3. DIGESTION

To incorporate nutrients contained in foods, organisms have to be able to reduce particle size to sugars, fatty acids, amino acids or small peptides (Fig. 3-1). This process is called digestion.

Once the materials have reached these absorbable sizes they have to be translocated from the lumen of the intestine to the extracellular fluid of the gut for further processing and distribution throughout the body. This process of is called absorption (Figs. 3-2, 3-3).

To follow a somehow structured sequence in this complex subject, a general view of the digestive processes will be discussed first, followed by a review of some anatomical pertinent details, and then the types of foodstuff used by animals. Finally a review of the digestive process throughout the digestive tract and then a more detailed view for each type of material throughout the digestive system will be done.

The process of digestion is carried out with the support of mechanical reduction in particle size within the oral cavity and stomach and by enzymatic separation of individual elements in the stomach and small intestine. To sustain life, the organism also has to absorb micro and macronutrients, as well as, water.

The digestive process starts in the oral cavity where mastication reduces particle size and incorporates saliva into the ingesta. Saliva contains enzymes that will commence the degradation of some of the carbohydrates and lipids. The stomach contributes to the grinding and mixing of the food and starts the digestion of proteins with the help of acid and enzymes. Once the chyme passes into the small intestine, it receives pancreatic enzymes that almost complete the process of digestion for most materials. In the enterocytes of the small intestine, there are membrane bound enzymes which complete the digestion process and makes available for absorption the basic units of nutrients (Fig. 3-4).
DIGESTIVE PHASES

There are two phases to the digestive process going on simultaneously in the organism (Fig. 3-5). The luminal phase, which takes place in the lumen of the digestive tract, is dedicated to the initial hydrolysis of large particles into smaller components. This phase is carried out by the acid secreted in the stomach and by a variety of enzymes secreted either by the stomach, pancreas or intestine. The other phase is called the membranous phase and it is conducted by enzymes which are bound to the membranes of the enterocytes in the villi of the small intestine. This is the final step in the digestion of carbohydrates and proteins before their basic components are absorbed.

FUNCTIONAL ANATOMY

The small intestine is covered with villi, which contain mucus-producing goblet cells and enterocytes (Fig. 3-6). Between the villi exist the crypts of Lieberkühn where the enterocytes and goblet cells are generated before starting a migration pattern towards the tip of the villi where they reach the extrusion zone and are dislodged from the villi. As shown in the previous class, while in the crypts, the enterocytes are fluid secreting cells and when they reach the walls of the villi they are fluid and nutrient absorbing cells (Fig. 3-6).

In a more detailed view of adjacent enterocytes (Fig. 3-7), it can be seen that each cell has microvilli in the apical region to increase the absorptive area of the apical membrane. These microvilli are immersed in a mucus-like substance that reduces the speed of movement of the food particles, so they can be digested by the membrane bound enzymes associated with the membranous phase of digestion. The microvillus and the glycocalix constitute the brush border of the cells. Between cells there are tight junctions that prevent large molecules from infiltration. These junctions are not as tight as to prevent the escape of water from

TYPES OF DIGESTION

- **Luminal phase**
  - Takes place in the lumen of the digestive tract
  - Is the initial hydrolysis of food
  - Is carried out by secreted enzymes and acid

- **Membranous phase**
  - Conducted by enzymes attached to membranes of enterocytes

Figure 3-5 Phases of digestion

Figure 3-6. Transversal cut of the intestinal villi. Between villi are the crypts of Lieberkühn, in the middle enterocytes and goblet cells and, at the tip the extrusion zone where these aged cells are sloughed off.
the intracellular space which is also called lateral space. The sides of the cells are covered by the basolateral membrane and the base by the basement membrane, which contains fenestration among cells in the area of the lateral space.

NUTRIENTS

Carbohydrates

There are many types of carbohydrates (Fig. 3-8). They can be classified by size and degree of complexity or by their type of structure. Following the first criteria, carbohydrates can be grouped as complex polysaccharides, disaccharides and monosaccharides. The second classification criteria appear to be more useful to understand composition (Fig. 3-9).

Fibers

The most abundant carbohydrates are the fibers such as cellulose, which can not be digested by mammals. Ruminants, with bacterial fermentation can utilize these materials. Fibers contain a β-acetal bond between carbons 1 and 4 for which mammals do not produce the enzyme to hydrolyze it.

Sugars

The second types of carbohydrates are the sugars, such as sucrose and lactose, which are combinations of monosaccharides as glucose, fructose or galactose.

Starches

Starches are polysaccharides made of chains of glucose molecules that are linked by α-acetal (glycosidic) bonds between carbons 1 and 4. They...
are produced by vegetables. The enzyme to hydrolyze this bond is available in mammals. There are several types of starches. The more common starches are amylose and amylopectin (Fig. 3-10). Amylose is made of a single straight chain of glucoses joined by α-acetal bond between carbons 1 and 4 while amylopectin has the same shorter chains with branches generated by 1-6 α-acetal bonds.

Glycogen

A molecule similar to starches, but of animal origin. The molecule of glycogen is started with a nucleus called glycogenin that serves as the initial anchor for the growing chains (Fig. 3-9).

Lipids

The diet of animals contains a variety of lipids (Fig. 3-11). These lipids can range from simply emulsified fats to triglycerides complexe made of a glycerol molecule with three fatty acids. The fatty acids by themselves constitute a huge variety of compounds, which are classified according to the number of carbons and position of multiple bonds.

Cholesterol is another important lipid which is essential for the production of vital hormones, detergents and vitamins. Although an excess of cholesterol can be harmful to the organism, a lack of cholesterol is undoubtedly fatal.

Proteins

Proteins are sequences of amino acids. They range from very short to extremely long. The basic unit is an amino acid, which when joined with others becomes a small peptide. Larger chains of amino acids are called polypeptides and much longer ones are called protein chains (Fig. 3-12).

Structure of proteins

Proteins have primary, secondary, tertiary and quaternary structures. The sequence of amino acids in the molecule determines the primary structure. The spatial arrangement that the protein adopts, based on other forces or bonds, determine the secondary structure. The term shape serves to visualize this. Among these a protein may adopt a fibrous arrangement or a globular arrangement. The final rigid compact structure that the protein adopts after other chains have bound determines the tertiary structure of the protein. The term conformation is used to describe the combined secondary and tertiary structure. The quaternary structure depends on joining of identical or different chains in space.

OVERALL DIGESTIVE PROCESS

The digestive process commences as soon as the food enters the oral cavity (Fig. 3-13). Initially, mastication reduces the size of particles increasing the surface area to allow the enzyme digestion. The main

LIPIDS

- Emulsified fats
- Triglycerides
  - Fatty acids
  - Glycerol
- Cholesterol

Figure 3-11. Types of dietary lipids

PROTEINS

- QUATERNARY STRUCTURE
- POLYPEPTIDES
- AMINO ACIDS
- SMALL PEPTIDES

Figure 3-12. Composition of proteins

ORAL CAVITY

- MASTICATION
  - REDUCE SIZE
  - INCREASE SURFACE AREA
- SALIVARY
  - PROVIDES α-AMYLASE (absent in carnivores)
  - START CARBOHYDRATE DIGESTION
  - LINGUAL LIPASE (present in calves)
  - START LIPID DIGESTION
- SALIVARY ENZYMES ACT IN THE STOMACH
  - UNTIL INACTIVATED BY LOW pH

Figure 3-13. Digestion in the oral cavity
enzyme released in saliva is α-amylase, which reduces carbohydrates to smaller polysaccharides leaving chains as small as disaccharides, such as maltose, to units of 3-9 monosaccharides. In the mouth, only about 5% of the ingested carbohydrates get digested. This enzyme continues working in the stomach, but only for a short time until the drop in pH inactivates it. By this time about 30-40% of the carbohydrates has been partially digested, maltose being the predominant product. Carnivores do not produce α-amylase in saliva.

Calves and other lactating animals produce lingual lipase, an enzyme which starts the process of lipid digestion (Fig. 3-13). Once the food enters the stomach, there is significant mixing and maceration of the particles to further reduce particle size and to increase the surface area.

The acid produced in the stomach lowers the pH and starts hydrolyzing proteins. Low pH also contributes to the activation of proteolytic enzymes, thus, furthering the digestion of protein matter (Fig. 3-14).

In the intestine, the main digestive activity takes place. With the incorporation of bile, the fat is emulsified, its droplet size is reduced and packaged to be water soluble (Fig. 3-15).

The triglycerides are hydrolyzed to fatty acids and monoglycerides. These smaller molecules form micelles. At the same time the luminal phase of the carbohydrate digestion takes place producing a variety of sugars (Fig. 3-15, 3-16).

The large variety of proteolytic enzymes secreted by the pancreas contributes to further reduce the size of peptides producing small peptides and amino acids.
The final step in digestion takes place in the membranous phase of digestion for carbohydrates and proteins. As a result the monosaccharides glucose, fructose, galactose, etc are generated, as well as, amino acids, di and tripeptides.

**Carbohydrate digestion**

The initial digestion takes place in the luminal phase. As it should be clear by now, $\alpha$-amylase secreted in the saliva hydrolyzes starches into smaller polysaccharides. This generates material ranging from disaccharides (maltose) to oligosaccharides of up to 9 glucose.

This process continues in the stomach for about one hour, specifically in the body and fundus of the stomach. The digestion ceases when the enzyme is degraded by the acidic environment. By now 30-40% of the starches have been converted to maltose and other oligosaccharides (Figs. 3-15, 3-16).

### CARBOHYDRATE DIGESTION  
(membranous phase)

- Enzymes bound to enterocyte apical membrane
  - Lactase
  - Sucrase
  - Maltase
  - $\alpha$-dextrinase
  - Maltotriase
  - Isomaltase

In the intestine, the enzyme pancreatic $\alpha$-amylase, which is significantly more powerful than the salivary version, converts the reminder of the starches and oligosaccharides in only 15 minutes into di or polysaccharides, such as maltose, isomaltose, maltotriose, dextrin (Fig. 3-16). This completes the luminal phase of carbohydrate digestion.

From here on the membranous phase of digestion takes place (Fig. 3-17). The small polysaccharides move from the lumen of the intestine towards the surface of the villi epithelium where the intestinal mucus and gyocalyx in the brush border have created a zone of very little or no flux of water called the unstirred water layer. This layer permits molecules of polysaccharides to be captured and the membrane bound enzymes (lactase, sucrase, maltase, $\alpha$-dextrinase, maltotriase, isomaltase) digest them further (Figs. 3-18, 3-19).
The final product being only monosaccharides, such as glucose, fructose and galactose (Fig. 3-20).

**Protein digestion**

The process of digestion of proteins is similar to that used for carbohydrates. They both have a luminal phase which generates smaller polypeptides and a membranous phase which completes the digestion. In the case of protein there is a much larger number of enzymes involved and they are all secreted as proenzymes in order to protect the tissue that synthesizes them, and are then activated to perform digestion (Fig. 3-21).

**PROTEIN DIGESTION**

- **Similar to carbohydrates**
  - Luminal phase
    - Produce some single amino acids
  - Membranous digestion
    - Completes digestion
- **Many more enzymes involved**
  - Many different amino acids
- **All enzymes secreted as proenzymes**
  - Prevents self destruction

The digestion of proteins only starts in the stomach. In the oral cavity the particle size is reduced, but no specific proteolytic enzyme is added. The first exposure to a digestive environment that proteins encounter is the HCl in the stomach. HCl can hydrolyze some of the bonds in proteins, but its more important role is to provide an acidic environment in which other proteolytic enzymes may function. As pointed out previously all proteolytic enzymes are secreted as zymogens, that is, inactive enzymes. The HCl secreted in the stomach activates *pepsin* and *chymosin* from pepsinogen and chymosinogen respectively. These are two endopeptidases, or enzymes which hydrolyze bonds in the middle of the protein molecule, generating smaller polypeptides (Fig. 3-22).

Once the chyme moves to the duodenum the acidity activates enterokinase which in turn activates the zymogen trypsinogen to *trypsin* and trypsin activates the other pancreatic produced zymogens to chymotrypsin, elastase, carboxypeptidase A and B. Trypsin, as well as, *chemotrypsin* and *elastase* are all endopeptidases, while the two *carboxypeptidases* are exopeptidases, or enzymes that hydrolyze the last amino acid in a peptide.

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The membranous digestion for proteins is again similar to that of carbohydrates with the difference being that the proteases bound to the enterocytes do not always divide the chains to single amino acids and di or tripeptides can be absorbed by enterocytes.

**Fat digestion**

There is a minimal amount of digestion of fat by lipase in lactating animals. In adults, digestion starts with the preparation of the material in the stomach. Here it is emulsified and the solid fat globules start to liquify forming lipid droplets. Entering the small intestine, the bile acids from the liver or gallbladder completely emulsify the fat generating small droplets containing triglycerides, cholesterol, cholesterol esters as well as phospholipids (Fig. 3-23).

Once the droplets are formed these are attacked by two pancreatic enzymes which work in association. The *pancreatic co-lipase* displaces the bile acids coating the droplet, thus generating an area where the other enzyme, the *pancreatic lipase*, can access the triglycerides and hydrolyze two of the fatty acids leaving a monoglyceride. At the same time, other components of the droplet are hydrolyzed by other types of *pancreatic lipases*, particularly *cholesterol esterase* and *phospholipase*. The results of this hydrolysis are cholesterol, nonesterified fatty acids and lysophospholipids. All of these compounds are then released into the lumen of the intestine where they are rapidly grouped and coated with bile salts, and phospholipids to form micelles in preparation for absorption (Fig. 3-24).

**FAT DIGESTION**

- **Oral cavity**
  - Minimal initial digestion lipase
- **Stomach**
  - Initial emulsification
  - Fat globules liquify
    - Lipid droplets
- **Small intestine**
  - Emulsification is completed
  - Bile acids and phospholipids
  - Emulsified droplets are digested
    - *Pancreatic lipase* and *co-lipase*
      - Produce free fatty acids
      - Monoglycerides
    - *Cholesterol esterase* and *phospholipase*
      - Free fatty acids
      - Cholesterol
      - Lyso phospholipids
- **Micelle formation**
  - All digestion products surrounded by bile acids

*Figure 3-23. Sequence of events in the digestion of fats*

*Figure 3-24. Action of lipase and co-lipase on a lipid droplet, and formation of a micelle*