I. Heterotrophic Processes

Figure 1: Stages of Food Processing

- Upon obtaining a food item, it is taken into the body or **Ingested**. Organisms cannot **DIRECTLY** utilize the macromolecules in a food item because:
  a) Food macromolecules are **too large to pass through cell membrane**.
  b) Food macromolecules are **not chemically identical to those of the organisms consuming it**. Therefore, they must be broken down & reassembled to form **species-specific molecules**.

- **Digestion**, the second stage of food processing, is the process of physically & chemically **breaking food molecules down into its constituent monomers** (simplest forms) that are small enough to be absorbed into body cells.

- **Absorption** involves the **passage of digestive end products into the cells** (often via the bloodstream) upon which they can be utilized for energy, growth, & repair.

- **Egestion/Defecation** involves the **elimination of undigested & unabsorbed materials** from the body into the surrounding environment.

II. Digestion (a Closer Look)

**Phases of Digestion**

- Mechanical Digestion: ________________________________________________________________
  ________________________________________________________________

- Chemical Digestion: ________________________________________________________________
  ________________________________________________________________

  a) Both phases of digestion occur **simultaneously**, with the mechanical phase **increasing surface area** of the food to facilitate & speed up the chemical phase.
Sites of Digestion

* Intracellular Digestion:

  a) Unicellular organisms (e.g., protists) practice intracellular digestion by chemical means with the help of lysosomes & their complement of hydrolytic enzymes.

* Extracellular Digestion:

  a) Animals exhibit extracellular digestion by both mechanical & chemical means in various cavities throughout the alimentary canal (certain WBC’s are the only components of the body that exhibit intracellular digestion).

III. Digestive Anatomy & Physiology

Figure 2: General Anatomy

* The smooth muscle comprising the alimentary canal is stimulated largely by the parasympathetic division ("rest & digest") of the autonomic nervous system. The activity of these same structures is inhibited by nerves of the sympathetic division of the autonomic nervous system.

* Alimentary Canal:

  a) Is associated with Accessory Organs such as the teeth, tongue, salivary glands, liver, gallbladder, & pancreas. These structures are NOT part of the canal, but contribute to the mechanical & chemical digestion of food within it.
  b) At some of junctions between segments, the canal’s wall is modified into ring-like valves called Sphincters, which close off sections of the canal like drawstrings, regulating the passage of material between successive chambers.
  c) Since the alimentary canal is open to the environment at both ends (mouth & anus), any material in it is considered to be external to the body until it is absorbed into the bloodstream.
Peristalsis:

- Peristalsis: __________________________________________________________________________

Figure 4: Peritoneum & Mesenteries

- The Peritoneum is a membrane that both lines the abdominal cavity (parietal aspect) & covers all abdominal organs (visceral aspect). These membranes & the fluid between them reduce friction as organs move w/in the abdomen.
- The Mesenteries are sheets of connective tissue that arise from the peritonium & bind organs to the abdominal wall. They provide a route by which vessels & nerves can pass from the body wall to the abdominal organs.
Components of the Alimentary Canal

Figure 5: Oral Cavity

- **Oral Cavity:**
  
a) **Mechanical Digestion:** during chewing, teeth cut, smash, & grind food, making it easier to swallow & increasing its surface area for the action of digestive enzymes.

b) **Chemical Digestion:** the salivary glands deliver *Saliva* (1L/day) through ducts into the oral cavity. Dissolved in saliva are many substances that aid in food processing:
  - **Mucin:** lubricates the soft lining of the oral cavity to protect it from abrasion. Its lubricating effect also facilitates the swallowing of food.
  - **Lysozyme:** antibacterial agent that limits the bacterial colonization of the oral cavity.
  - **Salivary Amylase:** hydrolyzes starch (plants) & glycogen (animals) into both smaller polysaccharides & the disaccharide maltose.
  - **Lingual Lipase:** enzyme secreted in an inactive form (zymogen) that is activated by stomach acid. Serves to hydrolyze a small amount of fat in the stomach.

Figure 5.1: Pharynx

- **Pharynx:**
While chewing, the tongue manipulates food against the palate (roof of the mouth) to form a “ball” or **Bolus**. During this time, following conditions exist in the lower pharynx (hypopharynx):

a) The upper esophageal (cardiac) sphincter is contracted.

b) The **Epiglottis**, a cartilaginous flap immediately above the larynx is up. Consequently, the **Glottis**, or opening within the larynx leading into the trachea, is open.

**Figure 5.2: Swallowing Mechanism**

- **ORAL PHASE**
  - Hard palate
  - Tongue
  - Epiglottis
  - Trachea
  - Esophagus
  - Soft palate
  - Bolus

- **PHARYNGEAL PHASE**
  - Vocal Folds: Open
  - Vocal Folds: Closed

- **The Swallowing Reflex** is comprised of a voluntary oral phase & an involuntary pharyngeal phase that includes the following actions:
  a) During the voluntary **Oral Phase** of the swallowing reflex:
     - the tongue pushes a bolus of food into the lower region of the pharynx (a).
     - the soft palate at the back of the oral cavity rises to block the nasal passages (b).
     - vocal folds associated with the vocal cords within the larynx are in an “open” position.
  b) During the involuntary **Pharyngeal Phase** of the swallowing reflex:
     - the root (base) of the tongue pushes against the epiglottis, forcing it **downward**.
     - at the same time, the larynx moves up to meet the descending epiglottis, causing it to cover the glottis & help prevent food & fluids from entering the trachea.
     - vocal folds within the larynx **come together & close off the glottis** to further prevent the passage of food & fluids from entering the trachea.
     - the upper esophageal sphincter (UES) relaxes, allowing the esophagus to open & the bolus or fluids to enter.
Esophagus:

- **Figure 5.3: Esophagus**

  - **Esophageal Peristalsis**
    - Direction of food movement
    - Contracted muscle
    - Food bolus
    - Relaxed muscle

Stomach:

- **Figure 5.4: Stomach**

  - **Gastric Gland**
    - Three layers of smooth muscle
    - Gastric lumen
    - Simple columnar epithelium
    - Gastric pit
    - Gastric gland

  - **Mechanical Digestion**: accomplished by *contractions of the smooth muscle* that comprises the stomach walls.

  - **Chemical Digestion**: accomplished by the action of **Gastric Glands** located w/in pits within the stomach lining. These glands produce & secrete digestive enzymes & acids by the action of the following cells:
    - **Regenerative Cells**: exhibit a *rapid rate of mitosis* to keep pace with the erosion of the stomach lining as it is exposed to acidic gastric juices.
- **Mucus Cells:** secrete a *thick, alkaline mucus* to slow the erosion of the stomach lining enough to allow the action of the regenerative cells to keep pace.

- **Chief Cells:** secrete the enzyme *Pepsin* (in an inactive form called *pepsinogen*) that initiates the *partial hydrolysis of proteins into smaller polypeptide chains*.

- **Parietal Cells:** secrete HCl (pH .8) that, once secreted into the stomach cavity, functions to:
  - Activates the zymogens pepsinogen & lingual lipase to their active forms to initiate the partial hydrolysis of protein & fats, respectively.
  - Breaks down connective tissue in animal matter & cell walls in plant matter.
  - Destroys most pathogens ingested with food.
  - The combination of HCl from parietal cells & pepsin from chief cells is called *Gastric Juice*.

- **Enteroendocrine Cells:** when we see, smell, taste, or even think about food, parasympathetic nerves will stimulate the release of the hormone Gastrin from enteroendocrine cells w/in gastric glands. As this hormone re-circulates back to the stomach, it stimulates parietal & chief cells of gastric glands to produce gastric juice.

**Investigation of Pepsin**
- Chief cells w/in a gastric gland initially secrete the enzyme pepsin in the form of the *inactive protein Pepsinogen* (contains an extra 44 amino acids blocking its active site). Upon its interaction with HCl, it is converted into its active form, pepsin.

Figure 5.5: Activation of Pepsinogen (→ Pepsin)

![Figure 5.5: Activation of Pepsinogen (→ Pepsin)](image)

Figure 5.6: Auto-Activation of Pepsinogen (+ Feedback)

![Figure 5.6: Auto-Activation of Pepsinogen (+ Feedback)](image)

- Since pepsin has the ability to activate pepsinogen, once some pepsin is formed via the interaction of pepsinogen w/HCl, even more pepsinogen can be quickly activated, an example of *positive feedback*.

- Pepsin hydrolyzes proteins by *breaking peptide bonds between tyrosine subunits*, thereby reducing the protein into *smaller polypeptide chains*.
The small intestine is the longest region of the alimentary canal & is the site where most all macromolecules within food are digested. It is also the site where the end products of digestion are absorbed into the bloodstream.

The inner wall of the small intestine is composed of large, Circular Folds that slow the migration of the chyme in order to maximize macromolecule digestion & the absorption of digestive end products.

These circular folds are covered in finger-like extensions called Villi, which in turn, are covered by even smaller fingerlike extensions called Microvilli. These microvilli constitute the Brush Border & are the actual site within the small intestine along which macromolecules are ultimately reduced to their simplest forms & absorbed into the body.
The interior of each villus is equipped with capillaries & extensions of the lymphatic system called **Lacteals** for the absorption of digestive end products into the body.

**Figure 5.9: Intestinal Brush Border**

**Figure 6: Motility of the Small Intestine**

- **Segmentation** involves contractions that move chyme back & forth within the small intestine. This action serves the following purposes:
  - Segmentation mixes chyme more completely w/pancreatic juices & enzymes.
  - Segmentation serves to increase chyme's contact w/the brush border enzymes.
  - These contractions also slowly *push chyme* further along the SI's length. Segmentation rate decreases w/distance to slowly move chyme toward colon. Ceases when most nutrients are absorbed. After segmentation ceases, peristalsis commences to remove any residual chime.
Figure 6.1: Activity of the Duodenum

Endocrine Activity of Duodenum

- As chyme from the stomach enters the Duodenum, the first 25cm (10in) of the small intestine, it stimulates it to release Enterogastrone that inhibits the digestive activity of the stomach by slowing peristalsis & the production of stomach secretions.

- Chyme’s low pH stimulates duodenal cells to secrete the hormone Secretin. This hormone signals the pancreas to release bicarbonate to neutralize chyme & ensure the proper functioning of pancreatic enzymes.

- A second hormone, CCK, is secreted in response to the presence of amino acids & fatty acids. CCK causes the gallbladder to contract & release Bile into the small intestine. CCK also stimulates the pancreas to release of Pancreatic Enzymes (bile duct & pancreatic duct join to form a single tube upon entering the SI). These enzymes, along with enzymes associated with the Brush Border, reduce ALL organic macromolecules to their simplest forms.

Figure 6.2: Fat Emulsification & Chemical Digestion
**Fat Emulsification & Chemical Digestion**

- As chyme enters duodenum, its fat molecules aggregate to form large **Globules** in order to shield themselves from their hydrophilic surroundings. In doing so, the globules exhibit very little surface area for the efficient chemical digestion by pancreatic lipases.

- Rhythmic segmentation in the SI serves to break the large fat globules into smaller **Droplets**, increasing the overall surface area that can be acted on by pancreatic lipases. Bile salts stick to the fat droplets, preventing them from reforming large globules (preserves the large surface area for efficient digestion).

- The mechanical mixture of fat droplets (hydrophobic) with the rest of the components of chyme (hydrophilic) by way of the action of segmentation & bile salts is called **Emulsification**. Following this process, the action of pancreatic lipase then reduces fats in the droplets to 2 free fatty acids & a monoglyceride.

**Table 1: Chemical Digestion of Macromolecules (Summary)**

![Chemical Digestion Diagram]

*Pancreatic Trypsin & Chymotrypsin* cleave peptide bonds between certain amino acids to form yet smaller polypeptides & dipeptides. **Pancreatic Carboxypeptidase** reduces small polypeptides to individual amino acids starting from the chain’s carboxyl end. **Duodenal Carboxypeptidase** & **Aminopeptidase** dismantle small polypeptides from both carboxyl & amino ends, respectively. **Duodenal Dipeptidases** act to dismantle dipeptides.

**IV. Absorption of Digestive End Products**

- Absorption of digestive end products occurs mainly across the **brush border** w/in the **Jejunum & Ileum** of the small intestine.

- As a general rule, **ALL DIGESTIVE END PRODUCTS OTHER THAN FATS ARE ABSORBED INTO THE CAPILLARIES OF EACH VILLUS**. Fats, on the other hand, are absorbed into the **lacteals** within each villus.
**Figure 7: Carbohydrate Absorption**

Steps of Carbohydrate Absorption:
1) **Na⁺ - K⁺ Pump**: establishes an electrochemical gradient (low Na⁺, (-) charge) w/in epithelial cell of villus.
2) **SGLT1 Cotransporter**: permits influx of extracellular Na⁺ down electrochemical gradient as glucose follows.
3) **GLUT5**: facilitates diffusion of fructose into epithelial cell of villus.
4) **GLUT2**: facilitates diffusion of all absorbed simple sugars from basolateral membrane into lumen of villus.

**Figure 7.1: Amino Acid/Peptide Absorption**

Steps of Amino Acid Absorption:
1) **Na⁺ - K⁺ Pump**: establishes an electrochemical gradient (low Na⁺, (-) charge) w/in epithelial cell of villus.
2) **NHE Cotransporter**: permits influx of extracellular Na⁺ down electrochemical gradient as free amino acids follow.
3) **PepT1 Cotransporter**: uptake of di/tripeptides stimulated by passive migration of H⁺ into villus epithelial cell.
4) All free amino acids pass into the lumen of the villus by way of facilitated diffusion.
The digestive tract receives 9 L of H₂O/day via food, fluids, & digestive juices (saliva, gastric/pancreatic juices, etc).

The small intestine reabsorbs 8 L of this water while the colon of the large intestine reabsorbs an additional .8 L (only .2 L mixed w/feces!). Thus, approximately 98% of the water that enters the digestive tract is reabsorbed into the bloodstream.

Together, the small & large intestine minimize the amount of water lost to the environment & are therefore adaptations against dehydration in terrestrial environments (the kidneys also minimize water loss during urine production).

**Hepatic Portal System**

The capillaries of the intestinal villi converge into a single channel, the Hepatic Portal Vein, which leads directly into the liver. This ensures that the liver has first access to amino acids & sugars absorbed following a meal (excess amino acids are deaminated & converted 1st into glucose & then to glycogen; glucose converted directly into glycogen). From the liver, blood travels to the heart, which pumps the blood & the nutrients it contains to all body tissues.
Steps of Fat Absorption:
1) Free fatty acids (FFA’s), monoglycerides, fat-soluble vitamins, & cholesterols absorbed & transported to the brush border by Micelles from bile.
2) FFA’s & monoglycerides dissociate from micelle & diffuse into villi epithelial cells where they reform fats.
3) Golgi forms Chylomicrons, hydrophilic association of FFA’s & monoglycerides w/cholesterol & proteins.
4) Large size of chylomicron complex requires diffusion into Lacteals instead of capillaries.

Figure 7.4: Large Intestine

- Large Intestine:
  a) Receives any undigested material that has **not been absorbed by the small intestine**. Enterobacteria residing within the colon digest plant fiber for which we have no enzymes, enabling us to get more nutrition from our food.
  b) Some enterobacteria also synthesize vitamin B (coenzymes) & K (blood clotting), which are subsequently absorbed.
  c) The colon also reabsorbs residual water that has not been absorbed by the small intestine (0.2L).
  d) Movement of material through the colon is slow, generally taking 12 to 24 hours to travel the length of the organ.
    As it does so, the reabsorption of water causes it to harden to form **Feces**.
  e) The terminal portion of the colon is called the **Rectum**, where feces are stored until they can be eliminated.