Digestive System
Alimentary Tract and Accessory Organs

Function of Digestive System

1. Take in food and water
2. Break food down into nutrient molecules
3. Absorb molecules into the bloodstream
4. Rid body of any indigestible remains
5. Allows disposal of some metabolic wastes

Overview of Digestive System

1. **Alimentary canal (gastrointestinal or GI tract or gut)**
   - Continuous muscular tube that runs from the mouth to anus
   - Breaks down food into smaller fragments. Digests food: enzymes
   - Absorbs nutrient molecules through lining into blood
   - Organs: mouth, pharynx, esophagus, stomach, small intestine, large intestine, anus

2. **Accessory digestive organs**
   - Teeth
   - Tongue
   - Gallbladder
   - Digestive glands: produce secretions that help break down foodstuffs
     - Salivary glands
     - Liver
     - Pancreas

   - **Mechanical**
   - **Chemical**
   - **Lubrication**
Digestive Processes

• Processing of food involves six essential activities:

1. Ingestion
2. Propulsion
   • Peristalsis
   • Swallowing
3. Mechanical breakdown
   • Chewing
   • Churning, mixing
   • Segmentation: local constriction of intestine that mixes food with digestive juices
4. Digestion
   • series of catabolic steps
5. Absorption
   • blood or lymph
6. Defecation - Elimination
   • indigestible substances
   • Certain wastes produced by liver

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Histology of the Alimentary Canal

1. Mucosa
   • Functions:
     • Secretes mucus, digestive enzymes, and hormones
     • Absorbs end products of digestion
     • Protects against infectious disease
   • Capillaries, lymphoid follicles, localized movement, glands
   • Made up of three sublayers
     • Epithelium – stratified squamous or simple columnar, mucus producing
     • Lamina propria – areolar: ample space for follicles, capillaries, and mucosal glands
     • Muscularis mucosae

2. Submucosa
   • Composed of areolar connective tissue
   • Abundant amount of elastic tissue
   • Blood and lymphatic vessels
   • Lymphoid follicles
   • Submucosal nerve plexus

3. Muscularis externa
   • Circular and longitudinal muscle layer responsible for segmentation, peristalsis, and sphincters

4. Serosa (adventitia in some areas)
   • The visceral peritoneum
Figure 23.5 Basic structure of the alimentary canal.

Intrinsic nerve plexuses
- Myenteric nerve plexus
- Submucosal nerve plexus

Glands in submucosa

Muscosa
- Lamina propria
- Muscularis mucosae

Submucosa
- Circular layer
- Longitudinal layer

Serosa
- Connective tissue
- Epithelium (mesothelium)

Lumen
- Muscosa-associated lymphoid tissue

Glands in mucosa

Duct of gland outside alimentary canal

Mucosa
- Epithelium
- Lamina propria
- Muscularis mucosae

Submucosa
- Circular layer
- Longitudinal layer

Serosa
- Connective tissue
- Epithelium (mesothelium)

Lumen
- Muscosa-associated lymphoid tissue

Nerve and Blood Supply to Walls

• Blood Supply:
  - Splanchnic circulation includes
    - Arteries that branch off aorta to serve digestive organs
    - Hepatic, splenic, and left gastric arteries
  - Inferior and superior mesenteric arteries
  - Hepatic portal circulation
    - drains nutrient-rich blood from digestive organs
    - Delivers blood to liver for processing

• Enteric Nervous System
  - Submucosal nerve plexus
  - Myenteric nerve plexus
  - Semiautonomous
    - Controls patterns of segmentation and peristalsis
    - Linked to CNS: visceral sensory fibers (afferent), autonomic motor fibers synapse with internal plexi (called long reflex arcs)
    - 100 million neurons in plexi

Neural reflex pathways initiated by stimuli inside or outside the gastrointestinal tract.
Path of Alimentary Tract Begins at Oral Cavity and Pharynx

- Ingestion
- Propulsion
- Saliva
- Oral mucosa
- Lubricants
- Antimicrobial proteins
- Early enzyme introduction
- Particle size reduction
- Mechanical mixing
- Taste cell activation
- Olfactory membrane involvement

The salivary glands and tongue papillae

Deglutition (swallowing)

Skeletal muscle used here

All 4 tunics present

All smooth muscle here
Stomach Organization

- Storage
- Expands from 50 ml to 4 l
- Gastric juice
- Food becomes chyme
- Region of the pylorus squishes chyme and allows (“filters”) small amount of chyme to pass to duodenum; remainder pushed back into fundus – prepares food for SI
- Enteric pacemaker cells – 3 peristaltic waves per minute
- Lesser and greater omentum
- Stretch receptors
- Environment best for protein digestion

Peristaltic waves in the stomach.

1. Propulsion: Peristaltic waves move from the fundus toward the pylorus.
2. Grinding: The most vigorous peristalsis and mixing action occur close to the pylorus. The pyloric end of the stomach acts as a pump that delivers small amounts of chyme into the duodenum.
3. Retropulsion: The peristaltic wave closes the pyloric valve, forcing most of the contents of the pylorus backward into the stomach.

Microscopic anatomy of the stomach.

Gastric juice:
- Mucus producing cells
- Parietal cells: HCl + intrinsic factor (for SI absorption of B12 & RBC production)
- Chief cells: pepsinogen, lipase
- Enteroendocrine cells: paracrine and endocrine substances influencing blood flow and stomach secretions
- Up to 3 l/day

Mucosal barrier:
- Tissue regeneration
- Tight junctions join epithelial cells
- Bicarbonate-rich, thick mucus

Stomach acid:
- Kills many bacteria
- Chemically degrades food
- Activates enzymes supplementing chemical breakdown
Neural and hormonal mechanisms that regulate release of gastric juice.

Stimulatory events
- Cephalic phase
- Inhibitory events
- Para-Vagus nerve
- Cerebral cortex of food
- Hypothalamus and medulla oblongata
- Taste and smell receptors

Gastric phase
- Distension activates stretch receptors
- Long reflexes (via medulla and vagus nerve)
- G cells
- Short reflexes (especially peptides and caffeine) and rising pH activate chemoreceptors
- Gastrin release to blood
- Stomach secretory activity
- Sympathetic nervous system activation (overrides parasympathetic controls)

Intestinal phase
- Partially digested foods in duodenum
- Distension of the duodenum when stomach begins to empty
- Intestinal (enteric) gastrin release to blood
- Enterogastric reflex (involves both short and long reflexes)
- Brief effect of duodenum; presence of fatty, acidic, or hypertonic chyme
- Release of enterogastrones (secretin, cholecystokinin)
- Stimulate
- Inhibit sympathetic activity
- Appetite, depression
- Loss of food chemicals
- Acidity (pH < 2)
- Excessive stress
- Emotions
- Gastrin

Presence of fatty, hypertonic, solids chyme in duodenum
- Duodenal enteroadenocrine cells
- Chemoreceptors and stretch receptors
- Secrete
- Trigger
- Enterogastric reflex
- Short reflex via enteric neurons
- Long reflex via CNS centers and sympathetic activity; parasympathetic activity

Contractile force of stomach
- Rate of stomach emptying

The Small Intestine

Gross Anatomy
- Small intestine is the major organ of digestion and absorption
- 2–4 m long (7–13 ft) from pyloric sphincter to ileocecal valve, point at which it joins large intestine
- Small diameter of 2.5–4 cm (1.0–1.6 inches)
- Subdivisions
  - Duodenum: mostly retroperitoneal; ~25.0 cm (10.0 in) long; curves around head of pancreas
  - Jejunum: ~2.5 m (8 ft) long
  - Ileum: ~3.6 m (12 ft) long
- Blood supply:
  - Superior mesenteric artery brings blood supply
  - Veins (carrying nutrient-rich blood) drain into superior mesenteric veins, then into hepatic portal vein, and finally into liver
- Nerve supply
  - Parasympathetic innervation via vagus nerve, and sympathetic innervation from thoracic splanchnic nerves
Mesenteries of the abdominal digestive organs.

Microscopic Anatomy

- Modifications of small intestine for absorption
  - Huge surface area for nutrient absorption
    - Surface area is increased 600- to ~200 m² (size of a tennis court)
- Modifications include:
  - Length
  - Circular folds
    - Permanent folds (~1 cm deep)
  - Villi
    - Fingerlike projections of mucosa (~1 mm high)
    - Dense capillary bed
    - Lacteals
    - Absorptive enterocytes
- Microvilli
  - Brush border enzymes, used for final carbohydrate and protein digestion

Loss of cells here and regeneration from crypt base

Enterocytes (absorptive cells)
Lacteal
Goblet cell
Blood capillaries
Mucosa-associated lymphoid tissue
Intestinal crypt
Muscularis mucosae
Ducdenal gland

Microvilli (brush border)

1-2 l intestinal juice/day
- Water
- Mucus
- Lipidase & defensins – Paneth cells
- Hormones – enteroendocrine cells
Gross anatomy of the human liver – anterior view

Lobes are artificial designations not structural or functional designations

Gross anatomy of the human liver – posterior view

Microscopic anatomy of the liver.

Liver Lobules:
- Hepatocytes lining sinusoidal capillaries
- Stellate macrophages
- Central vein
- Bile ducts

Portal triads ‘at the corners’
Microscopic anatomy of the liver – marvel of natural selection

Hepatocyte Function

- Hepatocytes have increased rough and smooth ER, Golgi apparatus, peroxisomes, and mitochondria
- Produce ~900 ml bile per day
- Process bloodborne nutrients
  - Example: store glucose as glycogen and make plasma proteins
- Store fat-soluble vitamins
- Perform detoxification
  - Example: converting ammonia to urea
- Regenerate readily – complete regeneration in 6-12 months after 80% loss

Bile

- Yellow-green, alkaline solution containing:
  - Bile salts: cholesterol derivatives that function in fat emulsification and absorption
  - Bilirubin: pigment formed from heme
  - Bacteria break down in intestine to stercobilin that gives brown color of feces
  - Cholesterol, triglycerides, phospholipids, and electrolytes
- Enterohepatic circulation
  - Recycling mechanism that conserves bile salts
  - Bile salts are:
    1. Reabsorbed into blood by ileum (the last part of small intestine)
    2. Returned to liver via hepatic portal blood
    3. Resecreted in newly formed bile
  - About 95% of secreted bile salts are recycled, so only 5% is newly synthesized each time
The Gallbladder

- Gallbladder is a thin-walled muscular sac on ventral surface of liver
- Functions to store and concentrate bile by absorbing water and ions
- Contains many honeycomb folds that allow it to expand as it fills
- Muscular contractions release bile via cystic duct, which flows into bile duct

The Pancreas

- Location: mostly retroperitoneal, deep to greater curvature of stomach
- Exocrine function: produce pancreatic juice
  - Acini: zymogen granules containing proenzymes
  - Ducts: secrete to duodenum via main pancreatic duct; smaller duct cells produce water and bicarbonate
  - 1200-1500 ml/day watery, alkaline solution (pH 8)
  - Electrolytes, primarily HCO₃⁻
  - Digestive enzymes:
    - Proteases (for proteins): secreted in inactive form to prevent self-digestion – activated by intestinal enzymes
    - Amylase (for carbohydrates)
    - Lipases (for lipids)
    - Nucleases (for nucleic acids)
- Endocrine function: secretion of insulin and glucagon by pancreatic islet cells – one control over blood sugar concentration

Structure of the enzyme-producing tissue of the pancreas.

- Small duct
- Acinar cell (secretes enzymes)
- Zymogen granules
- Rough endoplasmic reticulum
- Basement membrane

- One acinus

- Duct cell (secretes HCO₃⁻ and H₂O)
Activation of pancreatic proteases in the small intestine.

What Are Enzymes?

• Enzyme: “A protein molecule produced by living organisms able to catalyze, or facilitate, a specific chemical reaction involving other substances without itself being destroyed or changed in any way.”
• “…speeding the rate at which a biochemical reaction proceeds but not altering the direction or nature of the reaction.”
Bile and Pancreatic Secretion into the Small Intestine

- Bile duct and pancreatic duct unite in wall of duodenum
  - Fuse together in bulblike structure called hepatopancreatic ampulla
- Ampulla opens into duodenum via volcano-shaped major duodenal papilla
- Hepatopancreatic sphincter controls entry of bile and pancreatic juice into duodenum
- Accessory pancreatic duct: smaller duct that empties directly into duodenum

Regulation of bile and pancreatic secretions

- Bile and pancreatic juice secretions are both stimulated by neural and hormonal controls
- Hormonal controls include:
  - Cholecystokinin (CCK)
  - Secretin
- Bile secretion is increased when:
  - Enterohepatic circulation returns large amounts of bile salts
  - Secretin, from intestinal cells exposed to HCl and fatty chyme, stimulates gallbladder to release bile
  - Hepatopancreatic sphincter is closed, unless digestion is active
- Bile is stored in gallbladder and released to small intestine only with contraction

Mechanisms promoting secretion and release of bile and pancreatic juice.

1. **CCK and secretin** are secreted by duodenal enteroendocrine cells.
   - Cholecystokinin (CCK): release is stimulated by proteins and fats in chyme.
   - Secretin release is stimulated by acidity of duodenal chyme.
   - CCK and secretin enter the circulation and cause the following four events:

2. **Pancreatic secretion**:
   - CCK induces secretion by acinar cells of enzyme-rich pancreatic juice.
   - Secretin causes secretion by duct cells of bicarbonate-rich pancreatic juice.
   - Vagus nerve stimulates weak gallbladder contraction during cephalic and gastric phases.

3. **CCK causes gallbladder contraction**.
   - CCK causes gallbladder contraction.
   - Vagus nerve weakly stimulates weak gallbladder contraction during cephalic and gastric phases.

4. **CCK causes secretion by liver**.
   - Bile salts returning from enterohepatic circulation are the most powerful stimulus for bile secretion.
   - Secretin is a minor stimulus.
   - CCK causes gallbladder contraction.
   - Vagus nerve weakly stimulates weak gallbladder contraction during cephalic and gastric phases.

5. **CCK induces secretion of enzyme-rich pancreatic juice**.
   - Secretin causes secretion of bicarbonate-rich pancreatic juice.
   - Vagus nerve weakly stimulates weak gallbladder contraction during cephalic and gastric phases.

Gross anatomy of the large intestine.

- Right colic (hepatic) flexure
- Transverse colon
- Superior mesenteric artery
- Haustra
- Ascending colon
- Ileum
- Ileocecal valve
- Cecum
- Appendix
- Rectum
- Anus
- Transverse mesocolon
- Epiploic appendages
- Descending colon
- Sigmoid colon
- Rectosigmoid junction
- External anal sphincter
Subdivisions of large intestine
1. Cecum: first part of large intestine
2. Appendix: masses of lymphoid tissue
   - Part of MALT
   - Bacterial storehouse capable of recolonizing gut when necessary
3. Colon: has several regions, most of which are retroperitoneal (except transverse and sigmoid)
   - Ascending colon ends at right colic (hepatic) flexure
   - Transverse colon ends left colic (splenic) flexure
   - Descending colon
   - Sigmoid colon: S-shaped portion that travels through pelvis
4. Rectum: three rectal valves
5. Anal canal: last segment of large intestine
   - Has two sphincters
     - Internal anal sphincter: smooth muscle
     - External anal sphincter: skeletal muscle

Reflexes and the Colon and Rectum

Defecation reflex.
Carbohydrate digestion and absorption in the small intestine.

Pancreatic amylase breaks down starch and glycogen into oligosaccharides and disaccharides.

Disaccharides break oligosaccharides and disaccharides into monosaccharides.

Monosaccharide carrier cotransports across the apical membrane of the absorptive epithelial cell. This active transport uses the Na$^+$ concentration gradient established by the Na$^+$–K$^+$ ATPase (pump) in the basolateral membrane.

Monosaccharides exit across the basolateral membrane via facilitated diffusion and enter the capillary via intercellular clefts.

Protein digestion and absorption in the small intestine.

Pancreatic proteases break down proteins and protein fragments into smaller pieces and some individual amino acids.

Brush border enzymes break protein fragments into amino acids.

Amino acids are cotransported across the apical membrane of the absorptive epithelial cell. This active transport uses the Na$^+$ concentration gradient established by the Na$^+$–K$^+$ ATPase (pump) in the basolateral membrane.

Amino acids exit across the basolateral membrane via facilitated diffusion and enter the capillary via intercellular clefts.

Emulsification, digestion, and absorption of fats.

Bile salts in the duodenum break large fat globules into smaller fat droplets, increasing the surface area available to lipase enzymes.

Pancreatic lipases hydrolyze triglycerides, yielding monoglycerides and free fatty acids.

Micelle formation. Micelles (consisting of fatty acids, monoglycerides, and bile salts) ferry their contents to epithelial cells. Monoglycerides diffuse from micelles into epithelial cells.

Fatty acids and monoglycerides recombine and package with other fatty substances and proteins to form chylomicrons.

Chylomicron formation. Chylomicrons are extruded from the epithelial cells by exocytosis, enter lacteals, and are carried away from the intestine in lymph.

Diffusion. Fatty acids and monoglycerides diffuse from the capillary into the lymphatic vessels.
Nucleic Acid Digestion

<table>
<thead>
<tr>
<th>Feedstuff</th>
<th>Enzymes and source</th>
<th>Site of action</th>
<th>Path of absorption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nucleic acids</td>
<td>Nucleases, ribonuclease, deoxyribonuclease</td>
<td>Small intestine</td>
<td>Small intestine</td>
</tr>
<tr>
<td>Pentose sugars, N-containing bases, phosphate ions</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Path of absorption:
- Vitamins identified by underlined text can be absorbed in the duodenum, though some are absorbed in the jejunum and ileum. 

Absorption of Vitamins, Electrolytes, and Water

- **Vitamin absorption**
  - In small intestine:
    - Fat-soluble vitamins (A, D, E, and K) are carried by micelles, diffuse into absorptive cells
    - Water-soluble vitamins (C and B) are absorbed by diffusion or by passive or active transport
    - Vitamin K\textsubscript{a} (large, charged molecule) binds with intrinsic factor and is absorbed by endocytosis
  - In large intestine: vitamin K and B vitamins from bacterial metabolism are absorbed

- **Absorption of electrolytes**
  - Most ions are transported actively along length of small intestine
  - Iron and calcium are absorbed in duodenum
  - Na\textsuperscript{+} absorption is coupled with active absorption of glucose and amino acids
  - Ca\textsuperscript{2+} is transported actively
  - K\textsuperscript{+} diffuses in response to osmotic gradient; lost if water absorption is poor
  - Usually amount in intestine is unabsorbed

- **Absorption of water**
  - Water is absorbed in the small intestine by osmosis
  - Potentially occurs if concentration gradient is established by active transport of solutes
  - Net osmosis occurs if concentration gradient is established by active transport of solutes
  - Water uptake is coupled with solute uptake

Table 23.2 - Overview of the Functions of the Gastrointestinal Organs

- **Mouth and accessory organs**
  - Vegetation: food is voluntarily placed into oral cavity
  - Propulsion: voluntary movement of food bolus toward stomach
  - Tongue: project food back into pharynx
  - Digestive enzymes: production of saliva
  - Dilation: voluntary opening of lips and activation of teeth
  - Salivary amylase: production of enzymes
  - Production of enzymes: production of saliva

- **Esophagus**
  - Digestion begins with digestion of food
  - Salivary amylase: production of enzymes
  - Digestion: secretion of enzymes

- **Stomach**
  - Secretion: production of gastric juice
  - Secretion: production of pepsinogen
  - Secretion: production of intrinsic factor

- **Small intestine**
  - Secretion: production of intrinsic factor
  - Secretion: production of intrinsic factor
  - Secretion: production of intrinsic factor

- **Large intestine**
  - Secretion: production of intrinsic factor
  - Secretion: production of intrinsic factor

- **Rectum**
  - Secretion: production of intrinsic factor

- **Intestines**
  - Secretion: production of intrinsic factor

- **Liver**
  - Secretion: production of intrinsic factor

- **Pancreas**
  - Secretion: production of intrinsic factor

- **Gallbladder**
  - Secretion: production of intrinsic factor

- **Liver**
  - Secretion: production of intrinsic factor

- **Intestines**
  - Secretion: production of intrinsic factor

- **Rectum**
  - Secretion: production of intrinsic factor
Table 23.2
Overview of the Functions of the Gastrointestinal Organs (continued)

<table>
<thead>
<tr>
<th>Organ</th>
<th>Major Functions</th>
<th>Comments/Additional Functions</th>
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<tbody>
<tr>
<td>Mouth (oral cavity)</td>
<td>Mechanical breakdown and propulsion</td>
<td>Small surface area modified for digestion and absorption (tongue, lips, and cheeks).</td>
</tr>
<tr>
<td>Tongue*</td>
<td>Mechanical breakdown and propulsion</td>
<td>Small surface area modified for digestion and absorption (tongue, lips, and cheeks).</td>
</tr>
<tr>
<td>Parotid gland</td>
<td>Salivary glands*</td>
<td>Small surface area modified for digestion and absorption (tongue, lips, and cheeks).</td>
</tr>
<tr>
<td>Sublingual gland</td>
<td>Small surface area modified for digestion and absorption (tongue, lips, and cheeks).</td>
<td></td>
</tr>
<tr>
<td>Submandibular gland</td>
<td>Small surface area modified for digestion and absorption (tongue, lips, and cheeks).</td>
<td></td>
</tr>
<tr>
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<td></td>
</tr>
</tbody>
</table>
| Esophagus | | - 
| Pharynx | | - 
| Stomach | | - 
| Pancreas* | | - 
| (Spleen) | | - 
| Liver* | | - 
| Gallbladder* | | - 
| Small intestine | | - 
| Duodenum | | - 
| Jejunum | | - 
| Ileum | | - 
| Transverse colon | | - 
| Descending colon | | - 
| Rectum | | - 
| Anal canal | | - 
| Large intestine | | - 
| Appendix | | - 
| Sigmoid colon | | - 
| Colon | | - 
| Rectum | | - 
| Anal canal | | - |

*The colored boxes indicate the major functions of the digestive system (gastrointestinal tract) illustrated in Figure 2.2.