Chapter 7

Digestive System

♦ Overview

-The cells in our bodies perform a wide variety of activities such as protein synthesis, cell division, and active transport of substances across cell membranes.

-Food must be consumed in order to provide the energy for these cellular activities.

-However, the food that you ingest typically contains polymers, which are too large to be used by the cells of the body.

-Therefore, the polymers in food must first be broken down into monomers that are small enough to be taken up by cells and then used for energy.

-The process by which the polymers in food are broken down into their constituent monomers is called digestion.

-Digestion involves digestive enzymes that catabolize (break down) the polymers in the food in the lumen of the digestive tract (Figure 7.1, Derrickson).

As the monomers are released, they are absorbed from the lumen of the digestive tract into the blood and then transported to the cells in the rest of the body.

Once inside of the cells, the monomers are further broken down via the process of cellular (aerobic) respiration in order to provide ATP as the energy source for different cellular activities:

-The organs of the digestive system are divided into 2 main groups (Figure 7.2, Derrickson):

1. gastrointestinal (GI) tract
   -consists of organs that collectively form a continuous tube:

   mouth → pharynx → esophagus → stomach → small intestine → large intestine → anus

2. accessory organs
   -connected to but are not continuous with the organs of the GI tract
   a. teeth
   b. tongue
   c. salivary glands
   d. pancreas
   e. liver
   f. gallbladder

-The digestive system performs six basic processes: ingestion, secretion, motility, digestion, absorption, and defecation (Figure 24.2, Tortora).
Histology of the GI Tract

In general, the organs of the GI tract consist of the same 4 layers: the mucosa, submucosa, muscularis, and serosa (Figure 24.3, Tortora)

1. **mucosa**
   - inner layer of the GI tract
   - subdivided into the following:
     a. **epithelium**
        - located closest to the lumen of the GI tract
     b. **lamina propria**
        - consists of connective tissue containing collagen fibers, elastic fibers, blood vessel, and lymphatic vessels
     c. **muscularis mucosae**
        - consists of a thin layer of smooth muscle

2. **submucosa**
   - also consists of connective tissue containing collagen fibers, elastic fibers, blood vessels, and lymphatic vessels

3. **muscularis**
   - consists of either skeletal muscle or smooth muscle, depending on the organ
   - The muscularis of the mouth, pharynx, and upper esophagus contains skeletal muscle.
   - The muscularis of the rest of the GI tract (lower esophagus, stomach, small intestine, and large intestine) contains smooth muscle.
     - The smooth muscle is usually arranged into an inner circular layer and an outer longitudinal layer.
     - Contraction of the smooth muscle in the muscularis is responsible for peristalsis.

   **peristalsis**
   - wavelike contractions within the wall of the GI tract that propel food over a long distance in an analward direction
   - similar to squeezing a tube of toothpaste from the bottom to the top of the tube
   - The function of peristalsis is to propel food down the lumen of the GI tract from the esophagus to the anus.
   - Peristaltic contractions occur throughout the GI tract, but the intensity of these contractions varies depending on the location.
     - Peristaltic contractions are strong in the esophagus, moderate in the stomach, and weak in the intestines.

4. **serosa**
   - also called the **peritoneum**
   - outer layer of the GI tract
   - consists of epithelial tissue and connective tissue
Enteric Nervous System

-The **enteric nervous system (ENS)** consists of about 100 million neurons found within the wall of the GI tract.

-arranged into two plexuses (groups) of neurons (Figures 24.3 and 24.4, Tortora):
  
  1. **submucosal plexus**
     -also known as the **plexus of Meissner**
     -located in the submucosa
     -regulates GI secretion
  
  2. **myenteric plexus**
     -also known as the **plexus of Auerbach**
     -located in the muscularis
     -regulates GI motility (movement)

Autonomic Innervation of the Gastrointestinal Tract

-Parasympathetic Innervation

-Parasympathetic nerves innervate the organs of the GI tract via the Vagus (X) nerves.

-Stimulation of the parasympathetic nerves to the GI tract increases peristalsis and GI secretion of fluids (gastric juice, pancreatic juice, intestinal juice, etc.) into the GI lumen.

-Sympathetic Innervation

-The organs of the GI tract are also innervated by sympathetic nerves.

-Stimulation of sympathetic nerves to the GI tract inhibits peristalsis and GI secretion.

-In addition, stimulation of sympathetic nerves also causes vasoconstriction of the blood vessels that supply the organs of the GI tract, which results in shunting blood away from these organs.

The Organs of the Digestive System

1. **mouth**

-contains the oral cavity

-surrounded by the following (Figure 24.6, Tortora):
  
  a. **lips**
  b. **cheeks**
  c. **hard palate**
     -forms the anterior region of the roof of the mouth
     -consists of bones (maxilla and palatine) covered by a mucosa
  d. **soft palate**
     -forms the posterior region of the roof of the mouth
     -consists of skeletal muscle that is covered by a mucosa
     -The **uvula** is an extension of the soft palate.

-During **deglutition** (swallowing), the soft palate closes off the entrance to the nasal cavity, thereby preventing reflux of food into the nose (Figure 24.11, Tortora).
e. **tongue**
- forms the floor of the mouth
- consists of 2 components:
  1. **mucosa**
     - the outer layer of the tongue
     - consists of epithelium and connective tissue
     - contains taste buds and lingual glands
     - The **taste buds** of the tongue are involved in the detection of taste.
     - The **lingual glands** of the tongue are exocrine glands that secrete the enzyme **lingual lipase** into the oral cavity.
     - Lingual lipase initiates the digestion of triglycerides in small globules of fat:
       \[
       \text{lingual lipase} \hspace{1cm} \text{triglyceride} \quad \overset{\text{2 fatty acids, 1 monoglyceride}}{\rightarrow} \quad \text{in a small fat globule}
       \]
  2. **skeletal muscles**
     - form the inner layer of the tongue
     - responsible for the movements of the tongue during speech and also during ingestion
     - Posteriorly, the mouth becomes continuous with the pharynx.

2. **teeth**
   - Types of Teeth
     - An adult contains 32 **permanent teeth** (16 on the top and 16 on the bottom), which have replaced the 20 **deciduous teeth** (baby teeth) that he or she had as a child (Figure 24.9, Tortora).
     - The permanent teeth are divided into groups:
       a. incisors
       b. canines
       c. premolars (bicuspids)
       d. molars (tricuspids)
   - Connections
     - The teeth insert into the **sockets** of the alveolar processes of the maxilla and mandible (Figure 24.8, Tortora).
     - The border of the alveolar processes is lined by a mucosa called the **gingivae (gums)**.
     - Each tooth is held in the alveolar socket by a **periodontal ligament**.
       - Recall that the joint formed between each tooth and the alveolar socket via the periodontal ligament is called a gomphosis, which is a type of synarthrosis (immovable joint).
-Structure (Figure 24.8, Tortora)
  -External Anatomy
    -A tooth consists of 3 external regions:
      a. **crown**
         -the exposed part of the tooth that is above the gingiva
      b. **neck**
         -the part of the tooth that is flush (i.e. continuous) with the gingiva
         -connects the crown with the root
      c. **root**
         -the part of the tooth that is below the gingiva and inserts into the alveolar socket
  
  -Internal Anatomy
    -A tooth has the following internal layers:
      a. **enamel**
         -the outer layer
         -calcified substance that is harder than bone
         -In fact, enamel is the hardest substance in the body, which should be the case since it has to crush and tear food for the duration of your lifetime.
         -Enamel is harder than bone because it contains more hydroxyapatite (i.e. crystals of calcium phosphate) compared to bone.
         -Hydroxyapatite crystals make up 97% of enamel’s weight, whereas they comprise only 65% of the weight of bone.
      b. **dentin**
         -the middle layer
         -forms the majority of the tooth
         -calcified substance that has a hardness that is intermediate between bone and enamel
         -Hydroxyapatite crystals constitute about 70% of dentin’s weight.
      c. **pulp cavity**
         -located internally to dentin
         -contains **pulp**, which consists of connective tissue containing blood vessels and nerves
         -In the crown and neck of the tooth, the pulp cavity is dilated.
         -However, in the root, the pulp cavity tapers off, forming the **root canal**, which eventually opens up at the end of the tooth as the **apical foramen**.
  
  -Function
    -The teeth crush and tear food during mastication (chewing).
3. salivary glands
-exocrine glands that produce saliva
-Types
-There are 3 pairs of salivary glands (Figure 7.3, Derrickson).
  a. parotid glands
     -located anterior to each ear
  b. submandibular glands
     -located beneath the mandible
  c. sublingual glands
     -located beneath the tongue
-Note that each salivary gland has a duct that empties a portion of
the saliva into the oral cavity.

-Function
-The salivary glands produce about 1 L of saliva each day.

  saliva
  -Composition
    a. H₂O
       -constitutes 99% of saliva
       -The H₂O in saliva dissolves any food taken into the
mouth.
    b. ions (HCO₃⁻, Na⁺, K⁺, and, Cl⁻)
       -The HCO₃⁻ ions in saliva buffer any ingested food that
is acidic (like tomato sauce).
    c. salivary amylase
       -enzyme that hydrolyzes a large starch molecule into
       several short chains of glucose molecules called
       α-dextrins.

        salivary
        starch → α-dextrins
        amylase

d. mucus
   -The mucus in saliva lubricates food.
e. lysozyme
   -an enzyme that destroys bacteria
   -The lysozyme in saliva protects the mouth from
   pathogens.
f. lingual lipase
   -Recall that lingual lipase is produced by the lingual glands
   of the tongue, not by the salivary glands.
   –Nevertheless, once it is secreted by the lingual glands it
   then mixes with the other components of saliva.
4. pharynx
   -also called the throat
   -a tube that is located between the nasal cavity and the esophagus (Figure 7.4, Derrickson)
   -Structure
      -Anatomy
         -The pharynx consists of 3 regions (Figure 23.3b, Tortora):
           a. nasopharynx
              -the region of the pharynx that is continuous with the nasal cavity
           b. oropharynx
              -the region of the pharynx that is continuous with the oral cavity (mouth)
           c. laryngopharynx
              -the region of the pharynx that is continuous with the larynx and with the esophagus
      -Histology
         -The pharynx consists of an inner mucosa and an outer muscularis that consists of skeletal muscle.
   -Functions
      -The pharynx is involved in 2 major functions:
        a. It serves as a passageway for the movement of food and beverages from the mouth to the esophagus.
        b. It serves as a passageway for the movement of air from the nose and mouth to the larynx.

5. esophagus
   -a tube that is located between the pharynx and the stomach (Figure 7.4, Derrickson)
   -Structure
     -Histology
        -The esophagus consists of the same 4 layers as the rest of the GI tract.
        -However, the type of muscle in the muscularis varies depending on the location.
        -The muscularis in the upper half of the esophagus consists of skeletal muscle, while the muscularis in the lower half of the esophagus contains smooth muscle.
        -Each end of the esophagus is modified into a sphincter:
          a. upper esophageal sphincter (UES)
             -consists of skeletal muscle
          b. lower esophageal sphincter (LES)
             -consists of smooth muscle
     -sphincter
        -a region of muscle that regulates the opening to the lumen of an organ
-Function
- The esophagus serves as a passageway for the movement of food and beverages from the pharynx to the stomach (Figure 24.11, Tortora).
- During swallowing, the UES opens to allow food to enter into the esophagus from the pharynx.

Once food is in the esophagus, the UES closes, preventing reflux of food into the pharynx.

Food is then propelled down the esophagus via peristalsis.

The LES opens in order to allow the food to move out of the esophagus and into the stomach.

Once the esophagus is empty, the LES closes in order to prevent reflux of food and gastric contents into the esophagus.

6. stomach
- The stomach is located between the esophagus and the small intestine.
- Structure
- Anatomy
- The stomach consists of 4 major regions (Figure 24.12, Tortora):
  a. cardia
     - the initial region of the stomach
     - The cardia is separated from the esophagus via the lower esophageal sphincter (LES).
  b. fundus
     - the region of the stomach that is superior and lateral to the cardia
  c. body
     - the large, central region of the stomach
  d. pylorus
     - the terminal region of the stomach
     - divided into 2 subcomponents:
       1. pyloric antrum
          - located closest to the body of the stomach
       2. pyloric canal
          - located closest to the duodenum of the small intestine
- The pyloric canal is separated from the duodenum by the **pyloric sphincter**, which consists of smooth muscle.

- **Histology**
  - The stomach consists of the same 4 layers as the rest of the GI tract: the mucosa, submucosa, muscularis, and serosa (Figure 24.13, Tortora).

- **Functions**
  - The stomach has several functions:
    a. The stomach produces gastric juice.

  **gastric juice**
  - **Volume**
    - Each day the stomach secretes about 2 L of gastric juice.

- **Source**
  - Gastric juice is produced by **gastric glands** that are located in the mucosal epithelium of the stomach (Figure 24.13, Tortora).
  - Each gastric gland contains 4 cell types:
    1. **mucous neck cells**
      - secrete mucus into the stomach lumen
    2. **parietal cells**
      - secrete hydrochloric acid (HCl) and intrinsic factor (IF) into the stomach lumen.
    3. **chief cells**
      - also called **zymogenic cells**
      - secrete pepsinogen and gastric lipase into the stomach lumen
        - Note that pepsinogen is the inactive form of the enzyme pepsin.
        - Pepsinogen is converted into the active form pepsin via HCl.
    4. **G cells**
      - enteroendocrine cells that secrete the hormone **gastrin** into the blood

- **Composition**
  1. **HCl**
    - a strong acid
    - causes gastric juice to have a low pH value of 2
    - kills pathogens in food and it provides the acidic pH that is required for pepsin and gastric lipase to function.
  2. **pepsin**
    - a **protease** that catabolizes proteins into smaller peptides (Figure 7.5, Derrickson)
    - Pepsin functions only in an acidic environment, which is provided by the HCl in gastric juice.
-Note that pepsin is an unusual enzyme in this respect; most other enzymes in the digestive tract (and in the body) require a neutral to slightly alkaline pH (i.e. a pH of 7 to 8) to function optimally.

3. **gastric lipase**
   - Like lingual lipase, gastric lipase is an enzyme that catabolizes triglycerides in a small fat globule into fatty acids and monoglycerides.
   - Like pepsin, gastric lipase also requires an acidic pH to function.

4. **mucus**
   - The mucus found in gastric juice coats the surface of the gastric mucosa, thereby protecting these cells from HCl.

5. **intrinsic factor**
   - A protein that helps vitamin B₁₂ undergo absorption in the small intestine
   - We obtain Vitamin B₁₂ from the diet (meat and dairy products) and it is necessary for erythropoiesis.
   - If intrinsic factor is not produced, vitamin B₁₂ will not undergo absorption and the individual will have difficulty producing red blood cells—a condition called pernicious anemia.

b. The stomach converts food into chyme.
   - Once food enters the stomach, the muscularis in the lower body and pylorus of the stomach contracts and the food is mixed with gastric juice. The HCl, pepsin, and gastric lipase in the gastric juice further break down the large particles in food into smaller particles, resulting in the formation of chyme. Therefore, chyme is a thin, soupy mixture that consists of partially digested food and digestive fluids.

   ![Diagram of stomach and chyme](image)

   Some of the chyme moves through the pyloric sphincter and into the duodenum of the small intestine, a process called **gastric emptying**. Gastric emptying is a slow process: only 2 mL of chyme are emptied at any given time. Realize that gastric emptying should be a slow process in order to prevent the small intestine from being overloaded with chyme.

c. The stomach stores food.
   - About 2 L of food can be stored temporarily in the fundus and upper body of the stomach while waiting to be converted into chime.

d. The stomach produces the hormone gastrin.
   - G cells in gastric glands secrete the hormone gastrin into the blood.
7. pancreas
  - The pancreas is a gland that is posterior to the stomach and lateral to the duodenum of the small intestine (Figure 7.6, Derrickson).

-Structure
  -Anatomy
    - The pancreas consists of 3 external components:
      a. head
      b. body
      c. tail

-Histology
  - The pancreas is both an endocrine gland and an exocrine gland.

-Internally, the pancreas consists of 2 major components:

  a. **pancreatic islets**
     - also called **islets of Langerhans**
     - comprise 1% of the total weight of the pancreas and are found scattered throughout the pancreas
     - Each pancreatic islet consists of a cluster of endocrine cells:
       1. **alpha (α) cells**
          - secrete the hormone **glucagon** into the blood
       2. **beta (β) cells**
          - secrete the hormone **insulin** into the blood

  b. **acini**
     - constitute about 99% of the total weight of the pancreas
     - Each acinus consists of several exocrine cells called **acinar cells** that secrete pancreatic juice into a small duct.

The small ducts that surround the acinar cells empty into the large **pancreatic duct (duct of Wirsung)**.

The pancreatic duct unites with the **common bile duct** to form the **hepatopancreatic ampulla (ampulla of Vater)**, which opens into the lumen of the duodenum. The opening of the hepatopancreatic ampulla is regulated by a region of smooth muscle that is called the **sphincter of the hepatopancreatic ampulla (sphincter of Oddi)**.
-Functions
- The pancreas is involved in 3 major functions:
  a. The pancreas produces pancreatic juice.

  **pancreatic juice**
  - Source
    - The acinar cells of the pancreas secrete about 2 L of pancreatic juice into the pancreatic duct on a daily basis.
  - Composition
    1. H$_2$O
      - the main component
    2. ions (HCO$_3^-$, Na$^+$, Cl$^-$, and K$^+$)
      - The HCO$_3^-$ causes the pancreatic juice to have a slightly alkaline pH of 7.5 to 8.
    3. enzymes
      - Pancreatic juice contains many types of digestive enzymes that continue to digest food particles in the chyme that enters the lumen of the small intestine.

  a. proteases
    1. trypsin
    2. chymotrypsin
    3. elastase
    4. carboxypeptidase

    - Trypsin, chymotrypsin, and elastase catabolize proteins into smaller peptides; carboxypeptidase (along with the small intestinal brush border enzyme aminopeptidase) cleaves off individual amino acids from smaller peptides (Figure 7.5, Derrickson).

    - Figure 7.7 (Derrickson) illustrates the sites where digestive proteases cleave dietary proteins.

    - Pancreatic proteases are initially released as inactive precursors (trypsinogen, chymotrypsinogen, proelastase, and procarboxypeptidase).
      - Trypsinogen is first activated to trypsin by the small intestine brush border enzyme enterokinase.

      Once activated, trypsin in turn activates the remaining inactive precursors (chymotrypsinogen, proelastase, and procarboxypeptidase) to produce chymotrypsin, elastase, and carboxypeptidase, respectively.
b. **pancreatic lipase**  
-an enzyme that hydrolyze triglycerides in a small fat globule into fatty acids and monoglycerides  

\[
\text{triglyceride} \xrightarrow{\text{pancreatic lipase}} 2 \text{ fatty acids, 1 monoglyceride}
\]

(in a small fat globule)

-similar to lingual lipase and gastric lipase

c. **pancreatic amylase**  
-enzyme that hydrolyzes starch into \(\alpha\)-dextrins, which are short chains of glucose molecules  

\[
\text{pancreatic amylase} \xrightarrow{\text{starch}} \alpha\text{-dextrins}
\]

-similar to the salivary amylase in saliva

-The pancreas uses its pancreatic juice to further digest carbohydrates, proteins, and fats that are in the chyme in the lumen of the small intestine.  
- In order to achieve this goal, the sphincter of Oddi must be open during the digestion of a meal, thus allowing pancreatic juice to move into the small intestine to interact with the chyme.  
- When there is no chyme present in the small intestine, the sphincter of Oddi is closed and pancreatic juice remains in the pancreas.  
- In addition, recall that pancreatic juice is slightly alkaline (pH 7.5 to 8).  
  - This neutralizes the acid chyme that enters the duodenum from the stomach.  
  - The chyme must be neutralized because pancreatic enzymes as well as small intestinal enzymes require a neutral to slightly alkaline pH to function optimally.  
  - Also note that pancreatic enzymes and small intestinal enzymes are crucial to the digestion of a meal.  
- In the absence of these enzymes, there is malabsorption of nutrients.  
- The enzymes in saliva and gastric juice, however, are not as essential; if these enzymes do not function, pancreatic enzymes and small intestinal enzymes can still get the job done, although it make take them a little while longer.
b. The pancreas produces the hormone insulin.
   - Beta cells secrete insulin into the blood.

c. The pancreas produces the hormone glucagon.
   - Alpha cells secrete glucagon into the blood.

8. **liver**
   - The liver weighs about 3 lbs and is the largest gland in the body.
   - Located below the diaphragm (Figure 7.6, Derrickson)
   - Structure
     - Anatomy
       - The liver consists of 2 major lobes: the right lobe and the left lobe.
     - Histology
       - The liver consists of cells called **hepatocytes**.
   - Functions
     - The liver is involved in several functions:
       a. The liver screens blood for excess nutrients and toxic substances.
          - The hepatocytes screen the blood from the hepatic portal vein for excess nutrients and toxic substances.
          • If there is excess glucose, the hepatocytes take up the glucose and store it as **glycogen**.
          • Excess vitamins (A, D, E, K, and B₁₂) and minerals (iron and copper) in the blood are also removed and stored in the hepatocytes.
          • Any toxic substances (like drugs and alcohol) are removed and detoxified by the hepatocytes and then either reintroduced back into the blood or excreted into bile.

b. The liver produces **bile**.
   - The hepatocytes of the liver also produce bile and then secrete it into the **right hepatic duct** or **left hepatic duct**.

The right hepatic duct and the left hepatic duct then combine to form the **common hepatic duct**, which emerges from the liver.

The common hepatic duct combines with the **cystic duct** extending from the gallbladder to form the **common bile duct**. The common bile duct is so-named because it contains fresh bile from the liver via the hepatic ducts and stored bile from the gallbladder via the cystic duct. The common bile duct eventually unites with the **pancreatic duct** to form the **hepatopancreatic ampulla**, which empties into the duodenum. Recall that the **sphincter of Oddi** regulates the opening of the
hepatopancreatic ampulla. During the digestion of a meal, the sphincter of Oddi is open and bile is released into the duodenum to interact with chyme that is present there. When digestion is not occurring, the sphincter of Oddi is closed and any bile produced by the liver backs up into the cystic duct and then goes to the gallbladder for storage.

**Bile**

- **Volume**
  - The hepatocytes of the liver secrete about 1 L of bile on a daily basis.
  - a fluid that is yellow to green in color
  - pH is slightly alkaline (7.5 to 8)

- **Composition**
  1. \( \text{H}_2\text{O} \)
     - the major constituent
     - makes up 97% of bile
  2. cholesterol
  3. bile salts
     - derivatives of cholesterol
     - Examples (Figure 7.8, Derrickson)
       - b. glycocholate
       - c. taurocholate
     - **Bile salts are amphipathic; this means that each bile salt has a hydrophilic region and a hydrophobic region.**
  4. bile pigments
     - The main pigment found in bile is **bilirubin**, which has a yellowish green color.
     - **Origin of Bilirubin**
       - Recall that macrophages in the spleen break down worn-out red blood cells. During this process, the porphyrin ring of the heme in hemoglobin is eventually converted to bilirubin, which is subsequently released into the blood.

The hepatocytes remove the bilirubin from the blood and then secrete it as a component of bile.
-The bile salts of bile promote the emulsification of fat, which is vital to the digestion and absorption of lipids by the small intestine.

**emulsification**
- the process by which a large fat globule is converted into many small fat globules (Figure 7.8, Derrickson).
- Emulsification of fats must occur before pancreatic lipase can act on the triglycerides in the fat globule.

-Fate of Bile

Bile is released into the lumen of the duodenum.

As bile moves through the small intestine, it mixes with chyme, promoting fat emulsification.

Near the end of the small intestine, the bile salts are absorbed into the blood and eventually return back to the liver via the hepatic portal vein. The hepatocytes remove the bile salts from the blood and use them to make more bile. This process of moving the bile from the small intestine back to the liver is called the **enterohepatic circulation**, which functions to recycle the bile salts.

The rest of the bile components (H₂O, cholesterol, and bilirubin) continue into the large intestine as part of chyme and eventually become part of the feces. During this process, bilirubin is eventually converted into a brown pigment called **stercobilin**. Stercobilin is responsible for the brown color of feces (Figure 19.5, Tortora).

### 9. gallbladder

- The gallbladder is a pear-shaped organ that is located underneath the liver (Figure 7.6, Derrickson).

- **Structure**
  - The gallbladder consists of 3 internal layers:
    a. mucosa
    - inner layer
    - surrounds the lumen
    - consists of an epithelial layer and a connective tissue layer
b. smooth muscle
   - middle layer

c. serosa
   - outer layer
   - connective tissue

- Function
  - The gallbladder has 2 major functions:
    a. It stores bile.
       - When digestion is not occurring, the sphincter of Oddi is closed
         and bile backs up into the gallbladder for storage.
    b. It concentrates bile.
       - The gallbladder is a small organ and can hold about 50 mL of
         bile at one given time.
       - However, the liver secretes about 1000 mL of bile per day.
       - Hence, the gallbladder concentrates the bile (and hence reduces
         the volume) by removing some of the water.

10. small intestine
    - Location
       - The small intestine is located between the stomach and the large intestine
         (Figure 7.9, Derrickson).

    - Size
       - The small intestine has the following dimensions:
         Diameter: 1 inch
         Length: 20 feet
       ♦ The small intestine is the longest part of the digestive tract.

    - Structure
      - Anatomy
        - The small intestine consists of 3 major external regions (Figure 7.9, Derrickson):
          a. duodenum
             - the initial portion of the small intestine
             - The duodenum is separated from pyloric canal of the stomach via the
               pyloric sphincter.
          b. jejunum
             - the middle portion of the small intestine
          c. ileum
             - the terminal and longest portion of the small intestine
             - The ileum is separated from the cecum of the large intestine
               by the ileocecal sphincter.

      - Histology
        - The small intestine consists of the same 4 layers as the rest of the GI tract:
          the mucosa, submucosa, muscularis, and serosa  (Figure 7.9, Derrickson).
- Note that the mucosa of the small intestine differs from the mucosa of the rest of the GI tract due to modifications in the epithelium and lamina propria.

- The epithelium of the small intestinal mucosa contains a superficial covering and lining epithelium that is surrounded by intestinal glands called crypts of Lieberkuhn.

covering and lining epithelium
- consists of 2 types of cells:
  a. absorptive cells
     - absorb nutrients (monomers) from the lumen of the small intestine
  b. goblet cells
     - secrete mucus into the lumen of small intestine

crypts of Lieberkuhn
- also called an intestinal gland
- consists of 6 types of cells
  a. absorptive cells
     - absorb nutrients (monomers) from the lumen of the small intestine
  b. goblet cells
     - secrete mucus into the lumen of the small intestine
  c. Paneth cells
     - secrete lysozyme into the lumen of the small intestine
     - Recall that lysozyme is an enzyme that destroys bacteria; in this case, it is used to kill any bacteria that contaminate the intestinal chyme.
  d. S cells
     - enteroendocrine cells that secrete the hormone secretin into the blood
  e. I cells
     - enteroendocrine cells that secrete the hormone cholecystokinin (CCK) into the blood
  f. K cells
     - enteroendocrine cells that secrete the hormone gastric inhibitory peptide (GIP) into the blood
     - Gastric inhibitory peptide is also called glucose-dependent insulinotropic peptide.
Each day the crypts of Lieberkuhn secrete about 1 L of intestinal juice that mixes with incoming chyme, bile, and pancreatic juice.

**Intestinal juice**

- Composition
  a. **H₂O**
     - major constituent
  b. mucus
  c. ions (HCO₃⁻, Na⁺, and Cl⁻)
    - The bicarbonate ions give intestinal juice an alkaline pH, ranging from 7.5 to 8.
    - The slightly alkaline pH of intestinal juice helps to provide the ideal environment for small intestinal enzymes and for pancreatic enzymes.
    - Recall that these enzymes require a neutral to slightly alkaline pH for optimal activity.

- The lamina propria of the small intestinal mucosa contain connective tissue and lacteals.

**Lacteal**

- Unlike the rest of the GI tract, the lamina propria of the small intestine contains lacteals.
  - specialized lymphatic vessels involved in fat absorption

- The mucosa of the small intestine is folded extensively to increase surface area for absorption.

**Absorption**

- the movement of digested food (monomers) from the lumen of the gastrointestinal tract into the blood

- Most absorption occurs in the small intestine and to a lesser extent in the large intestine.

- Absorption in the small intestine occurs due to 3 types of folds:
  a. **circular folds**
     - also called **plicae circularis**
     - folds of the mucosa and submucosa
     - increase the absorptive surface area of the small intestine about 3 times
b. villi
- fingerlike projections of the mucosa caused by the folding of its epithelium cells and lamina propria
- give the small intestine a velvety appearance
- increase the absorptive surface area of the small intestine about 10 times
- Each villus contains an overlying covering and lining epithelium and a core of capillaries and lacteals from the lamina propria.
- The thin, folded structure of the villus facilitates absorption of nutrients in the small intestine:
  - Nutrients easily pass from the lumen of the small intestine through the absorptive cells covering the villus and then into the capillary or lacteal (depending on nutrient type) to complete the absorption process.

c. microvilli
- folds of the apical (luminal) membranes of the absorptive cells of the mucosa
- also referred to as the brush border because they resemble the bristles of a brush.
- increase the absorptive surface area of the small intestine about 20 times
- Collectively, the circular folds, villi, and microvilli increase the absorptive surface area of the small intestine by a factor of 600 (3 x 10 x 20)!!

- Functions
  - The small intestine has 4 major functions:

a. The small intestine completes the digestion of nutrients
  - The absorptive cells of the small intestinal mucosa possess several types of digestive enzymes that are located in their brush borders; these brush border enzymes complete the digestion of food.

- Types of brush border enzymes (Figure 7.10, Derrickson):
  1. α-dextrinase
     - hydrolyzes α-dextrins into individual glucose molecules

\[
\begin{align*}
\text{α-dextrinase} & \\
\text{α-dextrins} & \rightarrow \text{glucose molecules}
\end{align*}
\]
2. **disaccharidases**  
- hydrolyze disaccharides into monosaccharides  
- Examples:  
  a. **maltase**  
  - hydrolyzes maltose into 2 molecules of glucose  
  \[ \text{maltose} \rightarrow \text{glucose, glucose} \]  
  b. **sucrase**  
  - hydrolyzes sucrose into a molecule of glucose and a molecule of fructose  
  \[ \text{sucrose} \rightarrow \text{glucose, fructose} \]  
  c. **lactase**  
  - hydrolyzes lactose into a molecule of glucose and a molecule of galactose  
  \[ \text{lactose} \rightarrow \text{glucose, galactose} \]  

3. **aminopeptidase**  
- smaller peptide \[ \rightarrow \text{amino amino acid} \]  

-Figures 7.11, 7.12, and 7.13 (Derrickson) illustrate how various organs of the digestive system work together to digest any carbohydrates, proteins, and lipids that may be present in food that is consumed.

b. The small intestine absorbs solutes.  
- Once digestion is completed by the brush border enzymes, the monomers are then absorbed by the absorptive cells of the small intestine (Figure 7.14, Derrickson)

- **absorption of monosaccharides and amino acids**  
  - Transporters within the plasma membrane of each absorptive cell absorb any monosaccharides (glucose, galactose, or fructose) or amino acids that may be present in the small intestinal lumen.
  - Transporters are required for movement across the cell membranes of the absorptive cells because
carbohydrates and amino acids are hydrophilic, while the phospholipids in the cell membranes are hydrophobic.

- **lipid absorption**
  - Digestion of triglycerides by pancreatic lipase typically liberates monoglycerides and fatty acids, which can be either long chain fatty acids or short chain fatty acids.
  - Recall that fatty acids and monoglycerides are hydrophobic; consequently, they can move across the cell membrane of an absorptive cell without the help of a transporter.
  - Since short chain fatty acids are so small, they can be absorbed into the blood, which is hydrophilic.
  - Long chain fatty acids and monoglycerides, however, are large and hydrophobic. Thus, they cannot be absorbed into the blood directly.
    - Instead, once inside of an absorptive cell, several long chain fatty acids and monoglycerides recombine to form triglycerides. The triglycerides are then surrounded by a protein coat, forming a **chylomicron**, which is a type of **lipoprotein**.

    The chylomicrons then undergo exocytosis across the basolateral membrane of the absorptive cell and subsequently move into the **lacteals** to become part of the lymph.

    From the lymph, the chylomicrons eventually are dumped into the blood. Hence, chylomicrons increase the solubility of the long chain fatty acids and monoglycerides in the blood.

c. The small intestine absorbs H₂O.
   - The absorptive cells of the small intestine also absorb water from chyme via **osmosis** (i.e. the water follows the absorbed solute).
   - About 8 L of the 9L of fluid that enters the small intestine is absorbed (Figure 24.23, Tortora).
   - The small intestine is the major site of water absorption in the GI tract.

d. The small intestine secretes hormones.
   - These hormones include CCK, secretin, and GIP.
11. **large intestine**

- **Location**
  - The large intestine is located after the small intestine and is the last organ of the gastrointestinal tract.

- **Size**
  
  - Diameter: 2.5 inches
  - Length: 5 ft

  ✤ Compared to the small intestine, the large intestine has a greater diameter (hence the name “large”) and a shorter length.

- **Structure**
  - **Anatomy**
    - The large intestine is divided into 3 major external regions (Figure 24.24, Tortora):
      
      a. **cecum**
      - the beginning portion of the large intestine
      - The cecum is separated from the ileum of the small intestine by the **ileocecal sphincter**.
      - Attached to the lower end of the cecum is the wormlike **appendix** (also called the **vermiform appendix**).
      - In humans, the appendix is a **vestigial organ**, which means that it is a useless organ that has no known function in the body.
      - Structurally, it consists of scattered reticular connective tissue that plays an insignificant role in immunity.

      b. **colon**
      - consists of the following:
        1. **ascending colon**
        2. **transverse colon**
        3. **descending colon**
        4. **sigmoid colon**

      c. **rectum**
      - the terminal portion of the large intestine
      - At the very end of the rectum is the **anus**.
        
        - the region of the rectum that opens up to the exterior surrounded by 2 sphincters:
          1. **internal anal sphincter**
          - consists of smooth muscle
          - This sphincter is controlled involuntarily.
          2. **external anal sphincter**
          - consists of skeletal muscle
          - This sphincter is under voluntary control.
Histology

- The large intestine consists of the same 4 layers as the rest of the GI tract; however, there are some modifications in the mucosa and in the muscularis (Figure 24.25, Tortora):
  - The mucosal epithelium of the large intestine, that like of that small intestine, consists of a superficial covering and lining epithelium that is surrounded by deep crypts of Lieberkuhn:
    - consisting of
      a. absorptive cells
        - absorb H₂O from the lumen of the large intestine
      b. goblet cells
        - secrete mucus into the lumen of the large intestine

- The absorptive cells of the large intestinal mucosa do contain microvilli; however, there are no villi present.
  - Consequently, the absorptive surface area of the large intestine is significantly lower than that of the small intestine.
  - This should make sense because more absorption occurs in the small intestine than in the large intestine.

- The smooth muscle of the large intestinal muscularis is divided into bands called taenia coli that are visible underneath the serosa.
  - The taenia coli are usually contracted, causing pouches called haustra to form in the wall of the large intestine.
-Functions
-The large intestine has 3 major functions:
  a. The large intestine further processes intestinal chyme using enteric bacteria.
     -The chyme that enters into the large intestine contains water (about 1 L), waste products, undigestible materials, and the bile pigment bilirubin.
     -Recall that bile salts (but not bilirubin) were absorbed near the end of the small intestine as part of the enterohepatic circulation.
     -Living within the large intestine are enteric bacteria (usually a harmless strain of Escherichia coli); the enteric bacteria further process this chyme in the following ways:

     1. The enteric bacteria convert some of the chyme’s undigestible carbohydrates and peptides into gases like methane (CH₄), H₂, CO₂, and hydrogen sulfide (H₂S), which smells like rotten eggs. These gases contribute to intestinal flatus (also called flatulence if excessive).
        -Baked beans contain a large number of undigestible carbohydrates that typically are converted into flatus by enteric bacteria.
     2. The enteric bacteria convert bilirubin into stercobilin, a brown pigment.

  b. The large intestine absorbs H₂O.
     -The large intestine absorbs a significant amount of water, but not nearly as much as the small intestine.
     -About 900 mL of the 1 L of H₂O that enters the large intestine is absorbed; the remaining 100 mL passes out of the body as part of the feces (Figure 24.23, Tortora).

  c. The large intestine forms and stores feces.
     -As H₂O is absorbed in the large intestine, the chyme in the lumen gradually solidifies into feces.
        -Feces consists of waste products, any remaining undigestible materials, small amounts of water, bacteria, and stercobilin.
        -The stercobilin causes the feces to have a brown color.

-Defecation Reflex
-spinal reflex that involves peristaltic contractions in the wall of the rectum, thereby extruding feces out of the body

-It takes about 3 to 10 hours for food to complete its course through the digestive system.
  -Carbohydrates are digested the quickest, proteins are intermediate, and lipids take the longest.
Regulation of the Digestive System

- Phases
  - The regulation of the digestive system involves 3 **sequential** phases:

1. cephalic phase
   - the first phase
   - During this phase, the sight, smell, thought, or initial taste of food causes salivation and gastric juice production in order to prepare the GI tract for the food that is about to be digested.
   - **Mechanism**
     - The cephalic phase of digestion involves the ANS (Figure 7.15, Derrickson).

2. gastric phase
   - the second phase
   - begins as soon as food enters the stomach.
   - The following activities occur during the gastric phase of digestion:
     ♣ **gastric secretion and motility**
       - This promotes the formation of gastric chyme.
     ♣ **contraction of the LES**
       - This prevents reflux of gastric juice into the esophagus.
     ♣ **relaxation of the pyloric sphincter**
       - This promotes gastric emptying.
     ♣ **gastrocolic reflex**
       - The presence of food in the stomach causes increased motility in the colon.
       - This reflex clears out the intestinal chyme/feces from the last meal to make way for the new chyme it is about to receive.
       - It is because of the gastrocolic reflex that a person has an urge to defecate during or just after a meal.
   - **Mechanism**
     - The gastric phase is mediated by the hormone gastrin (Figure 7.16, Derrickson).

3. intestinal phase
   - the third phase
   - begins as soon as a significant amount of chyme enters into the small intestine.
   - The following activities occur during the intestinal phase of digestion:
     ♣ **release of pancreatic juice and bile into the lumen of the small intestine**
- The pancreatic juice and bile aid the small intestine in the digestion of food particles in luminal chyme.

- inhibition of gastric motility, secretion, and emptying
  - This prevents the small intestine from being overloaded with too much chyme.

- a feeling of satiety is experienced
  - The intestinal phase is mediated by several hormones: secretin, cholecystokinin, and GIP (Figures 7.17, 7.18, and 7.19, Derrickson).

♦ Clinical Applications and Disorders
  - Look up the following clinical applications and disorders in Tortora:

  1. mumps
     p. 908

  2. root canal therapy
     p. 909

  3. gastroesophageal reflux disease
     p. 914

  4. pylorospasm and pyloric stenosis
     p. 916

  5. vomiting
     p. 919

  6. pancreatitis and pancreatic cancer
     p. 922

  7. jaundice
     p. 925

  8. gallstones
     p. 926

  9. lactose intolerance
     p. 932

  10. absorption of alcohol
     p. 935
11. appendicitis  
   p. 938

12. polyps in the colon  
   p. 940

13. occult blood  
   p. 941

14. dietary fiber  
   p. 941

15. dental caries  
   p. 946

16. periodontal disease  
   p. 946

17. peptic ulcer disease  
   p. 946

18. diverticular disease  
   p. 946, 948

19. colorectal cancer  
   p. 948

20. hepatitis  
   p. 948

21. achalasia  
   p. 948

22. borborygmus  
   p. 948

23. canker sore  
   p. 948

24. cirrhosis  
   p. 948

25. colitis  
   p. 948
26. colonoscopy  
   p. 948, 949

27. colostomy  
   p. 949

28. dysphagia  
   p. 949

29. flatus  
   p. 949

30. food poisoning  
   p. 949

31. gastroscopy  
   p. 949

32. hemorrhoids  
   p. 949

33. hernia  
   p. 949

34. inflammatory bowel disease  
   p. 949

35. irritable bowel syndrome  
   p. 949

36. malocclusion  
   p. 949

37. Traveler’s diarrhea  
   p. 949

38. anorexia nervosa  
   p. 988

39. bulimia  
   p. 989
Figure 7.1
Overview of GI Function

**Digestion**
(occurs in the lumen of the GI tract)

- **Fish, chicken, steak, or pork** (protein) → digestive enzymes → **amino acids**
- **Baked potato** (starch) → digestive enzymes → **glucose molecules**
- **Butter** (triglyceride/fat) → digestive enzymes → **2 fatty acids, 1 monoglyceride**

**Cellular (Aerobic) Respiration**
(occurs inside body cells)

- **Monomer** (such as glucose, amino acid, or a fatty acid) + **O₂** → **CO₂ + H₂O + 32 ATP** (energy)
Figure 7.2
Components of the Digestive System

- Mouth (oral cavity) contains teeth and tongue
- Salivary glands
- Pharynx
- Esophagus
- Liver
- Stomach
- Gallbladder
- Pancreas
- Small intestine
- Large intestine
- Anus
Figure 7.3
Salivary Glands

- Parotid Gland
- Tongue (raised in mouth)
- Sublingual Gland
- Ducts of salivary glands
- Submandibular Gland
Figure 7.4
Pharynx and Larynx

- Nasal cavity
- Oral cavity
- Larynx
- Upper esophageal sphincter
- PHARYNX
- ESOPHAGUS
- Lower esophageal sphincter
- Stomach
Figure 7.5
Enzymes Involved in Protein Digestion
Figure 7.6
Pancreas, Liver, and Gallbladder

(a) Connections among the pancreas, liver, gallbladder, and duodenum

(b) Enlarged view of part of the pancreas

(c) Details of hepatopancreatic ampulla
Figure 7.7
Sites of Peptide Bond Cleavage by Protein-Digesting Enzymes
Figure 7.8
Bile Salts and Emulsification

(a) Examples of bile salts

(b) Representative structure of a bile salt

(c) Emulsification of a large lipid globule
Figure 7.9
Small Intestine
Figure 7.10
Brush Border Enzymes of the Small Intestine
Figure 7.11  CARBOHYDRATE DIGESTION

**MOUTH**

Saliva: SALIVARY AMYLASE

- salivary amylase

- starch → α-dextrins

**PANCREAS**

Pancreatic Juice

**SMALL INTESTINE**

Pancreatic Juice: PANCREATIC AMYLASE

- pancreatic amylase

- starch → α-dextrins

Brush Border Enzymes: α-DEXTROINASE, LACTASE, MALTASE, and SUCRASE

- α-dextrinase

- α-dextrins → glucose molecules

- lactase

- lactose → glucose, galactose

- maltase

- maltose → glucose, glucose

- sucrase

- sucrose → glucose, fructose
Figure 7.12 PROTEIN DIGESTION

STOMACH

Gastric Juice: PEPSIN

pepsin
protein $\rightarrow$ smaller peptides

PANCREAS

Pancreatic Juice

SMALL INTESTINE

Pancreatic Juice: TRYPSIN, CHYMOTRYPSIN, ELASTASE, and CARBOXYPEPTIDASE

trypsin
protein $\rightarrow$ smaller peptides

chymotrypsin
protein $\rightarrow$ smaller peptides

elastase
protein $\rightarrow$ smaller peptides

carboxypeptidase
smaller peptide $\rightarrow$ carboxyl amino acid

Brush Border Enzyme: AMINOPEPTIDASE

aminopeptidase
smaller peptide $\rightarrow$ amino amino acid
Figure 7.13  LIPID DIGESTION

MOUTH
Saliva: LINGUAL LIPASE

lingual lipase
triglyceride → 2 fatty acids, 1 monoglyceride
(in a small fat globule)

STOMACH
Gastric Juice: GASTRIC LIPASE

gastric lipase
triglyceride → 2 fatty acids, 1 monoglyceride
(in a small fat globule)

PANCREAS
Pancreatic Juice

GALLBLADDER
Bile

SMALL INTESTINE

Large fat globule → small fat globules
(bile (emulsification))

Pancreatic Juice: PANCREATIC LIPASE

pancreatic Lipase
triglyceride → 2 fatty acids, 1 monoglyceride
(in a small fat globule)
Figure 7.14
Absorption in the Small Intestine

(a) Mechanisms for nutrient absorption

(b) Movement of absorbed nutrients through blood and lymph
The sight, smell, thought, or initial taste of food activates neural centers in the cerebral cortex, hypothalamus, and medulla oblongata.

These regions of the brain then activate the facial (VII), glossopharyngeal (IX), and vagus (X) nerves.

The facial (VII) and glossopharyngeal (IX) nerves stimulate the salivary glands to secrete saliva. The vagus (X) nerves stimulate the secretory cells of the gastric glands to produce gastric juice.
Figure 7.16
Gastric Phase of Digestion: Gastrin

- chyme present in stomach lumen
- G cells of stomach
- Gastrin
  - secretion of gastric juice
  - gastrocolic reflex
  - gastric motility
  - contraction of LES
  - relaxation of pyloric sphincter
Figure 7.17
Intestinal Phase of Digestion: Secretin

- Chyme present in lumen of small intestine
- S cells of small intestine
- Secretin
- Secretion of pancreatic juice rich in bicarbonate ($\text{HCO}_3^-$) (neutralizes intestinal chyme)
Figure 7.18
Intestinal Phase of Digestion: CCK

chyme present in lumen of small intestine

I cells of small intestine

cholecystokinin (CCK)

secretion of pancreatic juice rich in digestive enzymes

hypothesis (causes feeling of satiety)

contraction of gallbladder; release of stored bile

relaxation of sphincter of Oddi
Figure 7.19
Intestinal Phase of Digestion: GIP

- Chyme present in lumen of the small intestine
- K cells of small intestine
- Gastric inhibitory peptide (GIP)
  - Decrease in gastric juice secretion
  - Decrease in gastric motility
  - Decrease in gastric emptying