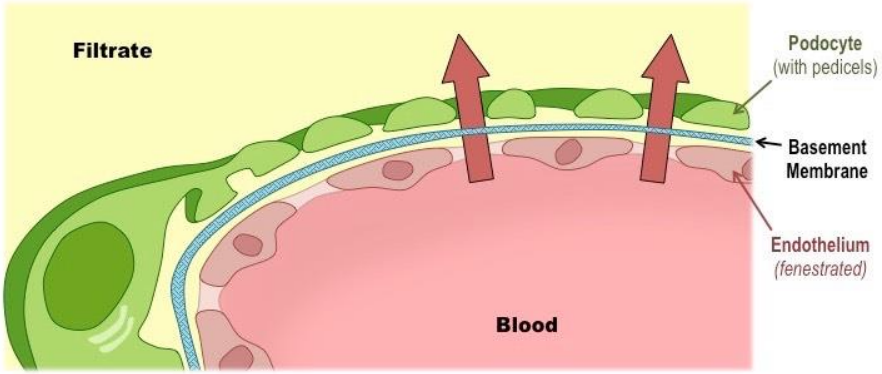


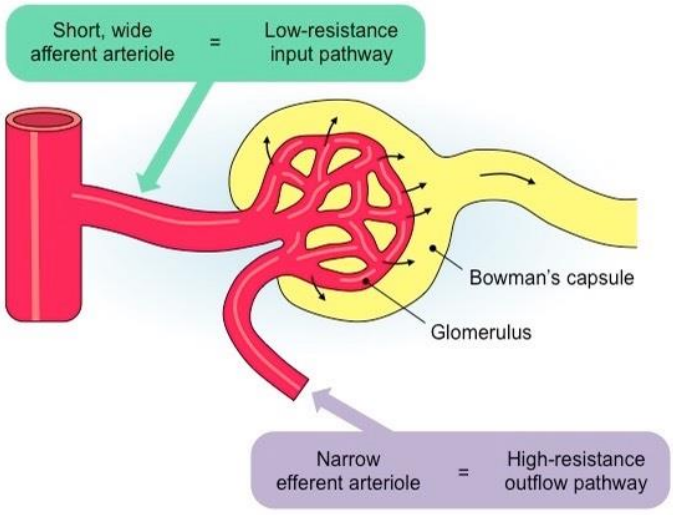
Basement Membrane

Blood is filtered by a mesh called the **basement membrane**, which lies between the glomerulus and Bowman's capsule. Glomerular blood vessels are fenestrated (have pores) which means blood can freely exit the glomerulus. The podocytes of the Bowman's capsule have gaps between their pedicels, allowing for fluid to move freely into the nephron. Consequently, the basement membrane functions as the sole filtration barrier within the nephron. The basement membrane is size-selective and restricts the passage of blood cells and large proteins. Hence when the blood is filtered, the filtrate formed does not contain any blood cells, platelets or plasma proteins.

Hydrostatic Pressure

Ultrafiltration involves blood being forced at *high pressure* against the basement membrane, optimizing filtration. This high **hydrostatic pressure** is created in the glomerulus by having a wide afferent arteriole and a narrow efferent arteriole. This means it is easy for blood to enter the glomerulus, but difficult for it to exit – increasing pressure within the glomerulus. Additionally, the glomerulus forms extensive narrow branches, which increases the surface area available for filtration. The net pressure gradient within the glomerulus forces blood to move into the capsule space (forming filtrate)

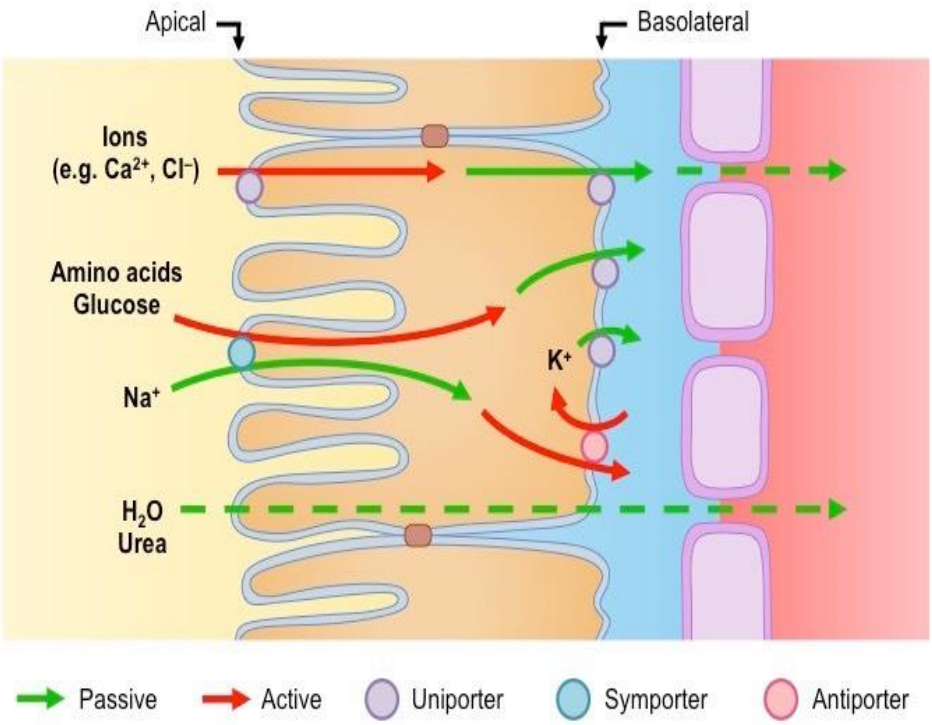




Selective reabsorption is the second of the three processes by which blood is filtered and urine is formed. It involves the reuptake of useful substances from the filtrate and occurs in the convoluted tubules (proximal and distal). Most of the selective reabsorption occurs in the **proximal convoluted tubule,** which extends from the Bowman's capsule

The proximal convoluted tubule has a **microvilli** cell lining to increase the surface area for material absorption from the filtrate. The tubule is a single cell thick and connected by *tight junctions*, which function to create a thin tubular

surface with no gaps. There are also many mitochondria within these tubule cells, as reabsorption involves **active transport.** Substances are actively transported across the apical membrane (membrane of tubule cells facing the tubular lumen). Substances then passively diffuse across the **basolateral membrane** (membrane of tubule cells facing the blood). The tubules reabsorb all glucose, amino acids, vitamins and hormones, along with most of the mineral ions (~80%) and water. Mineral ions and vitamins are actively transported by protein pumps and carrier proteins respectively. Glucose and amino acids are co-transported across the apical membrane with sodium (symport). Water follows the movement of the mineral ions passively via osmosis.

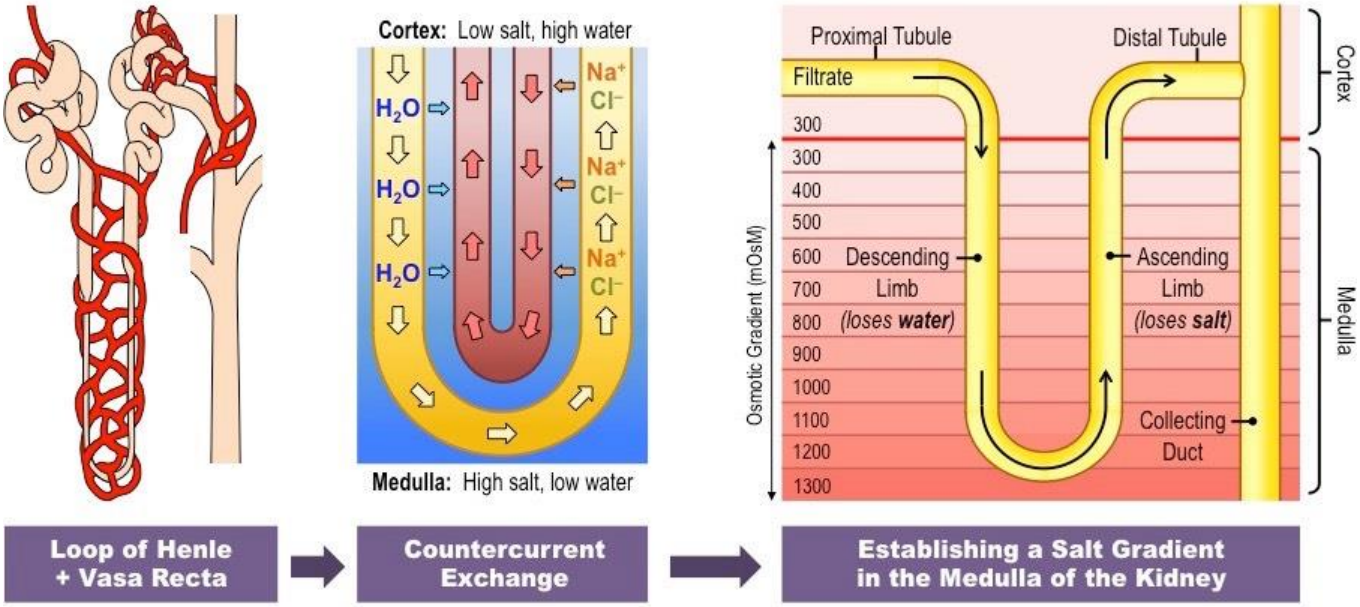


Osmoregulation is the third of three processes by which blood is filtered and urine is formed. **Osmoregulation** is the control of the water balance of the blood, tissue or cytoplasm of a living organism. Osmoregulation occurs in the medulla of the kidney and involves two key events:

- The loop of Henle establishes a salt gradient (hypertonicity) in the medulla
- Anti-diuretic hormone (ADH) regulates the level of water reabsorption in the collecting duct

Establishing a Salt Gradient

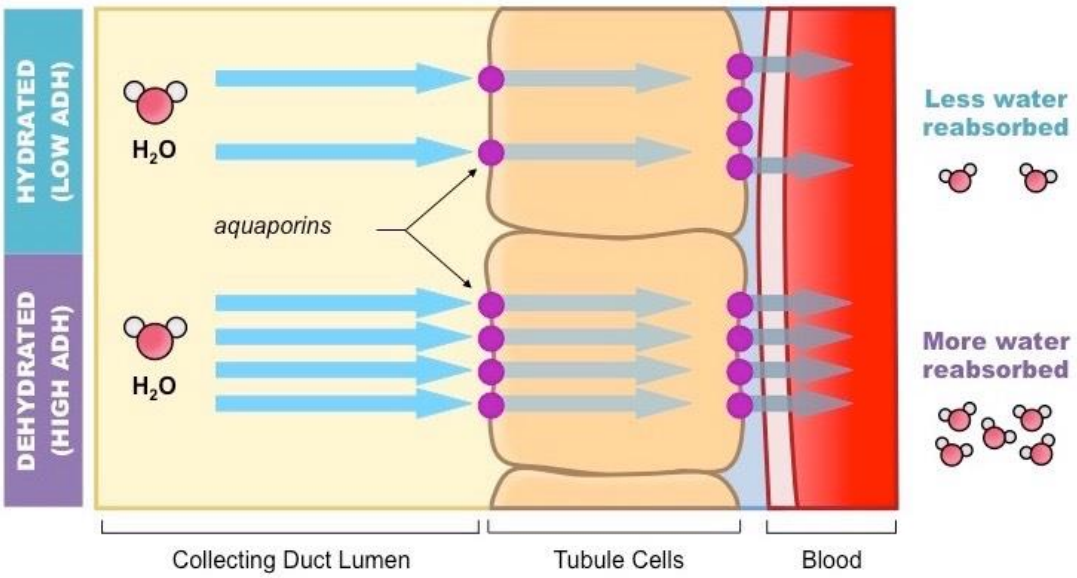
The function of the **loop of Henle** is to create a high solute (hypertonic) concentration in the tissue fluid of the medulla. The *descending* limb of the loop of Henle is permeable to **water** but <u>not</u> salts. The *ascending* limb of the loop of Henle is permeable to **salts** but <u>not</u> water. This means that as the loop descends into the medulla, the interstitial fluid becomes saltier and more hypertonic. Additionally, the vasa recta blood network that surrounds the loop of Henle flows in the opposite direction (counter-current). This means that salts released from the ascending limb are drawn down into the medulla, further establishing a salt gradient.



Water Reabsorption

As the collecting duct passes through the medulla, the hypertonic conditions of the medulla will draw water out by osmosis. The amount of water released from the collecting ducts to be retained by the body is controlled by **anti-diuretic hormone (**ADH). ADH is released from the posterior pituitary in response to dehydration (detected by osmoreceptors in the hypothalamus). ADH increases the permeability of the collecting duct to water, by upregulating production of aquaporins (water channels). This means less water remains in the filtrate, urine becomes concentrated and the individual urinates less (i.e. anti-diuresis). When an individual is suitably hydrated, ADH levels decrease and less water is reabsorbed (resulting in more dilute urine). *Remember:* **ADH** is produced when you **A**re **D**e**H**ydrated

Maintaining an appropriate water balance within the body's tissues and cells is critical to the survival of an organism. Homeostasis cannot be maintained if water levels drop (dehydration) or are raised (overhydration) without regulation

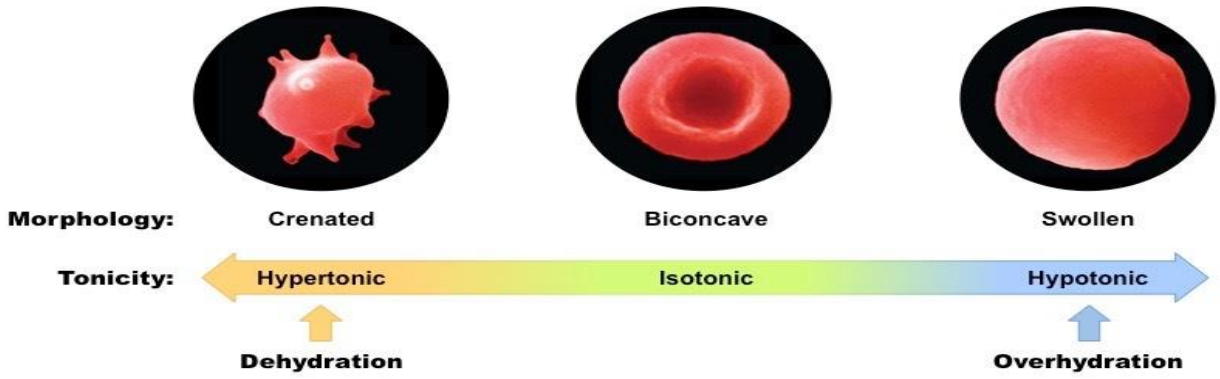


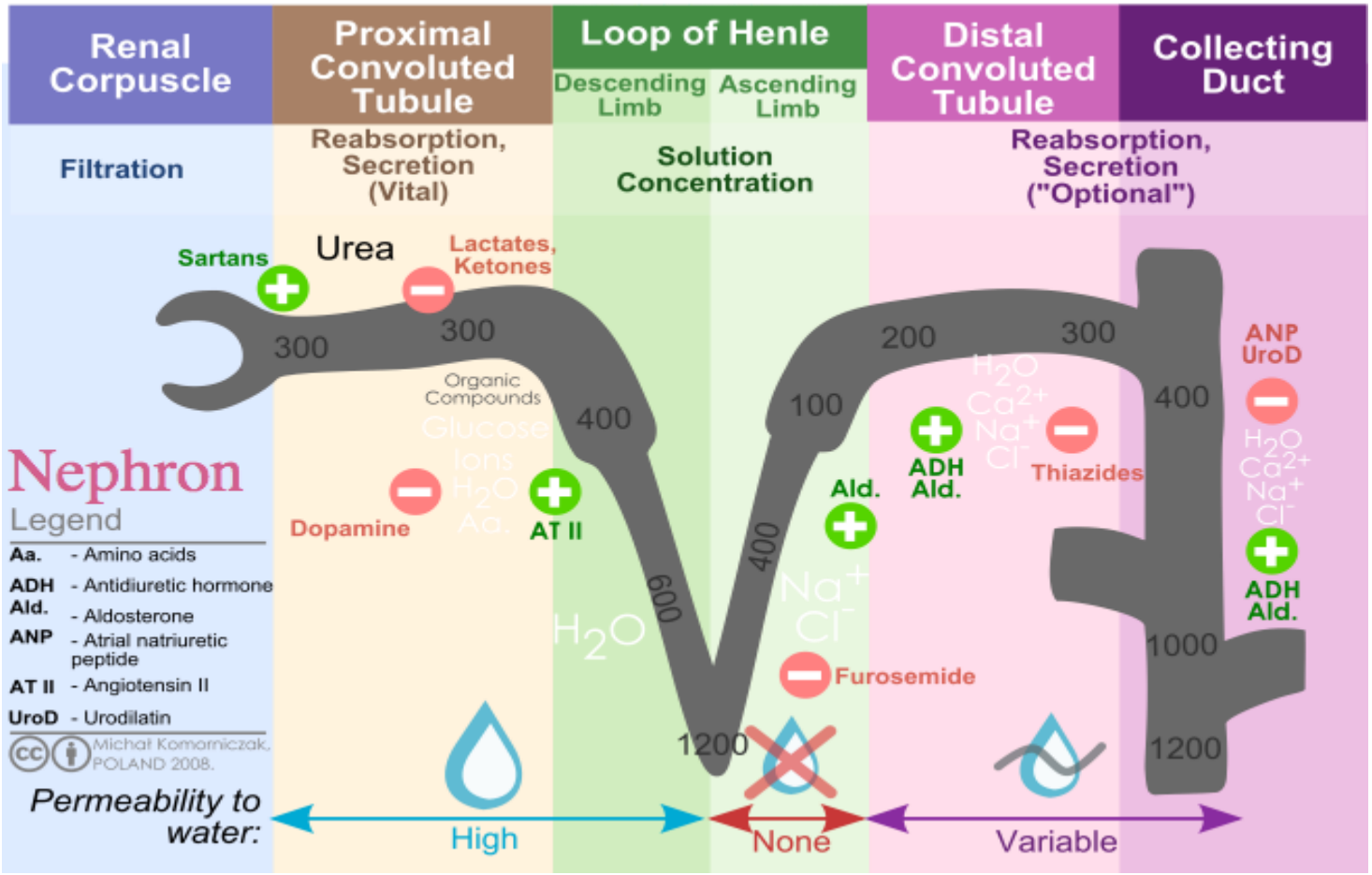
Dehydration

Dehydration is a loss of water from the body such that body fluids become hypertonic. Individuals will experience thirst and excrete small quantities of heavily concentrated urine (to minimize water loss). Blood pressure will drop (less water in plasma) and the heart rate will increase to compensate for this. The individual will become lethargic and experience an inability to lower body temperature (due to lack of sweat). Severe cases of dehydration may cause seizures, brain damage and eventual death

Overhydration

Overhydration is a less common occurrence that results when an over-consumption of water makes body fluids hypotonic. Individuals will produce excessive quantities of clear urine in an effort to remove water from the body. The hypotonic body fluids will cause cells to swell (due to osmotic movement), which can lead to cell lysis and tissue damage. Overhydration can lead to headaches and disrupted nerve functions in mild cases (due to swelling of cells). In severe cases, overhydration may lead to blurred vision, delirium, seizures, coma and eventual death


Morphology:
Crenated
Biconcave
Swollen
Tonicity:
Hypertonic
Isotonic
Hypotonic
Dehydration
Overhydration


Renal Corpuscle
Proximal Convoluted Tubule
Loop of Henle
Descending Limb
Ascending Limb
Distal Convoluted Tubule
Collecting Duct
Filtration
Reabsorption, Secretion (Vital)
Solution Concentration
Reabsorption, Secretion ("Optional")
Sartans
Urea
Lactates, Ketones
300
300
Organic Compounds
Glucose
Ions
H_2O
Aa.
400
Dopamine
AT II
600
H_2O
400
Ald.
Na^+
Cl^-
Furosemide
1200
100
200
300
H_2O
Ca^{2+}
Na^+
Cl^-
ADH
Ald.
Thiazides
400
ANP
UroD
H_2O
Ca^{2+}
Na^+
Cl^-
ADH
Ald.
1000
1200
Nephron
Legend
Aa. - Amino acids
ADH - Antidiuretic hormone
Ald. - Aldosterone
ANP - Atrial natriuretic peptide
AT II - Angiotensin II
UroD - Urodilatin
Michał Komorniczak, POLAND 2008.
Permeability to water:
High
None
Variable

Lesson 5: Urine

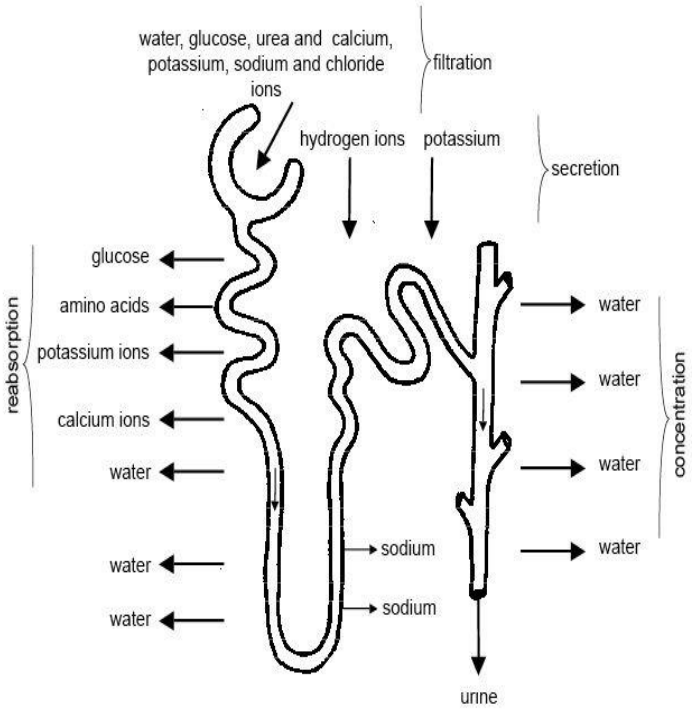
Objective:

- **Describe how normal urine consists of water, urea, salts and pigments**

Urine, a typically sterile liquid by-product of the body, is secreted by the kidneys through a process called **urination** and excreted through the urethra. Urine is often used as a diagnostic feature for many disease conditions. These may be based on either physical or chemical components, that may give insight to processes within the body, often through urinalysis, a common clinical analysis of urine.

Physical Characteristics

Physical characteristics that can be applied to urine include color, turbidity (transparency), smell (odor), pH (acidity – alkalinity) and density. Abnormalities in any of these of physical characteristics may indicate disease or metabolic imbalances. These problems may seem superficial or minor on their own but can be the symptoms for more serious diseases, such as diabetes mellitus, or a damaged glomerulus.



Chemical Composition of Urine

The normal chemical composition of urine is mainly water content, but it also includes nitrogenous molecules, such as **urea**, as well as **creatinine** and other metabolic waste components.

Other substances may be excreted in urine due to injury or infection of the glomeruli of the kidneys, which can alter the ability of the nephron to reabsorb or filter the different components of blood plasma.

Normal Chemical Composition of Urine

Urine is an aqueous solution of greater than 95% water, with a minimum of these remaining constituents, in order of decreasing concentration:

- Urea 9.3 g/L.
- Chloride 1.87 g/L.
- Sodium 1.17 g/L.
- Potassium 0.750 g/L.
- Creatinine 0.670 g/L.
- Other dissolved ions, inorganic and organic compounds (proteins, hormones, metabolites).

Urine is sterile until it reaches the **urethra,** where epithelial cells lining the urethra are colonized by facultatively anaerobic gram-negative rods and cocci. Urea is essentially a processed form of **ammonia** that is non-toxic to mammals, unlike ammonia, which can be highly toxic. It is processed from ammonia and carbon dioxide in the liver.

Abnormal Types of Urine

There are several conditions that can cause abnormal components to be excreted in urine or present as abnormal characteristics of urine. They are mostly referred to by the suffix -uria. Some of the more common types of abnormal urine include:

- Proteinuria—Protein content in urine, often due to leaky or damaged glomeruli.
- Oliguria—An abnormally small amount of urine, often due to shock or kidney damage.
- Polyuria—An abnormally large amount of urine, often caused by diabetes.
- Dysuria—Painful or uncomfortable urination, often from urinary tract infections.
- Hematuria—Red blood cells in urine, from infection or injury.
- Glycosuria— Glucose in urine, due to excess plasma glucose in diabetes, beyond the amount able to be reabsorbed in the proximal convoluted tubule.

Regulation of Urine Concentration and Volume

Antidiuretic hormone (ADH) is produced by the pituitary gland to control the amount of water that is reabsorbed through the collecting ducts.

Urine is produced not only to eliminate many cellular waste products, but also to control the amount of water in the body. In a way, urine volume regulation is part of homeostasis, in that it directly regulates blood volume, because greater amounts of urine will reduce the volume of waters in blood.

There are a few complex systems involved in regulating blood volume and urine production, such as the intricate renin–angiotensin system, and the simpler anti-diuretic hormone (ADH) feedback system.

Anti-Diuretic Hormone Feedback

An **anti-diuretic** is a substance that decreases urine volume, and ADH is the primary example of it within the body**. ADH** is a hormone secreted from the posterior pituitary gland in response to increased plasma osmolarity (i.e., increased ion concentration in the blood), which is generally due to an increased concentration of ions relative to the volume of plasma, or decreased plasma volume.

The increased plasma **osmolarity** is sensed by osmoreceptors in the hypothalamus, which will stimulate the posterior pituitary gland to release ADH. ADH will then act on the nephrons of the kidneys to cause a decrease in plasma osmolarity and an increase in urine osmolarity.

ADH increases the permeability to water of the distal convoluted tubule and collecting duct, which are normally impermeable to water. This effect causes increased water reabsorption and retention and decreases the volume of urine produced relative to its ion content.

After ADH acts on the nephron to decrease plasma osmolarity (and leads to increased blood volume) and increase urine osmolarity, the osmoreceptors in the hypothalamus will inactivate, and ADH secretion will end. Due to this response, ADH secretion is a form of negative feedback.

Diuretics

A diuretic is any substance that has the opposite effect of ADH— they increase urine volume, decrease urine osmolarity, lead to an increased plasma osmolarity, and often reduced blood volume. Many substances can act as diuretics, albeit with different mechanisms.

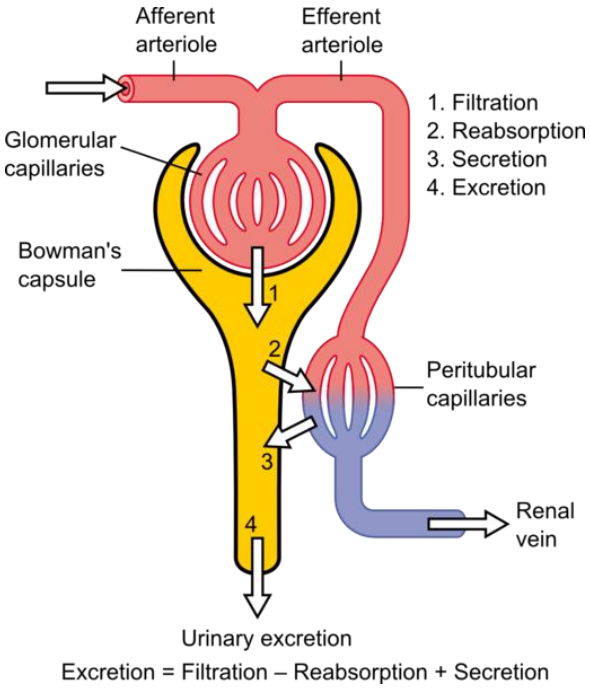
A common example is alcohol and water ingestion, which directly inhibit ADH secretion in the pituitary gland. Alternatively, caffeine is a diuretic because it interferes with sodium reabsorption (reducing the amount of water reabsorbed by sodium cotransport) and increases the glomerular filtration rate by temporarily increasing blood pressure. Many medications are diuretics because they inhibit the ATPase pumps, thus slowing water reabsorption further.

Summary of the process of urine formation: As the fluid flows along the proximal convoluted tubule useful substances like glucose, water, salts, potassium ions, calcium ions, and amino acids are reabsorbed into the blood capillaries that form a network around the tubules. Many of these substances are transported by active transport and energy is required.

Clearance

In renal physiology, **clearance** is a measurement of the renal excretion ability, which measures the amount of plasma from which a substance is removed from the body over an interval of time. Each substance has its own specific clearance that depends on its unique filtration characteristics.

Clearance is a function of glomerular filtration, secretion from the peritubular capillaries to the nephron, and reabsorption from the nephron back to the peritubular capillaries. Clearance can be either a constant or variable component over time, depending on the type of substance.



Clearance Mechanisms

Renal clearance depends mainly on GFR, tubular absorption, and tubular secretion. If any of those variables change, the renal clearance rate of a substance will change as well. These variables alter clearance through the following rules:

- Increased GFR will increase clearance, while decreased GFR will decrease clearance.
- Increased tubular secretion will increase clearance, while decreased tubular secretion will decrease clearance. This variable is sometimes altered through changes in the expression of ATPase pumps involved in active transport.
- Increased tubular reabsorption will decrease clearance, while increased tubular reabsorption will increase clearance.

Additionally, the characteristics of the substance of interest will also determine some components of clearance. For example, certain pharmaceuticals have the tendency to bind to plasma proteins or exist unbound in plasma. Only those that are unbound will be filtered and cleared from the body. Size and molecular structure will also alter the clearance rate.

It is also important to note that renal clearance is not the only form of clearance that occurs for the substances within the plasma of the body. The other types of clearance are

- Biliary (through bile).
- Salivary
- Pulmonary clearance (removed during alveolar gas exchange).

These types of clearance may also excrete certain molecules from the bloodstream based on their size and molecular structure; however, these forms of clearance are generally relatively minor compared to renal clearance. These types of clearance all add up to a summation known as total body clearance, which refers to the removal of a substance from the plasma over time, incorporating all routes of removal in the body.