# Digestion of Food

## Digestion of Carbohydrates

When carbohydrates are digested, they are converted into monosaccharides. Specific enzymes in the digestive juices of the gastrointestinal tract return the hydrogen and hydroxyl ions from water to the polysaccharides and thereby separate the monosaccharides from each other.

1. Digestion of Carbohydrates in the Mouth and Stomach.

i. When food is chewed, it is mixed with saliva, which contains the digestive enzyme ptyalin (an α-amylase) secreted mainly by the parotid glands.
ii. This enzyme hydrolyzes starch into the disaccharide maltose and other small polymers of glucose that contain three to nine glucose molecules. However, the food remains in the mouth only a short time, so probably not more than 5 percent of all the starches will have become hydrolyzed by the time the food is swallowed.
iii. Starch digestion sometimes continues in the body and fundus of the stomach for as long as 1 hour before the food becomes mixed with the stomach secretions. Then activity of the salivary amylase is blocked by acid of the gastric secretions because the amylase is essentially nonactive as an enzyme once the pH of the medium falls below about 4.0.

Starch $\xrightarrow{\text{Ptyalin (saliva)}}$ Maltose

2. Digestion of Carbohydrates in the Small Intestine by Pancreatic Secretion:

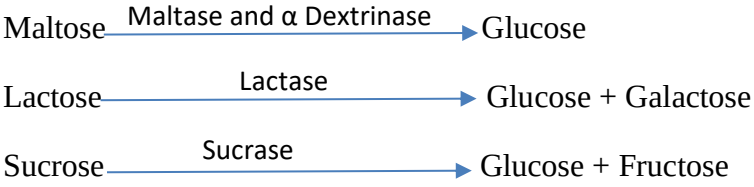
Pancreatic secretion, contains a large quantity of α-amylase that is several times as powerful. Therefore, within 15 to 30 minutes after the chyme empties from the stomach into the duodenum and mixes with pancreatic juice, virtually all the carbohydrates will have become digested.

Starch $\xrightarrow{\text{Pancreatic Amylase}}$ Maltose

3. Hydrolysis of Disaccharides and Small Glucose Polymers into Monosaccharides by Intestinal Epithelial Enzymes.

i. The enterocytes lining the villi of the small intestine contain four enzymes (lactase, sucrase, maltase, and α-dextrinase), which are capable of splitting the disaccharides lactose, sucrose, and maltose, plus other small glucose polymers, into their constituent monosaccharides.
ii. These enzymes are located in the enterocytes covering the intestinal microvilli brush border, so the disaccharides are digested as they come in contact with these enterocytes.
iii. Lactose splits into a molecule of galactose and a molecule of glucose.
iv. Sucrose splits into a molecule of fructose and a molecule of glucose.
v. Maltose and other small glucose polymers all split into multiple molecules of glucose.

vi. Thus, the final products of carbohydrate digestion are all monosaccharides. They are all water soluble and are absorbed immediately into the portal blood.




**Digestion of proteins**

1. Digestion of Proteins in the Stomach.

i. A large quantity of hydrochloric acid is secreted by the parietal (oxyntic) cells in the gastric glands at a pH of about 0.8. By the time it is mixed with the stomach contents and with secretions from the nonoxyntic glandular cells of the stomach, the pH then averages around 2.0 to 3.0, which is a highly favorable range of acidity for pepsin activity.
ii. Pepsin only initiates the process of protein digestion, usually providing only 10 to 20 percent of the total protein digestion to convert the protein to proteoses, peptones, and a few polypeptides. This splitting of proteins occurs as a result of hydrolysis at the peptide linkages between amino acids.
iii. The collagen, an albuminoid type of protein that is affected little by other digestive enzymes, can be digested by pepsin.

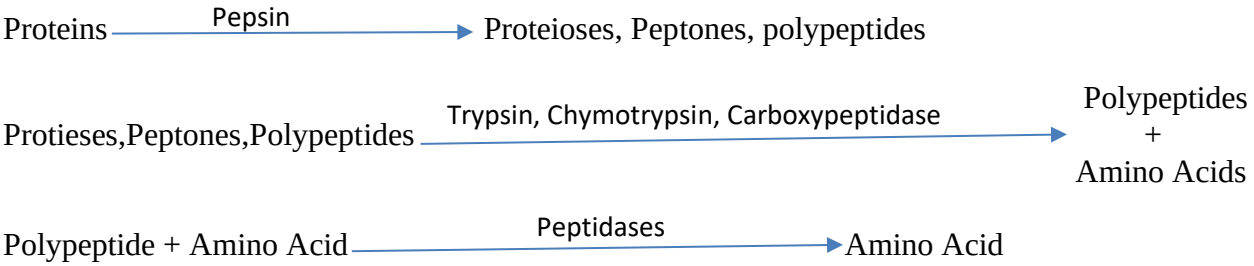
2. Protein Digestion by the Actions of Pancreatic Proteolytic Enzymes.

i. Most protein digestion occurs in the upper small intestine, in the duodenum and jejunum, under the influence of proteolytic enzymes from pancreatic secretion.
ii. Immediately on entering the small intestine from the stomach, the partial breakdown products of the protein foods are attacked by major proteolytic pancreatic enzymes: trypsin, chymotrypsin, carboxypolypeptidase, and proelastase.
iii. Both trypsin and chymotrypsin split protein molecules into small polypeptides; carboxypolypeptidase then cleaves individual amino acids from the carboxyl ends of the polypeptides.
iv. Proelastase, in turn, is converted into elastase, which then digests elastin fibers that partially hold meats together.
v. Only a small percentage of the proteins are digested all the way to their constituent amino acids by the pancreatic juices. Most remain as dipeptides and tripeptides.

3. Digestion of Peptides by Peptidases in the Small Intestinal Enterocytes:

i. The last digestive stage of the proteins in the intestinal lumen is achieved by the enterocytes that line the villi of the small intestine, mainly in the duodenum and jejunum.

ii. These cells have a brush border that consists of hundreds of microvilli projecting from the surface of each cell. In the membrane of each of these microvilli are multiple peptidases that protrude through the membranes to the exterior.
iii. Two types of peptidase enzymes are especially important, aminopolypeptidase and several dipeptidases. They succeed in splitting the remaining larger polypeptides into tripeptides and dipeptides and a few into amino acids.
iv. Both the amino acids plus the dipeptides and tripeptides are easily transported through the microvillar membrane to the interior of the enterocyte.
v. Finally, inside the cytosol of the enterocyte are multiple other peptidases that are specific for the remaining types of linkages between amino acids.
vi. All the last dipeptides and tripeptides are digested to the final stage to form single amino acids; these then pass on through to the other side of the enterocyte and thence into the blood.




**Digestion of Fats**

1. Digestion of Fats in the Intestine.

A small amount of triglycerides is digested in the stomach by lingual lipase that is secreted by lingual glands in the mouth and swallowed with the saliva. This amount of digestion is less than 10 percent and generally unimportant.

2. Digestion in small intestine by emulsification

i. The first step in fat digestion is physically to break the fat globules into small sizes so that the water-soluble digestive enzymes can act on the globule surfaces. This process is called emulsification of the fat, and it begins by agitation in the stomach to mix the fat with the products of stomach digestion.
ii. Then, most of the emulsification occurs in the duodenum under the influence of bile secreted from the liver. Bile contains a large quantity of bile salts, as well as the phospholipid lecithin.
iii. Both of these, but especially the lecithin, are extremely important for emulsification of the fat.
iv. The polar parts of the bile salts and lecithin molecules are highly soluble in water, whereas most of the remaining portions of their molecules are highly soluble in fat.

v. Therefore, the fat-soluble portions of these liver secretions dissolve in the surface layer of the fat globules, with the polar portions projecting. The polar projections, in turn, are soluble in the surrounding watery fluids, which greatly decreases the interfacial tension of the fat and makes it soluble as well.
vi. When the interfacial tension of a globule of nonmiscible fluid is low, this nonmiscible fluid, on agitation, can be broken up into many tiny particles far more easily than it can when the interfacial tension is great.
vii. Consequently, a major function of the bile salts and lecithin, especially the lecithin, in the bile is to make the fat globules readily fragmentable by agitation with the water in the small bowel.
viii. Each time the diameters of the fat globules are significantly decreased as a result of agitation in the small intestine, the total surface area of the fat increases manyfold. Because the average diameter of the fat particles in the intestine after emulsification has occurred is less than 1 micrometer, this represents an increase of as much as 1000-fold in total surface areas of the fats caused by the emulsification process.
ix. The lipase enzymes are water-soluble compounds and can attack the fat globules only on their surfaces. Consequently, this detergent function of bile salts and lecithin is very important for digestion of fats.

3. Digestion of Triglycerides by Pancreatic Lipase.

By far the most important enzyme for digestion of the triglycerides is pancreatic lipase, present in enormous quantities in pancreatic juice, enough to digest within 1 minute all triglycerides that it can reach. In addition, the enterocytes of the small intestine contain additional lipase, known as enteric lipase, but this is usually not needed. Most of the triglycerides of the diet are split by pancreatic lipase into free fatty acids and 2-monoglycerides.

4. Micelle formation of Bile Salts

i. Bile salts, when in high enough concentration in water, have the propensity to form micelles, which are small spherical, cylindrical globules 3 to 6 nanometers in diameter composed of 20 to 40 molecules of bile salt.
ii. These develop because each bile salt molecule is composed of a sterol nucleus that is highly fat-soluble and a polar group that is highly water-soluble.
iii. The sterol nucleus encompasses the fat digestate, forming a small fat globule in the middle of a resulting micelle, with polar groups of bile salts projecting outward to cover the surface of the micelle.
iv. Because these polar groups are negatively charged, they allow the entire micelle globule to dissolve in the water of the digestive fluids and to remain in stable solution until the fat is absorbed into the blood.

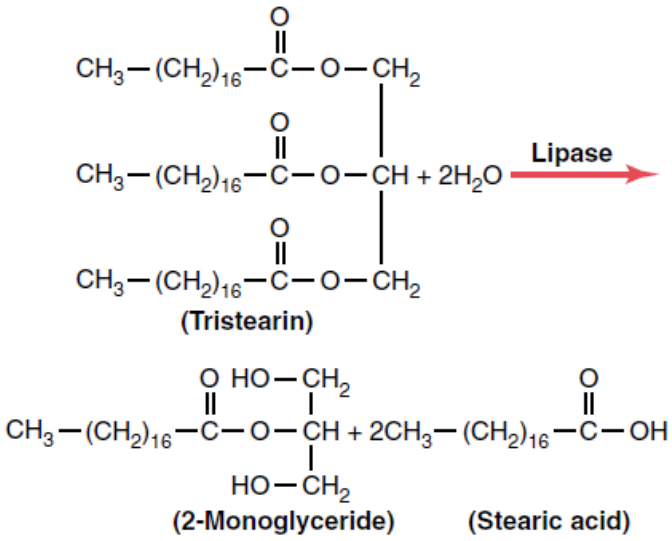
v. The bile salt micelles also act as a transport medium to carry the monoglycerides and free fatty acids, both of which would otherwise be relatively insoluble, to the brush borders of the intestinal epithelial cells.

vi. There the monoglycerides and free fatty acids are absorbed into the blood, but the bile salts themselves are released back into the chyme to be used again and again for this "ferrying" process.

vii. The bile salts play the additional important role of removing the monoglycerides and free fatty acids from the vicinity of the digesting fat globules almost as rapidly as these end products of digestion are formed.

Digestion of Cholesterol Esters and Phospholipids.

Both the cholesterol esters and the phospholipids are hydrolyzed by two other lipases in the pancreatic secretion that free the fatty acids—the enzyme cholesterol ester hydrolase hydrolyzes the cholesterol ester, and phospholipase A2 to hydrolyze the phospholipid. The bile salt micelles play the same role in "ferrying" free cholesterol and phospholipid molecule digestates.




**Absorption of carbohydrates**

Essentially all the carbohydrates in the food are absorbed in the form of monosaccharides. By far the most abundant of the absorbed monosaccharides is glucose, usually accounting for more than 80 percent of carbohydrate calories absorbed. The remaining 20 percent of absorbed monosaccharides is composed almost entirely of galactose and fructose, the galactose derived from milk and the fructose as one of the monosaccharides digested from cane sugar. Virtually all the monosaccharides are absorbed by an active transport process.

1. Glucose Transport

i. The glucose absorption occurs in a co-transport mode with active transport of sodium. There are two stages in the transport of sodium through the intestinal membrane.
ii. First is active transport of sodium ions through the basolateral membranes of the intestinal epithelial cells into the blood, thereby depleting sodium inside the epithelial cells.
iii. Second, decrease of sodium inside the cells causes sodium from the intestinal lumen to move through the brush border of the epithelial cells to the cell interiors by a process of secondary active transport.
iv. Intestinal glucose also combines simultaneously with the same transport protein and then both the sodium ion and glucose molecule are transported together to the interior of the cell.
v. Thus, the low concentration of sodium inside the cell literally "drags" sodium to the interior of the cell and along with it the glucose at the same time. Once inside the epithelial cell, other transport proteins and enzymes cause facilitated diffusion of the glucose through the cell's basolateral membrane into the paracellular space and from there into the blood.

2. Absorption of Other Monosaccharides.

Galactose is transported by almost exactly the same mechanism as glucose. Conversely, fructose transport does not occur by the sodium co-transport mechanism. Instead, fructose is transported by facilitated diffusion all the way through the intestinal epithelium but not coupled with sodium transport. Much of the fructose, on entering the cell, becomes phosphorylated, then converted to glucose, and finally transported in the form of glucose the rest of the way into the blood. Because fructose is not co-transported with sodium, its overall rate of transport is only about one half that of glucose or galactose.

**Absorption of Proteins**

i. Most proteins, after digestion, are absorbed through the luminal membranes of the intestinal epithelial cells in the form of dipeptides, tripeptides, and a few free amino acids.
ii. The energy for most of this transport is supplied by a sodium co-transport mechanism. Most peptide or amino acid molecules bind in the cell's microvillus membrane with a specific transport protein that requires sodium binding before transport can occur.
iii. After binding, the sodium ion then moves down its electrochemical gradient to the interior of the cell and pulls the amino acid or peptide along with it. This is called co-transport (or secondary active transport) of the amino acids and peptides.
iv. A few amino acids do not require this sodium co-transport mechanism but instead are transported by special membrane transport proteins in the same way that fructose is transported, by facilitated diffusion.

v. At least five types of transport proteins for transporting amino acids and peptides have been found in the luminal membranes of intestinal epithelial cells. This multiplicity of transport proteins is required because of the diverse binding properties of different amino acids and peptides.

**Absorption of Fats**

i. When fats are digested to form monoglycerides and free fatty acids, both of these digestive end products first become dissolved in the central lipid portions of bile micelles. Because the small molecular dimensions (3 to 6 nanometers in diameter only), and highly charged exterior, the micelles are soluble in chyme.
ii. In this form, the monoglycerides and free fatty acids are carried to the surfaces of the microvilli of the intestinal cell brush border and then penetrate into the recesses among the moving, agitating microvilli.
iii. Here, both the monoglycerides and fatty acids diffuse immediately out of the micelles and into the interior of the epithelial cells, which is possible because the lipids are highly permeable in the epithelial cell membrane.
iv. This leaves the bile micelles still in the chyme, where they function again and again to help absorb still more monoglycerides and fatty acids. Thus, the micelles perform a "ferrying" function that is highly important for fat absorption.
v. After entering the epithelial cell, the fatty acids and monoglycerides are taken up by the cell's smooth endoplasmic reticulum; here, they are mainly used to form new triglycerides that are subsequently released in the form of chylomicrons through the base of the epithelial cell, to flow upward through the thoracic lymph duct and empty into the circulating blood.
vi. Small quantities of short- and medium-chain fatty acids, such as those from butterfat, are absorbed directly into the portal blood.
vii. The cause of this difference between short- and long-chain fatty acid absorption is that the short-chain fatty acids are more water soluble and mostly are not reconverted into triglycerides by the endoplasmic reticulum. This allows direct diffusion of these short-chain fatty acids from the intestinal epithelial cells directly into the capillary blood of the intestinal villi.